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ORIGINAL PAPER

Estimation of anthropogenic heat emission in the Gyeong-In region of Korea

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Abstract The anthropogenic heat emission in the Gyeong-In region of Korea in 2002 is estimated based on the energy consumption statistics data. The energy consumption over the region is categorized into four energy sectors: electricity use, transportation, point sources, and area sources. The estimated annual mean anthropogenic heat emissions in Seoul, Incheon, and Gyeonggi are found to be 55, 53, and 28 W m^{-2}, respectively. A major contributing energy sector to anthropogenic heat emission in the Gyeong-In region is area sources including the residential, commercial, and small industrial sectors, which account for 40% of the total heat emission from the three administrative districts, and transportation and electricity use follow. The distributions of the annual, monthly, and hourly mean anthropogenic heat emission for all energy sectors are presented in the 0.01° longitude × 0.01° latitude grid domain. The presently estimated anthropogenic heat emission data can be used in mesoscale meteorological and environmental modeling in the Gyeong-In region.

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1 Introduction

The urban heat island (UHI), which is a well-known phenomenon in cities, can be influenced not only by urban physical and geometrical factors such as roughness length, thermal inertia, canyon aspect ratio and orientation, sky view factor, city size, and population but also by meteorological conditions such as wind speed, cloudiness, relative humidity, stability of the atmospheric boundary layer, and cold/warm advection (Vukovich 1971; Oke 1973; Oke and Maxwell 1975; Bornstein 1975; Seaman et al. 1989; Yoshikado 1992; Eliasson 1996; Klysik and Fortuniak 1999; Kim and Baik 2002; Atkinson 2003). Anthropogenic heat generated by human activities in urban areas can also have a significant influence on the dynamics and thermodynamics of an urban boundary layer (Ichinose et al. 1999; Block et al. 2004; Fan and Sailor 2005). Moreover, the increase in air temperature by the injected heat can enhance local circulations and photochemical processes (e.g., photochemical reaction rate, biogenic emission).

Accurate estimation of anthropogenic heat emission is of primary importance in investigating local circulations, local thermal environment, and associated pollution issues. The anthropogenic heat emission is basically dependent on energy consumption in the area of interest. Two approaches can be used to estimate anthropogenic heat emission: bottom-up and top-down approaches as is the case for the estimation of air pollutant emission. When the bottom-up approach is applied, it requires building-level energy-consumption data. The heat emission in this approach can be directly estimated by summing up the energy consumption spatially and temporally in the area of interest. However, the application of this approach would be limited to a part of a city due to great efforts and expenses for gathering highly specific energy consumption data. Ichinose et al. (1994) used a modified bottom-up approach for mesoscale atmospheric modeling, in which energy statistics data and a digital geographical land-use dataset with a spatial resolution of 25 m were used for the estimation of anthropogenic heat emission in Tokyo. Urban land-use types in Tokyo were classified into 12 categories (office, education, welfare, department store, shop, hotel, leisure, residence, apartment house, industry, vehicle, and train), then the representative energy consumption per floor of buildings was estimated using the energy statistics data, and finally the anthropogenic heat emission with a spatial scale of 250 m was calculated by multiplying the corresponding energy consumption by the number of floors of the land-use categories.

When the top-down approach is applied, total anthropogenic heat emission in a city scale or a larger region is estimated using seasonal or annual energy consumption data and then spatial and temporal allocating factors are applied for the horizontal and temporal distributions. This approach is of great benefit to mesoscale atmospheric modeling for cities with relatively large spatial ranges (Sailor and Lu 2004). However, it requires reliable spatial and temporal allocation factors. Recently developed methodologies are extended for better representing anthropogenic heating (Ohashi et al. 2007; Sailor et al. 2007).

There are many studies on the estimation of anthropogenic heat emission for various cities in the world (Kalma 1974; Harrison et al. 1984; Ichinose et al. 1994; Klysik 1996; Son et al. 2000; Khan and Simpson 2001; Sailor and Lu 2004; Pigeon et al. 2007). Among them, Ichinose et al. (1994) showed that the anthropogenic heat emission in the central area of Tokyo is 400 W m^{-2} in the daytime and has a maximum value of 1590 W m^{-2} at the winter morning hours. Sailor and Lu (2004) estimated the anthropogenic heat emission in large US cities using the top-down approach, along with representative temporal profiles for the cities. The analysis showed that the largest anthropogenic heat emission is found in winter with values of 70–75 W m^{-2} in Chicago, San Francisco, and Philadelphia when averaged over the entire city. Son et al. (2000) estimated anthropogenic heat emission in Pusan, Korea using a method similar to that of Ichinose et al. (1994). The annual mean anthropogenic heat emission over the 4 km^2 urbanized area was estimated to be about 42 W m^{-2} with spatial distributions from 31 to 60 W m^{-2} in winter. Note that the estimated anthropogenic heat emissions largely depend on temporal and spatial resolutions so that a quantitative comparison of heat emission intensity among cities may not be meaningful.

The purpose of this study is to estimate anthropogenic heat emission in the Gyeong-In region of Korea using a top-down approach for use in mesoscale meteorological and environmental modeling, in which energy consumption sources are classified into four sectors including electricity, transportation, point sources, and area sources.

2 Description of the study region

The Gyeong-In region is composed of three administrative districts of Seoul, Incheon, and Gyeonggi. The population over 20 million, about 50% of the total population of Korea, is concentrated in this region. Seoul is located in the west central part of the Korean Peninsula and has a population of 10 million with 3.7 million households, representing about a quarter of the entire population of the nation and one of the most densely populated cities in the world. Incheon is bordered on the east by Seoul and on the west by the Yellow Sea. Incheon has a population of about 2.6 million with 0.9 million households. The Gyeonggi province surrounds Seoul with as much population and households as Seoul. The fraction of urbanized land area used as residential area, industrial area, commercial area, school, road, and so on to the total area is as high as 55% in Seoul and 16% in Incheon, whereas a large portion of Gyeonggi is composed of forest and agricultural areas. Table 1 lists the total area, percentage of urbanized area, population, and numbers of households in Seoul, Incheon, and Gyeonggi.

Figure 1 shows the horizontal distribution of population density in the Gyeong-In region. High population density over 10,000 persons km^{-2} is largely distributed in Seoul and Incheon, whereas Gyeonggi has low population density except for a few satellite cities of Seoul. A maximum population density of 55,697 persons km^{-2} is found in Seoul. The mean population density in Seoul is about 17,000 persons km^{-2} which is greater than that in most of large US cities and Tokyo (Sailor and Lu 2004; Hung et al. 2006).

Table 1 Statistics of population and households in Seoul, Incheon, and Gyeonggi

	Total area (km^2) (%)	Population (million)	Household (million)
Seoul	605.5 (54.7)	10.28	3.7
Incheon	980.0 (16.2)	2.60	0.9
Gyeonggi	10137.0 (8.7)	10.36	3.6

The percentage of urbanized area to the total land area is shown in parentheses

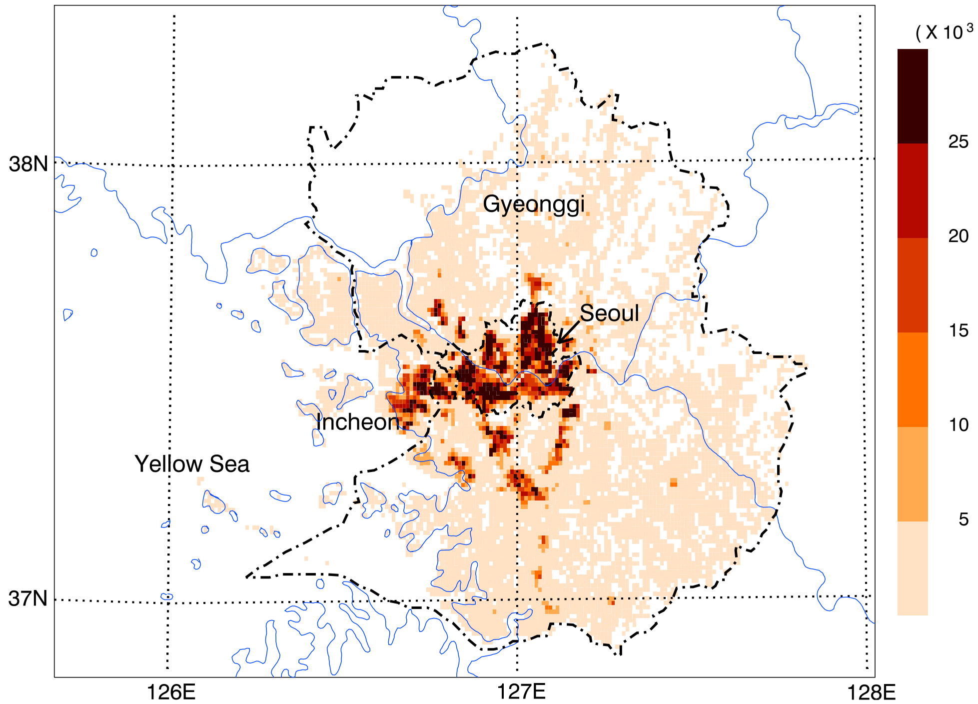


Fig. 1 Population density (persons km^{-2}) distribution in the Gyeong-In region. Administrative boundaries are indicated by *dashed-dot lines*

3 Estimation of anthropogenic heat emission

3.1 Methodology and statistical data used

In order to estimate anthropogenic heat emission in the region, four energy sectors of electricity, transportation, point sources, and area sources are separately considered based on a top-down approach except for point sources for which a bottom-up approach is applied. Table 2 shows the classification of the energy sectors and associated emission inventories. The sectors of electricity and area sources have four subcategories of residential, public, commercial/service, and industrial sectors in terms of land-use type. In the classification, area sources include fossil fuels such as coal, oil, liquefied petroleum gas (LPG), liquefied natural gas (LNG), and so forth. The energy consumption associated with the subway is included in the commercial/service subcategory of the electricity use sector. Point sources are characterized as large energy consuming facilities such as thermal power station and oil refining facilities. In this study, the facilities that are monitored by the Ministry of Environment of Korea are included. Transportation sector is divided into passenger car, bus, and truck in terms of vehicle types. Fuel types used for the cars include gasoline, LPG, and diesel fuel. Figure 2 represents a flow chart for calculating gridded anthropogenic heat emission in the Gyeong-In region. For the energy sectors, the annual anthropogenic heat emission is estimated based on the data of energy consumption statistics in the region. Given a spatial grid resolution, the annual anthropogenic heat emission is spatially distributed using spatial surrogates

Table 2 Classification of energy sectors and description of emission inventory for each sector

Classification	Description of emission inventory
Electricity	Subcategories: Residential sector (single family house, apartment, etc.) Public sector (public official buildings, military facilities, school, etc.) Commercial/service sector (commercial facilities, subway, etc.) Industrial sector (small factories, heat supply equipment, manufacturing facilities such as machinery, food, petroleum, metal, textile, clothes, etc.)
Transportation	Sources: Passenger car (personal passenger car, taxi, etc.) Bus (light-duty bus, medium-duty bus, heavy-duty bus, etc.) Truck (light-duty truck, medium-duty diesel truck, heavy-duty diesel truck, trailer, fire truck, etc.) Fuel types: gasoline, LPG, diesel fuel
Point sources	Large energy consuming facilities (thermal power stations, large heat supply facilities, oil refining facilities, boilers of industries, etc.) 28 points in Seoul 104 points in Incheon 365 points in Gyeonggi Fuel types: coal, oil, etc.
Area sources	Subcategories: Residential sector Public sector Commercial sector Industrial sector Fuel types: coal, oil, LPG, LNG, etc.

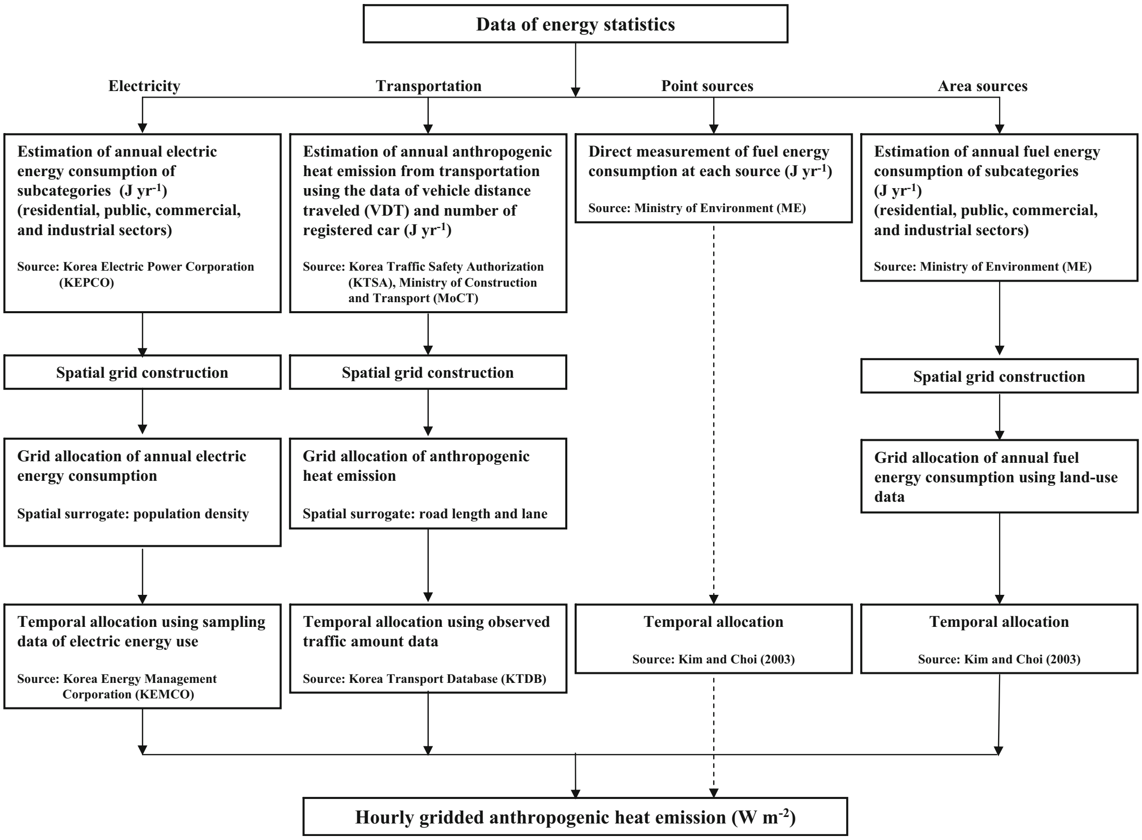


Fig. 2 A flow chart for gridded anthropogenic heat emission estimated from four energy sectors: electricity, transportation, point sources, and area sources. The heat from point sources (*dashed line*) emits at each stack height

such as population density, road length and lane, and land-use distribution and finally temporal profiles of the energy sectors are applied. Unlike the other energy sectors, the heat from point sources releases at the stack height.

Statistical data used in this study are from the Korea Statistical Yearbook published by the National Statistical Office (NSO), Statistical Yearbooks of Seoul, Incheon, and Gyeonggi (Seoul 2006; Incheon 2006; Gyeonggi 2006), Statistics Yearbook by the Ministry of Construction and Transport (MoCT 2006), Yearbook of Energy Statistics by the Korea Energy Economics Institute (KEEI 2003), and the statistics by the Korea Electric Power Corporation (KEPCO) and the Korea Energy Management Corporation (KEMCO).

3.2 Heat from electricity use

Electric energy use by lighting and cooking fixtures, and other electric-power consuming appliances in residential, public, commercial, and industrial sectors is taken into account as an important contributor for the anthropogenic heat emission (Klysik 1996; Sailor and Lu 2004). The consumed energy is not simultaneously released into the atmosphere. There exists a lag time between energy consumption and heat emission. However, it is hardly specified because of the complexity of energy conversion to thermal energy, the efficiency of conduction and ventilation, insulation levels, and so on. In this study, it is assumed that the total energy consumption is instantaneously converted into thermal energy and released into the atmosphere.

The anthropogenic heat from electricity use is estimated based on the general statistics of electric power in Korea which is available from KEPCO. During the year of 2002, the total electric energy use in the study region is 3.78×10^{17} J (Table 3). Gyeonggi has the largest annual electric energy use of 1.94×10^{17} J where the industrial sector covers about 49%. The annual electric energy use in Seoul is 1.26×10^{17} J among which the use at the commercial sector accounts for about 56%. The majority of the electric energy use in Incheon is consumed at the industrial sector. The annual mean anthropogenic heat emission from electricity use, averaged over the urbanized area in each district, is estimated as 11.5 W m^{-2} in Seoul, 10.8 W m^{-2} in Incheon, and 6.3 W m^{-2} in Gyeonggi.

Based on the statistics, the monthly variation of electric energy use for each district is given in Fig. 3. The monthly profile for Seoul varies within the fraction of 3% during the year with a peak value of about 10% in summer. This peak is caused mainly by the increase of air-conditioner use because Seoul has a large population density (Fig. 1) and

Table 3 Electricity use in Seoul, Incheon, and Gyeonggi in 2002

	Total energy (× 10^{16} J)	Residential (%)	Public (%)	Commercial (%)	Industrial (%)
Seoul	12.6	29.0	6.3	56.4	8.3
Incheon	5.8	14.5	2.6	21.8	61.1
Gyeonggi	19.4	16.6	4.1	30.5	48.8

The energy amount used by each energy sector is given in percentage to the total energy consumption

high air temperature in summer. On the other hand, the fractional profiles in Incheon and Gyeonggi vary from 8 to 9% with a relatively small monthly variation than that in Seoul. The KEMCO sampled the amount of electric energy use for different energy sectors (residential, commercial, and industrial sectors) for more than 9,000 electric consuming units during the period from June 2001 to May 2002 (KEMCO 2002). Based on the data, seasonal mean diurnal electricity use profiles for different energy sectors are shown in Fig. 4. The hourly profiles of electricity use for different sectors are significantly different each other. The residential sector has two peaks with a primary peak around 21–23 LST and a secondary peak around 08–09 LST (Fig. 4a). The summer profile for the residential sector has a larger diurnal variation than that in other seasons. The commercial sector shows a typical diurnal variation with high electric energy consumption during working hours (Fig. 4b). The seasonal difference is less than 1% during the day and night. For the industrial sector, the seasonal and diurnal variations of the energy use are smaller than those in residential and commercial sectors (Fig. 4c). The difference in seasonal profile of electricity use sector, compared to Sailor and Lu (2004), is shown. However, the different energy sectors were not considered for diurnal profiles of electricity use in the previous study. Population density is used as a surrogate to distribute heat emission from electricity use horizontally (Klysik 1996; Khan and Simpson 2001).

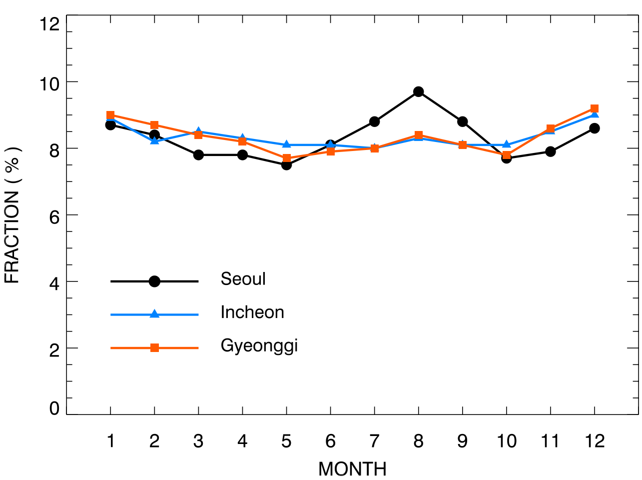


Fig. 3 Monthly variations of fractional electricity use in Seoul, Incheon, and Gyeonggi

3.3 Heat from transportation

The heat emission from transportation is an important contributor to the whole anthropogenic heat emission in various cities (Kalma 1974; Harrison et al. 1984; Khan and Simpson 2001; Sailor and Lu 2004). Sailor and Lu (2004) found that the heat from vehicles is dominant for estimated US cities in summer, having up to 62% of the total anthropogenic heat. In Brisbane of Australia, the contribution of the heat from vehicles is as large as about 72% of the total heat during the morning peak traffic hours (Khan and Simpson 2001).

Based on the data of annual average vehicle distance traveled (AAVDT, unit: km yr^{-1} $vehicle^{-1}$) and registered vehicles for different vehicle types, the annual heat emission from transportation can be estimated, and then it is distributed spatially and temporally using traffic volume observed or corresponding surrogates such as road information, population, and the number of registered vehicles. In this study, hourly heat emission from vehicles (Q_{TR}) is calculated by

$$Q_{TR}(t) = Q_{TR}^{y} \cdot f_{TR}^{m} \cdot f_{TR}^{h}, \tag{1}$$

where Q_{TR}^{y} is the annual heat emission from vehicles (J $year^{-1}$), and f_{TR}^{m} and f_{TR}^{h} are the monthly and hourly profile functions of traffic amount. With consideration of vehicle types, Q_{TR}^{y} is estimated by

$$Q_{TR}^{y} = \sum_{k} \left(AAVDT_k \cdot NV_k \cdot GH/FE_k \right), \tag{2}$$

where NV is the number of registered vehicles, GH is the amount of heat generation per fuel (J l^{-1}) and is assumed to be 3.43×10^{7} J l^{-1}, FE is the mean fuel efficiency (km l^{-1}), and the subscript k indicates vehicle category as in Table 4.

The monthly (f_{TR}^{m}) and hourly (f_{TR}^{h}) profile functions are estimated from the hourly traffic counts data at 299 traffic count points in 2002 (KTDB 2006). The majority of roads show a similarity in traffic profiles except for recreational roads where a salient peak of traffic amount occurs during the weekend and summer vacation season (Lim et al. 2005). However, the traffic amount on these roads has only small impact on the city-scale profiles due to its small fraction compared to entire road areas. Figure 5 shows the monthly profile function of traffic amount (f_{TR}^{m}) in the Gyeong-In

Fig. 4 Seasonal mean diurnal variations of fractional electricity use for **a** residential, **b** commercial, and **c** industrial sectors

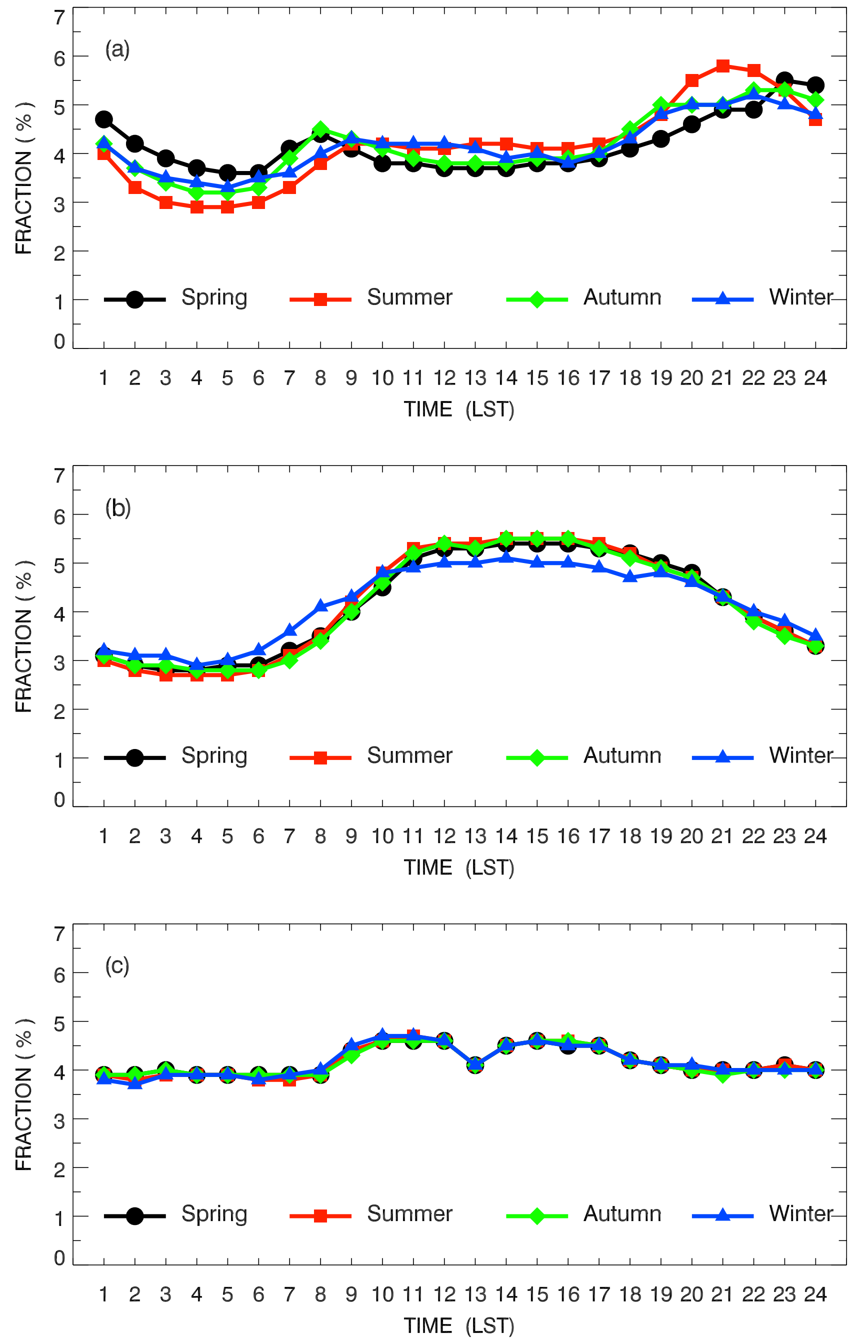


Table 4 The number of registered vehicles ($\times 10^3$) for different categories in Seoul, Incheon, and Gyeonggi in 2002

	Passenger car	Bus	Truck
Seoul	2,054	244	391
Incheon	526	77	146
Gyeonggi	2,168	299	566

region. Little difference in the monthly fraction is found in the three districts (not shown). The traffic volume in winter has lower values than that in other seasons. For the estimation of f_{TR}^{h}, the hourly observed traffic volume data are used. Figure 6 shows the annual mean diurnal variation of the mean traffic fraction. The traffic volume is larger in the daytime than in the nighttime with two small peaks in the morning and evening rush hours. The analysis shows that the seasonal difference in the profile function is found to be negligible, suggesting that driving patterns are not dependent on season in this study area.

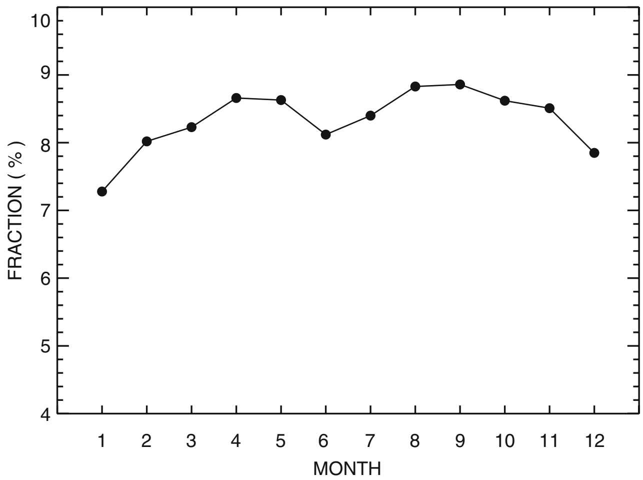


Fig. 5 Monthly profile function of heat emission from transportation (f_{TR}^{m}) in the Gyeong-In region

Based on the information of registered vehicles (Table 4) and daily distance traveled (Table 5), the estimated total annual heat emission (Q_{TR}^{y}) from transportation is 2.25×10^{17} J year^{-1} in Seoul, 6.67×10^{16} J year^{-1} in Incheon, and 2.69×10^{17} J year^{-1} in Gyeonggi, which corresponds to the anthropogenic heat emission of 21.5, 13.6, and 9.7 W m^{-2} in the urbanized area of each district, respectively. Cho (2002) suggested that the road length and lane information are useful surrogates for the spatial distribution of vehicular air pollutant emission under the lack of observed traffic amount. Because the estimation method for heat emission from vehicles is similar to that of air pollutant emission, the

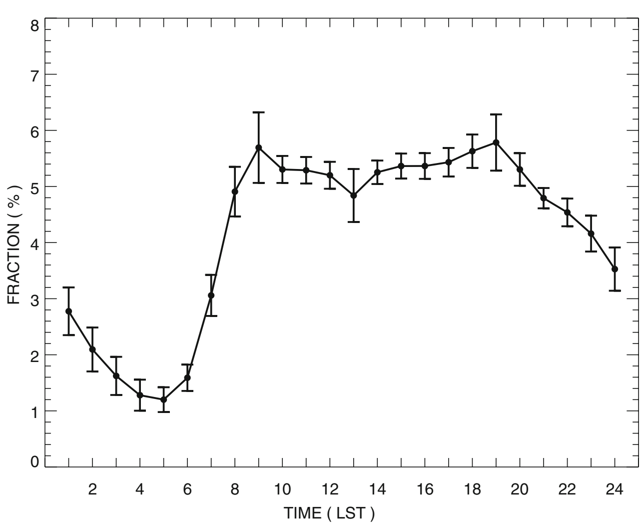


Fig. 6 Annual mean hourly profile function of heat emission from transportation (f_{TR}^{h}) in the Gyeong-In region. *Vertical bars* denote spatial standard deviations

Table 5 Annual average daily VDT (vehicle distance traveled) and fuel efficiency in 2002

Vehicle category	VDT (km day^{-1} vehicle^{-1})	Fuel efficiency (km L^{-1})
Passenger car	53.9	10.6
Bus	65.8	6.9
Truck	66.0	5.1

The daily VDT data are from the Korea Traffic Safety Authorization

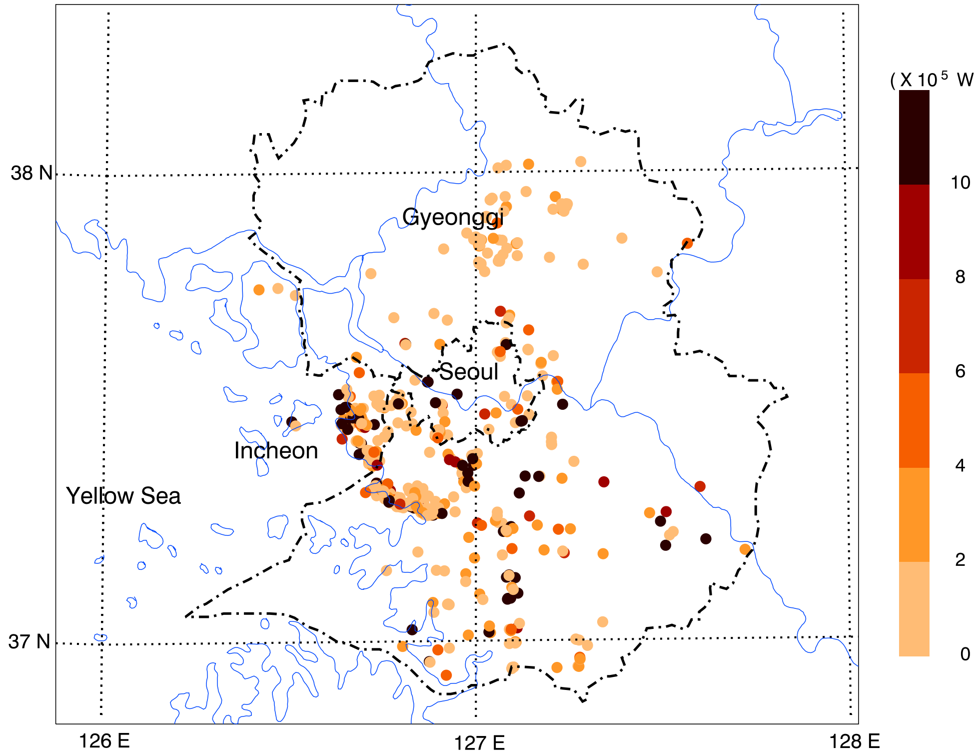
value of road length × lane is used to spatially allocate the anthropogenic heat emission from transportation.

3.4 Heat from point sources

Anthropogenic heat emission from point sources is estimated using a bottom-up approach. Large energy-consuming facilities such as thermal power stations, boilers of industries, and large heat-supply facilities are considered as point emission sources, which can be characterized as intensive sources of anthropogenic heat and air pollutants released from an elevated stack. The total of 497 point sources is included in the region: 28 points in Seoul, 104 in Incheon, and 365 in Gyeonggi. The total energy consumed at each district in 2002 is 2.22×10^{16} J year^{-1} in Seoul, 2.61×10^{17} J year^{-1} in Incheon, and 2.36×10^{17} J year^{-1} in Gyeonggi. For these major point sources, in general, only a small fraction of the heat energy of total fuel usage is released into the atmosphere due to high burning efficiency. Assuming that 10% of the total fuel energy is directly released into the atmosphere as a heat source (Klysik 1996; Khan and Simpson 2001), the annual mean anthropogenic heat emission from local point sources, averaged over the urbanized area in each administrative district, is estimated to be 0.2 W m^{-2} in Seoul, 5.2 W m^{-2} in Incheon, and 0.9 W m^{-2} in Gyeonggi. Even though the mean anthropogenic heat emission from each point source in each district is small, the heat emission at each point is much larger as shown in Fig. 7. The maximum annual mean anthropogenic heat emission averaged over a grid area of 1 km×1 km in each district is found to be 27 W m^{-2} in Seoul, 320 W m^{-2} in Incheon, and 198 W m^{-2} in Gyeonggi, with the mean stack height of about 30 m.

The temporal variation of heat emission from point sources depends on operation hours of the facilities. The monthly mean profile is shown in Fig. 8. A maximum value is found in winter and a minimum in summer with relatively large spatial variations. Operation hours at each emission facility are used to estimate temporal allocation factor (Kim and Choi 2003). A striking difference in the hourly allocating factor between point and area sources is seen in Fig. 9. The heat emission fraction for point sources is much larger in the daytime than in the nighttime.

Fig. 7 Spatial distribution of annual mean anthropogenic heat emission from point sources



3.5 Heat from area sources

Area sources include widely distributed heat-emission sources (e.g., detached houses, schools, commercial buildings, small factories, and small heat-supply equipment), which are subcategorized as residential, public, commercial, and industrial sectors. Unlike point sources, the heat emission from area sources is characterized to be much less intense but distributed over an extensive part of the urban area. In addition, the heat emission from area sources is closely related to spatial characteristics of population density, household density, and land-use pattern (Cho 1993).

Annual energy consumption from area sources in a grid cell j (Q^j) is estimated as

$$Q^j = \sum_i \left(Q_i^{yr} \cdot LUF_i^j \right), \tag{3}$$

where Q_i^{yr} is the annual energy consumption by subcategory i, LUF_i^j is the area fraction of subcategory i in a grid j to total land-use area of subcategory i, and i indicates residential, public, commercial, and industrial sectors. Based on the local energy statistics, the total consumed energy in 2002 is $2.22{\times}10^{17}$ J year^{-1} in Seoul, $1.18{\times}10^{17}$ J year^{-1} in Incheon, and $2.98{\times}10^{17}$ J year^{-1} in Gyeonggi. Therefore, the annual

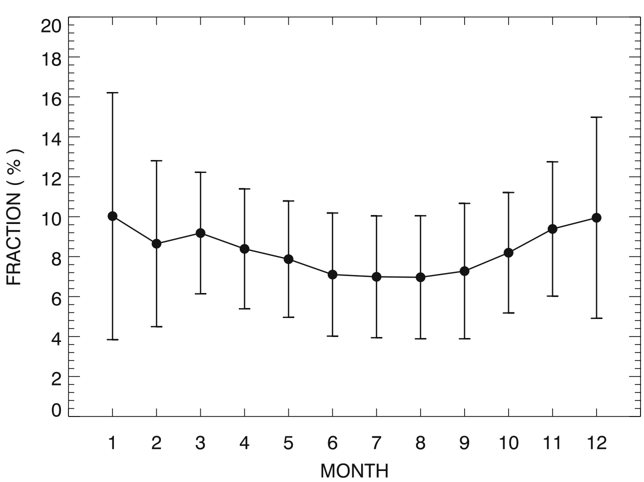


Fig. 8 Monthly variation of anthropogenic heat emission (%) from point sources in the Gyeong-In region. *Vertical bars* denote spatial standard deviations

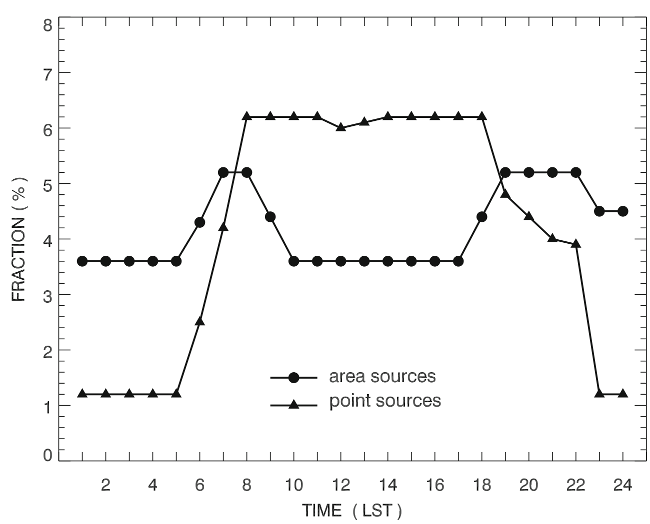


Fig. 9 Hourly heat emission profiles for point and area sources in the Gyeong-In region. After Kim and Choi (2003)

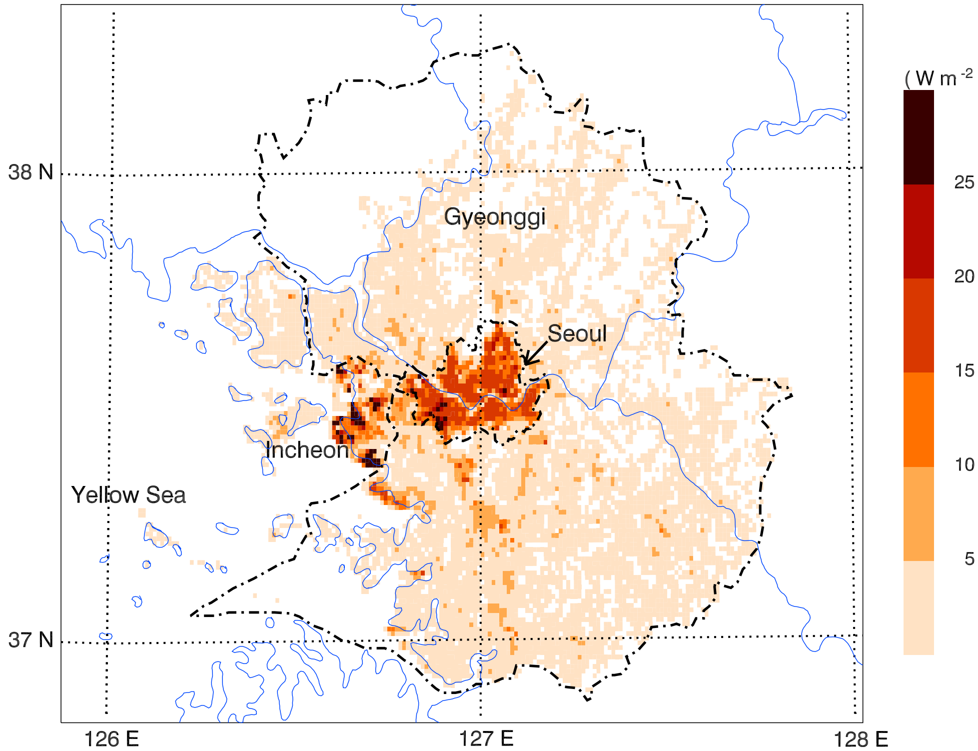


Fig. 10 Spatial distribution of annual mean anthropogenic heat emission from area sources in the Gyeong-In region

mean anthropogenic heat emission from area sources, averaged over the urbanized area, is estimated as 21.3 W m^{-2} in Seoul, 23.6 W m^{-2} in Incheon, and 10.7 W m^{-2} in Gyeonggi. Figure 10 shows 0.01° longitude × 0.01° latitude gridded heat emission from area sources. Seoul and the eastern part of Incheon have large heat emission due to high urbanization levels. The maximum annual mean anthropogenic heat emission is found to be about 60 W m^{-2} in the southwestern part of Seoul.

The temporal variation of energy consumption is relatively large, and the energy consumption in summer is relatively lower than that in winter (Fig. 11). According to Kim and Choi (2003), residential heating is one of the main contributors to the seasonal variation in the region. In addition, the diurnal variation of energy use shows that a relatively large fraction of energy is used in the morning and evening when residential activities are relatively high (Fig. 9).

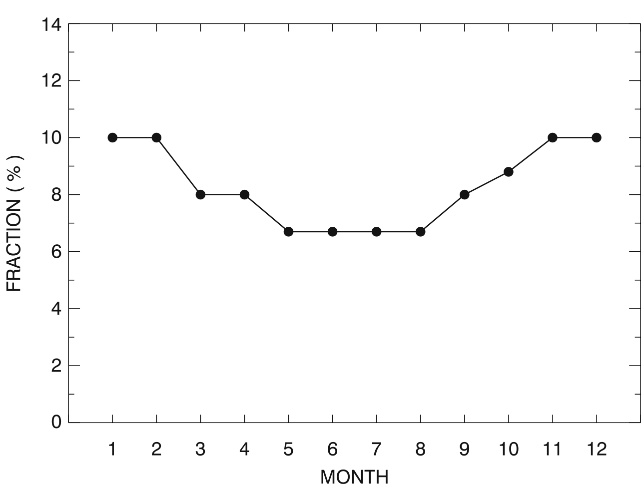


Fig. 11 Monthly variation of fractional anthropogenic heat emission from area sources in the Gyeong-In region. After Kim and Choi (2003)

3.6 Spatial and temporal distributions

Table 6 shows the annual mean anthropogenic heat emission estimated from different energy sectors and their contributions in the Gyeong-In region. The estimated values are 54.5 W m^{-2} in Seoul, 53.2 W m^{-2} in Incheon, and 27.6 W m^{-2} in Gyeonggi. In Seoul, 79% of the total heat emission is contributed by transportation and area sources, and 21% by electricity use. In Incheon, 44% of the total heat emission is contributed by area sources, 26% by transportation, and 20% by electricity use. The contribution

Table 6 Annual mean anthropogenic heat emissions estimated from four different energy sectors in Seoul, Incheon, and Gyeonggi in 2002

	Total	Electricity	Transportation	Point sources	Area sources
Seoul	54.5	11.5 (21.1)	21.5 (39.4)	0.2 (0.4)	21.3 (39.1)
Incheon	53.2	10.8 (20.3)	13.6 (25.6)	5.2 (9.8)	23.6 (44.4)
Gyeonggi	27.6	6.3 (22.8)	9.7 (35.1)	0.9 (3.3)	10.7 (38.8)

Values in parentheses indicate the percentage of the total heat emission. Unit is W m^{-2}

of point sources in Incheon is much larger than that in the other districts because many light and heavy industrial complexes are located. In Gyeonggi, the contribution of each energy sector to the total heat emission is similar to that in Seoul. However, the magnitude of heat emission is about half of Seoul.

Figure 12 shows the diurnal variation of anthropogenic heat emission in the three districts in summer and winter. In all districts, the emission in winter is greater than that in summer with two peaks in the morning (around 08–09 LST) and evening (around 19 LST). Compared to the US cities (Sailor and Lu 2004) and Tokyo in Japan (Ichinose et

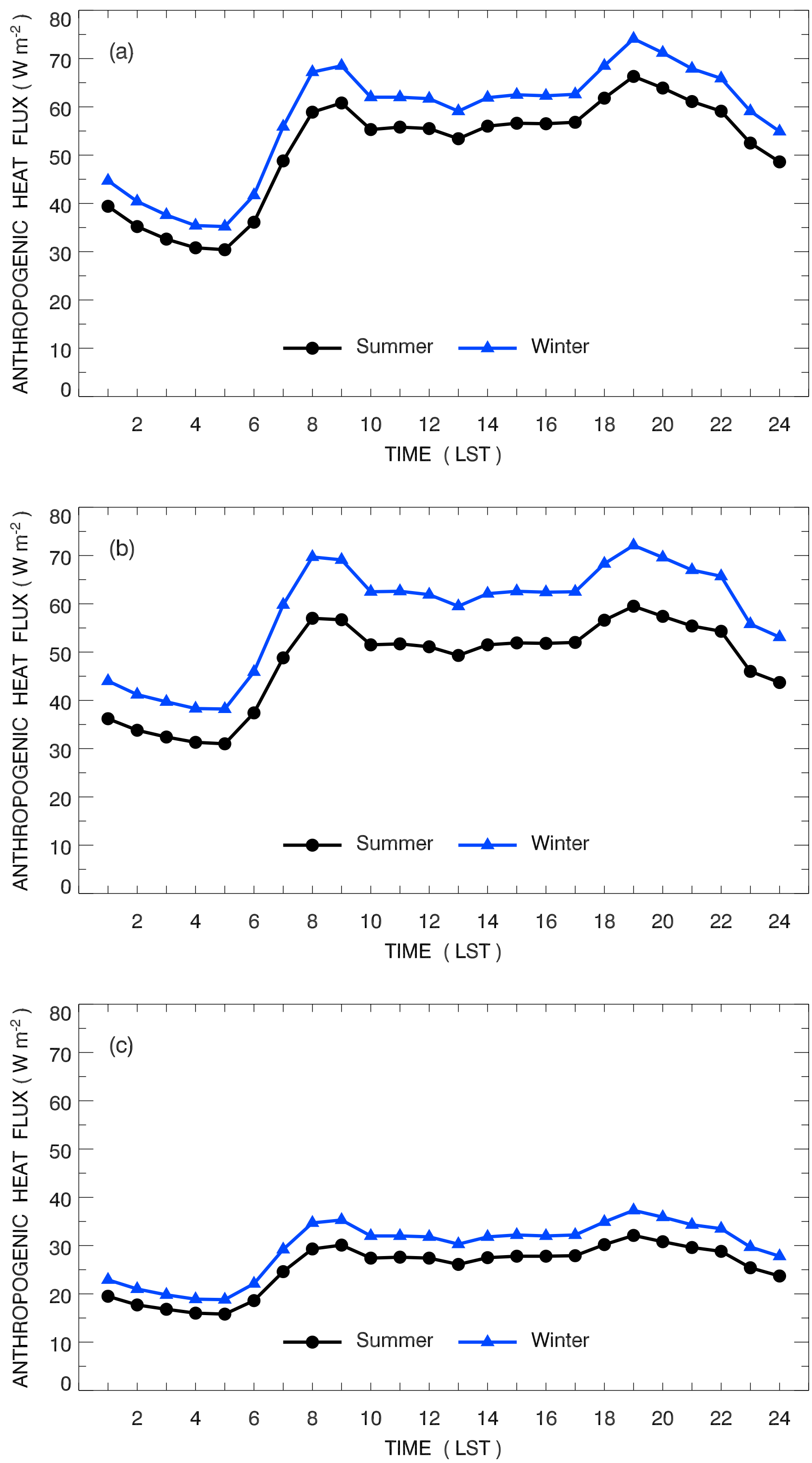


Fig. 12 Seasonal mean diurnal variations of anthropogenic heat emission in **a** Seoul, **b** Incheon, and **c** Gyeonggi

al. 1999), anthropogenic heat emission in the Gyeong-In region decreases slowly until midnight after the evening second peak time. Seoul has the largest heat emission in winter, ranging from about 35 W m^{-2} at 05 LST to about 75 W m^{-2} around 19 LST, while in summer it has a similar diurnal trend to that in winter but less heat emission by approximately 5–10 W m^{-2} (Fig. 12a). Anthropogenic heat emission in Incheon is comparable to that in Seoul, but the seasonal difference is larger than that in Seoul (Fig 12b). Gyeonggi has the smallest anthropogenic heat emission, diurnally ranging from 15 to 35 W m^{-2}. From seasonal mean diurnal variations obtained in a city scale, similar diurnal profiles in seasons with different magnitudes are also found in US cities (Sailor and Lu 2004) and Pusan in Korea (Son et al. 2000).

The 0.01° longitude × 0.01° latitude gridded annual mean anthropogenic heat emission in the Gyeong-In region is shown in Fig. 13. Heat emission from the point sources is not included in the calculation because heat release height as well as spatial and temporal magnitude varies significantly. The highly urbanized areas are distinctive for the heat emission. Most parts of Seoul show high anthropogenic heat emission exceeding over 30 W m^{-2} except for mountainous areas and the Han River. The heat emission in Incheon has a maximum in the western part of it where the residential and industrial areas are densely located, while in Gyeonggi, several satellite cities of Seoul release anthropogenic heat intensively, but the rest of regions have the heat emission of less than 5 W m^{-2}. The maximum anthropogenic heat emission in the Gyeong-In region is found to be about 120 W m^{-2} around 19 LST in winter. The estimated anthropogenic heat emission is expected to significantly affect thermal environment and urban circulation. Further study will investigate the impacts using a mesoscale meteorological model with the anthropogenic heat emission.

4 Summary and conclusions

The anthropogenic heat emission in the Gyeong-In region of Korea in 2002 is estimated on the basis of energy consumption data. The heat emitting sources are classified into four energy sectors: electricity use, transportation, point sources, and area sources. The gridded distribution of heat emission is also estimated in a spatial resolution of about 1 km. In addition, monthly and hourly allocating profiles for all sources are presented using the observed and statistical data, especially in detail for electricity and transportation sectors.

It is found that Seoul has the largest anthropogenic heat emission among neighboring three districts, especially in winter. The annual mean anthropogenic heat emission in the Gyeong-In region is found to be about 45 W m^{-2}, but that in Seoul is 55 W m^{-2}, which is comparable to that in the large US cities. The heat emissions from transportation and area sources are larger than those from electricity use and local point sources in Seoul and Gyeonggi, while in

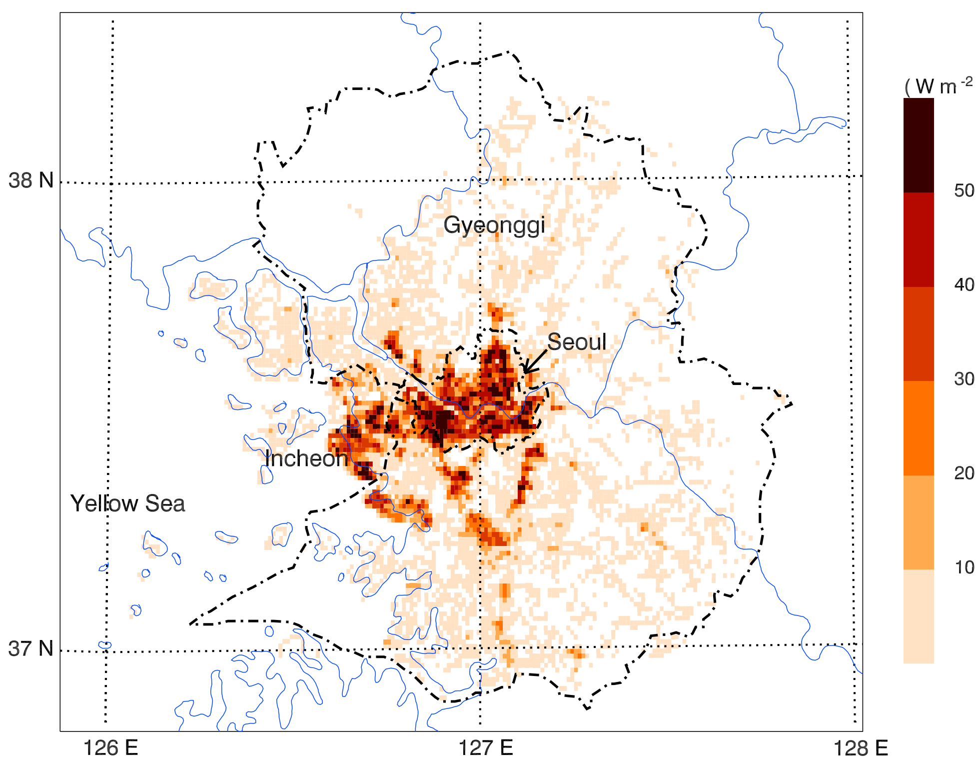


Fig. 13 Spatial distribution of annual mean anthropogenic heat emission in the Gyeong-In region

Incheon area sources are the most important contributor, covering over 40%. In all districts, the heat emission is larger in winter than in summer. The maximum anthropogenic heat emission is estimated to be about 120 W m^{-2} around 19 LST in winter.

Since the gridded anthropogenic heat emission is estimated, it can be easily used in mesoscale meteorological and environmental modeling to investigate the impacts of anthropogenic heating on urban weather and climate and air quality in the Gyeong-In region of Korea. In mesoscale meteorological models, estimated anthropogenic heat emission can be included as a heat source through a surface energy balance equation, a thermodynamic energy equation, and/or both the equations with fraction (Ichinose et al. 1999; Kim et al. 2000; Khan and Simpson 2001; Block et al. 2004; Fan and Sailor 2005; Makar et al. 2006). Fan and Sailor (2005), for example, distributed the anthropogenic heat emission evenly in atmospheric surface layer, while Ichinose et al. (1999) released on the ground surface instead of emitting directly into the atmosphere. The anthropogenic heat influence on the nocturnal urban heat island intensity is found to be up to 2.5°C in winter (Ichinose et al. 1999; Fan and Sailor 2005), suggesting the importance of anthropogenic heat emission on the urban environment. The presently estimated anthropogenic heat emission in the Gyeong-In region can be used for meteorological and environmental modeling studies in this region.

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