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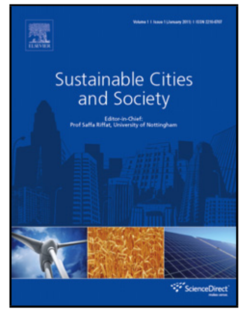

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PII: S2210-6707(18)32091-2

DOI: https://doi.org/10.1016/j.scs.2019.101784

Reference: SCS 101784

To appear in:

Received Date: 16 October 2018

Revised Date: 13 August 2019

Accepted Date: 13 August 2019

Please cite this article as: Murakami K, Kaneko S, Dhakal S, Sharifi A, Changes in per capita CO_2 emissions of six large Japanese cities between 1980 and 2000: an analysis using “The Four System Boundaries” approach, *Sustainable Cities and Society* (2019), doi: https://doi.org/10.1016/j.scs.2019.101784

Changes in per capita CO_2 emissions of six large Japanese cities between 1980 and 2000: an analysis using "The Four System Boundaries" approach

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Highlights

- With the use of four system boundaries for carbon accounting methods, we identify and compare per capita CO_2 emissions of six large Japanese cities in 1980 and 2000 with sufficient changes and diversities in socio-economic characteristics.
- The consumption-based emissions have not largely changed in large cities in Japan over the 20 years from 1980 to 2000, although those of the other three system boundaries increased.
- The consumption-based emissions should be adopted by local authorities in their pursuit of urban climate change mitigation goals.

Abstract

Cities can play a critical role in mitigating climate change. Although several carbon accounting methods have been proposed to identify mitigation responsibility of cities, there is still no single common and widely accepted method. In this study, we have adopted a method that is based on four system boundaries to identify and compare per capita CO_2 emissions of six large Japanese cities in 1980 and 2000. Despite the fact that substantial differences exist among these cities in terms of industrial structure and transformation, population, and local climatic conditions, we found that the per capita CO_2 emissions for the system boundary 4, which is CO_2 emissions attribution to city from the consumption perspectives, are very similar among them and are stable over the 20-year study period, although those for all the other system boundaries are not similar. This is in contrast to the general claims made by local authorities regarding their success in reducing per capita CO_2 emissions. Such claims are made on the basis of emissions estimated using the system boundary 2 method. We argue that using the system boundary 4 provides a more realistic account of changes in urban CO_2 emissions and trends and should be adopted by local authorities in their pursuit of urban climate change mitigation goals

Keywords: mitigation responsibilities; consumption-based emissions; input-output analysis; carbon accounting; climate change mitigation; Japanese cities

Abbreviations

GHG: greenhouse gas; GRDP: gross regional domestic product; GODLCs: government ordnance-designated large cities; EISSs: energy-intensive subsectors

1 Introduction

Accounting for about 70% of global CO_2 emissions, cities can play a critical role in mitigating climate change. Although several carbon accounting methods have been proposed to identify mitigation responsibility of cities, there is still no single common and widely accepted method. Poumanyvong and Kaneko (2010) demonstrated that the marginal effect of urbanization on national CO_2 emissions is generally positive both for developed and developing countries, whereas Dodman (2009) reported that per capita greenhouse gas emissions of several wealthy cities were significantly lower. This implies that cities become more efficient in terms of direct emissions within the boundary with long term economic development, while increasing dependency on the non-city regions of the country. In this study, in order to empirically examine this claim based on city level analysis, we focus on the 20 years longitudinal data of 6 large Japanese cities.

We have adopted a method that is based on four system boundaries (for emission accounting) to identify and compare per capita CO_2 emissions of six large Japanese cities in 1980 and 2000. Since the Statistical Survey on Energy Consumption Structure (Sekitutou Shohi Kozo Tokei), annually published by the Ministry of International Trade and Industry (MITI), was abolished in 2001, it is difficult to have consistent and detail energy consumption data at city scale afterwards. In addition, the input output tables at city scale are available since 1980. Therefore, we decided our study period from 1980 to 2000 as the longest period, for which sufficient data is available. Despite the fact that substantial differences exist among these cities in terms of industrial structure and transformation, population, and local climatic conditions, we found that the per capita CO_2 emissions for 'the system boundary 4'[1], which is CO_2 emissions attribution to city from the consumption perspectives, are very similar among them and are stable over the 20-year study period, although those for all the other system boundaries are not similar. This is in contrast to the general claims made by local authorities regarding their success in reducing per capita CO_2 emissions. Such claims are made on the basis of emissions estimated using the system boundary 2 method. The analysis supports the view that cities become more efficient in terms of direct emissions within the boundary with long term economic development, while increasing dependency on the non-city regions of the country. We argue that using the system boundary 4 provides a more realistic account of changes in urban CO_2 emissions and

1 See Section 2 for the detailed definition the four system boundaries.

trends and should be adopted by local authorities in their pursuit of urban climate change mitigation goals.

The paper is organized as follows. Section 2 summarizes the literature on carbon accounting methods and defines the four system boundaries approach of this paper. Section 3 provides the Japanese context. Section 4 details methodology and materials and Section 5 describes and discusses the results. Section 6 offers conclusions and policy implications.

2 Literature review and "The Four System Boundaries" approach

At national level, CO_2 emission inventories are prepared using the protocol for greenhouse gas emission inventories proposed by the International Panel on Climate Change (IPCC) (IPCC, 2006) for reporting to the United Nations Framework Convention on Climate Change (UNFCCC). These CO_2 emission inventories are for their territorial jurisdictions and are used primarily for inter-governmental discussions and negotiations regarding target setting for reducing emissions and for evaluating the progress of emission mitigation policies.

Many other types of carbon accounting methods also exist (Schaltegger & Csutora, 2012; Stechemesser & Guenther, 2012). These methods have been proposed and propagated in academic, business and political arenas and cover aspects that are of interest to different stakeholders. They take account of both direct and indirect or induced emissions. The most widely discussed types highlight the mitigation responsibilities of consumers, who do not necessarily contribute to emission responsibilities under the territorial principle. Consumption-based emissions are estimated by adjusting the emissions embodied in internationally-traded commodities (Ahmad & Wyckoff, 2003; Peters, 2008; Peters & Hertwich, 2008) and can be compared with production-based emissions, which are the same as those implied by the territorial principle. The concept of consumption-based emissions has an affinity for the export promotion strategies driven by energy-intensive industries of developing countries, especially China, which claim that the mitigation responsibility of nations stipulated by the territorial principle should be discounted (Huimin & Ye, 2010). Note that consumption-based carbon emissions differ from carbon footprints, which are analogous to ecological footprints[2] in the sense that carbon footprints do not consider the carbon emissions embodied in export commodities, which represent outflows and leakage.

Several studies estimate consumption-based CO_2 emission inventories[3] for each country and compile the results at the global scale (Davis & Caldeira, 2010; Davis, Peters, & Caldeira,

[2] Schulz (2010) provides a carbon footprint analysis of Singapore, which is an open city state, and finds that direct CO_2 emissions are only 20% of the carbon footprint of Singapore.
[3] Here, the term “consumption-based emissions” refers to the System 4 boundaries mentioned later.

2011; Peters, Davis, & Andrew, 2012; Peters, Minx, Weber, & Edenhofer, 2011). Collectively, it is found that the proportion of global emissions embodied in internationally traded commodities has increased from 20% in 1990 to 23% in 2004 and 26% in 2008, due mainly to increases in trade flows from developing countries to developed countries. In addition, 37% of global emissions are from fossil fuels traded internationally. Moreover, studies confirm that the aggregate CO_2 emissions from developing countries have already surpassed those of developed countries, even by consumption-based measures; the same is true of the comparison between China and the US, which are the largest emitters in each group (Le Quéré et al., 2018).

Another type of carbon accounting is based on the assertion that each country should be responsible for its cumulative historical CO_2 emissions since the Industrial Revolution, which is known as the Brazilian proposal in the UNFCCC negotiations (Friman & Linnér, 2008). This accounting is also used for setting long-term emission control goals. Further, Wei et al. (2014) argue that it is more consistent for current governments to be responsible for cumulative CO_2 emissions not from the Industrial Revolution, which represents a common base year, but from their establishment as individual nations. When historical emissions are used as a long-term goal, the study by Wei et al. (2014) shows that the base year significantly affects the allocation of mitigation responsibilities among countries.

Several accounting methods have been proposed that focus on stakeholders other than national governments. Among others, Frumhoff, Heede, and Oreskes (2015) proposes a carbon accounting method that attributes GHG emissions to stockholders to visualize investors' emission responsibilities. This especially concerns firms engaged in the fossil fuel industry. Evidence suggests that just 90 big companies in the fossil fuel industry are collectively responsible for two-thirds of global GHG emissions (Starr, 2016).

Cities represent another group of stakeholders for which carbon accounting methods have been studied and discussed. They are regarded as a major source of emissions; energy related CO_2 emissions from cities are in the range of 70 to 75% of corresponding global CO_2 emissions (Grubler et al., 2012; International Energy Agency, 2008; Seto et al., 2014). Cities are also expected to play a significant role in adopting sound climate policies that are adapted to local needs and requirements (Betsill & Bulkeley, 2006). In addition, it has been discussed that urbanization, as a phenomenon of collective growth of cities, has heterogeneous effects on national CO_2 emissions depending on the stage of development (Chikaraishi et al., 2015; Poumanyvong & Kaneko, 2010) and thus policy prescription is not so simple.

Urban carbon accounting lags far behind national-level carbon accounting. This is explained by issues such as difficulties in defining the boundaries of cities (as open systems);

availability and accessibility of comprehensive, verifiable and comparable data; lack of experienced staff to create local emission inventories; and costs associated with acquiring data and hiring data analysts (Creutzig et al., 2018; Gurney et al., 2015).

Due to these issues, existing studies have mainly concentrated on the production of data on city-scale emissions of CO_2 and other greenhouse gases. In an earlier study, Baldasano et al. (Baldasano, Soriano, & Boada, 1999) estimated CO_2 emissions in the city of Barcelona from 1987 to 1996 and discussed how the emissions increased. More recently, several studies have collected data on and provided estimates of energy consumption and CO_2 emissions in cities such as Bangkok (Phdungsilp, 2010), Kathmandu (Shrestha & Rajbhandari, 2010), and Indianapolis (Gurney et al., 2012). Relevant within-country comparative studies include those of Brown, Southworth, and Sarzynski (2009), who assessed emissions of CO_2 from the 100 most populous municipal areas in the US; Dhakal (2009), who assessed CO_2 emissions from 35 cities and 4 megacities, Beijing, Shanghai, Tianjin and Chongqing, in China; Minx et al. (2013), who estimated carbon footprint of many cities in the UK; and Chen et al. (2017) and Tong et al. (2018) who compiled and analyzed CO_2 emissions data for many Chinese cities; Ramachandra, Aithal, and Sreejith (2015) reported the results of GHGs accounting for multiple cities in India. Relevant international comparative studies include those of Kennedy et al. (2009, 2010), who assessed emissions of GHGs from 10 selected megacities worldwide. More recently, Moran et al., (2018) have developed a model to estimate and compare carbon footprints of 13,000 cities. Also, in the recent years, several online platforms have been developed for self-reporting of emissions by cities across the world. Examples are the Carbon Discloser Project (https://www.cdp.net) and the Carbon*n* Climate Registry platform (http://carbonn.org/).

In addition to these articles, which focus primarily on city-scale carbon emission estimates, information on carbon emission estimates is obtained as part of earlier step of further in-depth analyses. Examples include a discussion of urban policies related to mitigation measures for CO_2 emissions from Rio de Janeiro, especially with the benefit of clean development mechanisms (CDMs) (Dubeux & Rovere, 2007) and modeling studies that investigate the development of emission reduction roadmaps for Kyoto (Gomi, Ochi, & Matsuoka, 2010), Shanghai (Li et al., 2010) and Kathmandu (Shrestha & Rajbhandari, 2010).

City governments are not directly involved in international negotiations, and the emission inventories of cities reported in the literature are not standardized or comparable. This is because such inventories have not been prepared using consistent accounting methods and data collection/analysis protocols. However, several initiatives have been taken to clarify emission boundaries and develop consistent carbon accounting methods. The Global Protocol for

Communities (GPC) is one such initiative that is developed by major urban stakeholders with the aim of standardization of emission accounting (https://ghgprotocol.org/greenhouse-gas-protocol-accounting-reporting-standard-cities). This protocol classifies carbon accounting methods into three categories. 1) Scope 1 refers to direct CO_2 emissions generated within the administrative boundary of a city, from sources such as transportation and building heating. 2) Scope 2 accounts for CO_2 emissions embodied in the electricity supplied to the city from outside its administrative boundaries. Finally, 3) Scope 3 refers to all other CO_2 emissions embodied in all commodities, including electricity, supplied to the city from outside its administrative boundaries[4]. There have also been few efforts to standardize GHG inventorying and developing reporting protocol around these scopes in the past. Global Protocol for Communities (GPC) was one such latest effort which aim to standardize the emission estimation, scope definition and reporting protocol for GHG emissions of cities. However, the implementation of such harmonized approach has yet been a key challenge to overcome with only a handful of cities adopting it. As for the emissions and mitigation activity reporting, there are few initiatives such as Carbon Disclose Project (CDP) and Carbon Registry which solely rely on voluntary and self-reporting mechanisms. Such self-reported emissions data are increasingly stored and reported by platforms such as the Carbon

[4] Emissions determined using Scope 3 are equivalent to carbon footprints.

Disclosure Project, providing opportunities for researchers to use them for further analysis despite prevailing comparability issues. As a case in point, some standardization efforts have recently been made to develop a global dataset of over 330 cities' urban CO_2 emissions, based on CDP and other data, with the aim of integrating it with the well-established Global Carbon Atlas[5] (Nangini et al., 2019).Building on the GPC, Liu et al. (2015) introduced a fourth scope (Scope 4) that accounts for all emissions except for those embodied in product exports. Based on these four scopes, they developed a "four system boundaries" approach for emission accounting. As illustrated in Figure 1, we redefined the fourth scope (Scope 4) as the embodied emissions in export commodities and the four system boundaries are related to the previously-mentioned scopes as follows: System boundary 1 (hereafter refers to SB-1) and Scope 1 are identical to each other, system boundary 2 (SB-2) equals the sum of Scope 1 and Scope 2 emissions, system boundary 3 (SB-3) equals the sum of Scope 1 and Scope 3 emissions, and finally system boundary 4 (SB-4) equals to the sum of Scope 1 and Scope 3 minus Scope 4 (all emissions minus export-related ones). The fourth system boundary is comparable to the consumption-based emissions concept used in international comparisons of national emissions. We use the four boundaries from the SB-1 to the SB-4 in the rest of paper.

[5] http://www.globalcarbonatlas.org

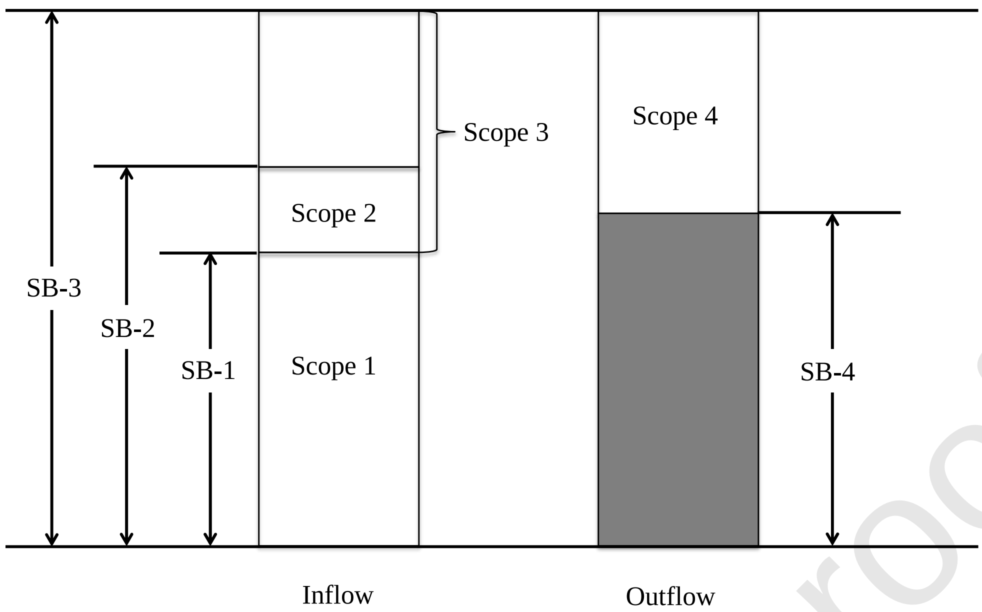


Figure 1. Scope and system boundaries (SBs) of this study

Although most of the above-mentioned city-scale studies focus on SB-1 and SB-2 emissions, the number of studies that measure carbon footprints (which are equivalent to SB-3) has recently increased. Larsen and Hertwich (2009) apply SB-3 to municipal services for the city of Trondheim and find that 93% of the city's CO_2 emissions are indirect. Hillman and Ramaswami (2010) estimate and compare carbon emission inventories using SB-3 boundaries for eight cities in the US (although, for the major cross-boundary inflows, accounting for indirect emissions is partially approximated by bottom-up approaches). With more comprehensive coverage, Kennedy et al. (2010) compared different carbon accounting methods across SB-1, SB-2, and SB-3 for 10 cities worldwide.

The number of studies that estimate and report carbon emissions using the "four system boundaries" is limited at the city scale, although there are many such studies at the national scale. Liu et al. (2015) adopted the "four system boundaries" approach to estimate and compare emissions of 30 cities and regions in China. The study on Singapore mentioned above (Schulz, 2010), also employs the "four system boundaries" approach. The author argues that this approach is more relevant for discussing the mitigation responsibilities of cities than countries, as the openness of the economic structure of cities is higher, and greater proportions of their CO_2 emissions are induced outside of their administrative boundaries.

Several studies have attempted to improve our understanding of the empirical characteristics of carbon inventories derived using the "four system boundaries" approach. For example, considering the relationship between city-scale economic indicators and carbon inventories obtained using the four system boundaries, Minx et al. (2013) analyzed emissions of British cities. They examine the relationship between emissions and income, household size, and the level of education of the head of the household. Similarly, Sudmant, Gouldson, Millward-Hopkins, Scott, and Barrett (2018) examine the gap between the emissions determined using SB-1 and SB-4 and discuss their relationships with income level and population density for cities in the US, the UK and China. Moreover, Feng, Hubacek, Sun, and Liu (2014) discusses the gap between the emissions obtained using SB-1 and SB-4 while elaborating in detail on the trade between large cities and their surrounding regions in China.

In practice, the "four system"-based carbon accounting methods are infrequently applied in setting goals for urban climate policies. For example, in Japan, Article 21 of the 2004 Act for the Promotion of Global Warming Countermeasures requires prefectural and municipal governments to formulate local action plans for the mitigation of greenhouse gas emissions. In these plans, specific goals must be set. In most cases, carbon accounting is performed using SB-2 as a typical target, and thus the CO_2 emissions embodied in imported electricity are only considered. Moreover, the action plans concentrate on building awareness through campaigns and school-based educational programs to promote energy saving, in particular for electricity use. Such efforts are not necessarily new and have been implemented since the oil crisis in the 1980s.

As mentioned earlier, carbon accounting using the "four system boundaries" approach has been frequently applied at the national level. This is mainly due to the increasing availability of global input-output tables which makes it possible to calculate the intensities of CO_2 or GHG emissions embodied in internationally-traded commodities according to major commodity groups and for each country. Meanwhile, although the national average embodied emission intensity can approximate the intensity of the import of commodities into cities, determining city-specific intensities of commodities exported from each city requires using input-output tables. Thus, the application of SB-3 to cities is much less costly and practically feasible than that of SB-4.

Although it is still costly approach, we investigate the homogeneity and long-term stability of the measurements of the four system boundaries approach for six large cities in Japan between 1980 and 2000, to accumulate empirical evidence and improve our understanding of the fundamental characteristics of the carbon emissions from cities based on the four system boundaries approach. Over the 20-year study period, these six cities have followed different trajectories in terms of economic growth and industrial transformation. Against this background, we like to see how the emissions in these cities with different system boundaries have evolved over the study period. In particular, we like to find out if there are differences of the emissions between the SB-4 and the other system boundaries (SB-1, SB-2 and SB-3).

3 The Japanese context

3.1 Cities in Japan and characteristics of the selected cities

Cities are defined differently in different countries. In Japan, article 8 of the Local Autonomy Act defines the required lower-bound conditions for local administrative units to be entitled as a city. First, the unit should have a population greater than 50,000. Second, a central area of the unit should have more than 60% buildings and facilities. Third, more than 60% of households in the unit should have at least one family member who is working in secondary or tertiary industries. In addition to these three requirements, the unit should satisfy the additional requirements specified by the local ordinance of the prefectural government. There were 210 cities at the time the Act was introduced in 1947, and the number increased to 651 in 1985 and further to 791 in 2018. Before 1985, new cities have been formed mostly by urban migration and population growth. However, after 1985, new cities have essentially been formed by merging towns and villages following the policies of the central government. Since the second condition is very vague and the share of agriculture in the Japanese labor market became less than 10% in the early 1980s, the conditions are not obstacles for towns and villages to be upgraded to cities. In other words, there is an increasing number of "cities", which are not largely different from towns and villages, particularly those that have become cities since 1985 when the population growth rate was already low.

Other definitions in the same Act are also given for larger cities. Currently, the Act allows government ordinance to designate two types of special large cities: large cities with a population of 500,000 or greater and core cities with a population of 200,000 or greater[6]. Although city governments are under the supervision of the prefectural government, Government Ordinance-

[6] The Tokyo metropolitan government (TMG) is treated differently by the special ward system, where 23 wards are designated in the TMG as fundamental administrative units.

Designated Large Cities (GODLCs) have special authorities and the same amount of political power as prefectures. Moreover, these cities have been granted a large level of local autonomy, especially regarding preparation and implementation of urban plans and policies. The designation of large cities has been practices since 1956, whereas that of core cities is relatively new and was introduced in 1995. There were 5 GODLCs in 1956, Osaka (2.55), Nagoya (1.34), Kyoto (1.20), Yokohama (1.14) and Kobe (0.98), where the numbers in parentheses represent the population in millions at the time of designation. In 1963, Kitakyushu (1.04) was added to the GODCs, and three more cities, Sapporo (1.01), Kawasaki (0.97), Fukuoka (0.85), were included in the GODLCs in 1972. The 10th GODLCs was Hiroshima (1.04), which was added in 1980. Thus, there were 10 GODLCs as of 1980. Currently, there are 20 GODLCs.

3.2 Characteristics of the six large cities

The selection criteria of study cities are twofold: (1) study cities should be the Government Ordinance-Designated Large Cities (GODLCs) as of 1980 and (2) study cities should officially published the input-output tables. Among the 10 GODLCs, which were designated by 1980, the six cities of Sapporo, Yokohama, Kobe, Hiroshima, Kitakyushu and Fukuoka City were selected to be examined in this study. It is noted that Hiroshima has just become the GODLCs in 1980 and the first input-output table was published for 1985. Thus, we use 1985 data instead of 1980 due to data unavailability of input output table in 1980. These cities are spatially distributed throughout the country, as shown in Figure 2. The socioeconomic profiles in 1980 and 2000 are summarized in Table 1.

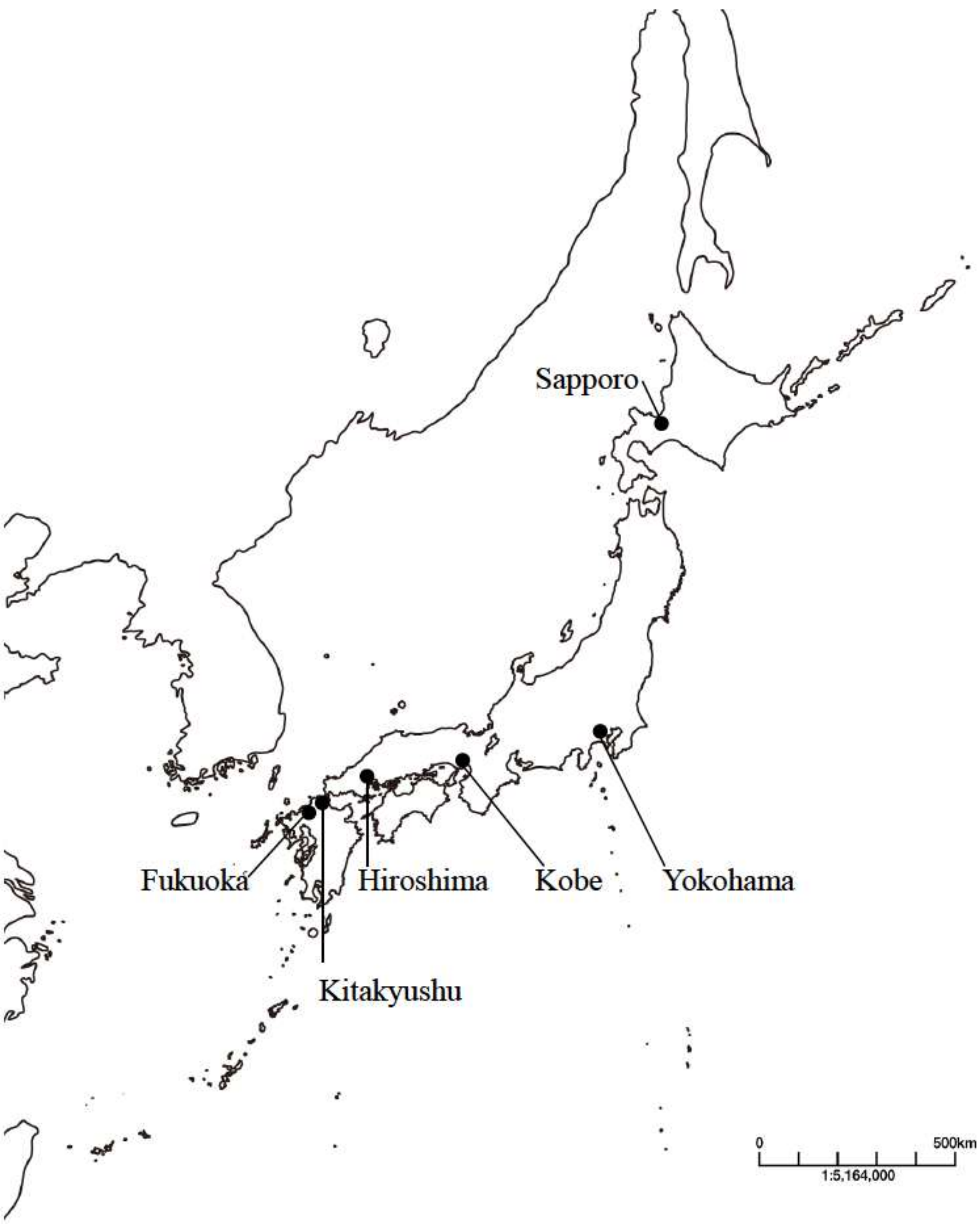


Figure 2. Geographic location of the selected cities

Table 1. Characteristics of the selected cities

		Sapporo	Yokohama	Kobe	Hiroshima	Kitakyushu	Fukuoka
Geography							
Area(km2)	1980	1,118	427	542	737	477	336
	2000	1,121	435	550	742	484	339
Average temperature	1980	-5.7	4.8	3.8	3.5	4.2	5.1
(Feb. in ℃)	2000	-3.8	5.6	4.7	4.7	5.3	6.1
Average temperature	1980	19.0	23.0	25.5	24.3	24.0	24.5
(Aug. in ℃)	2000	23.9	27.2	29.1	28.6	28.3	28.6
Demography							
Population (million	1980	1.40	2.77	1.37	1.04	1.07	1.09
people)	2000	1.82	3.43	1.49	1.13	1.01	1.34
Economy							
GRDP (trillion yen,	1980	5.3	13.0	8.0	6.2	7.0	5.8
nominal)	2000	11.4	22.5	11.1	9.3	7.6	10.5
Per capita GRDP	1980	3.7	4.7	5.8	5.9	6.6	5.3
(million yen, nominal)	2000	6.2	6.6	7.4	8.2	7.5	7.8
Manufacturing (%)	1980	30.0	55.1	49.0	40.1	63.9	24.4
	2000	15.3	34.4	32.0	28.1	40.2	16.8
Import (trillion yen,	1980	1.3	6.2	3.6	2.7	2.6	2.4
nominal)	2000	3.9	9.3	4.3	3.7	2.9	3.7
Export (trillion yen,	1980	-1.6	-7.0	-3.4	-2.3	-2.2	-1.6
nominal)	2000	-3.4	-9.6	-4.1	-2.7	-2.5	-2.7
Energy							
Total final energy	1980	23.1	122.2	92.5	29.5	257.8	29.6
consumption (Exa J)	2000	47.3	150.7	83.0	41.2	220.9	42.2
Per capita energy	1980	16.4	44.1	67.6	28.2	242.1	27.2
consumption (Mega J)	2000	26.0	44.0	55.6	36.6	218.4	31.5
Electricity in final	1980	23.0	15.7	15.5	28.9	13.2	22.4
energy consumption (%)	2000	38.1	24.4	24.7	35.3	15.6	39.9
	1980	58.8	65.1	34.5	43.3	30.7	58.1

Petroleum products in final energy consumption (%)	2000	38.2	53.1	20.6	32.8	17.7	34.6
Coal products in final energy consumption (%)	1980	12.6	7.8	47.0	16.9	51.8	13.2
	2000	14.3	8.0	45.4	23.8	54.5	14.8
Gas products in final energy consumption (%)	1980	5.5	11.4	3.0	10.9	4.3	6.3
	2000	9.4	14.5	9.3	8.1	12.3	10.6

Note: All data of Hiroshima is 1985.
Data sources: Statistical Council of Large Cities of Japan. (various years) and Ministry of Economy, Trade and Industry of Japan. (various years).

Sapporo located in a subarctic climate, where large heating energy is required during the winter season. The other five cities are located within a narrow latitude range and have similar climatic characteristics, even though the distance between Yokohama and Fukuoka is approximately 1,000 km. Sapporo has the largest administrative area, which is also different from the others, while Hiroshima is the second largest and Fukuoka is the smallest. In contrast, Yokohama is the largest in terms of population size and economic activity, and Kitakyushu is the largest with respect to final energy consumption. While Kitakyushu is the only city that experienced population decline between 1980 and 2000, the final energy consumption was reduced in two cities during the same period: Kobe and Kitakyushu. In addition, the per capita final energy consumption was reduced in three cities: Yokohama, Kobe, and Kitakyushu.

Although industrial transformation toward a service-oriented economic structure is common to all six cities, the stages are slightly different from one city to another. While manufacturing was the dominant sector in Yokohama, Kobe and Kitakyushu in 1980 and Hiroshima in 1985, the share of manufacturing in Sapporo and Fukuoka was less than 35%. Most of the cities, except Kitakyushu, have reduced their manufacturing share to less than 35% in 2000. The per capita gross regional domestic product (GRDP) of Sapporo was the lowest both in 1980 and 2000, even when the growth rate for the 20-year span was the highest. While Kitakyushu had the highest per capita GRDP in 1980, in 2000, the highest per capita GRDP was achieved by Hiroshima. The inter-city gaps of per capita GRDP have been reduced from 1.76 to 1.32. Imports are larger than exports for all of the six cities, except Yokohama.

As the most influential factors in determining carbon emission profiles, total final energy consumption, per capita final energy consumption and structure of final energy consumption by source are compared in Table 1. The large discrepancies can be found both in total energy consumption and per capita final energy consumption across the six cities, although the gaps between the largest and the smallest have been reduced from 11.2 to 5.4 and 14.7 to 8.4 times, respectively. While the energy sources are also different from city to city and although Sapporo and Fukuoka have relatively similar energy source structures, the direction of the changes in the structure of final energy consumption is similar. On the one hand, the shares of electricity and gas have been increased for all selected cities, except for Hiroshima where the share of gas was not increased and coal was exceptionally increased during the period. On the other hand, petroleum products have been lost in all six cities.

In summary, the disparities across the six cities have declined for many indicators from 1980 to 2000. However, large differences still exist for many key potential determinants of CO_2 emissions.

4 Methods and materials

4.1 Model

The methodological basis of the empirical analysis discussed in this paper originates in energy input-output analysis, a method that has become well established and widely applied since the 1970s (e.g., Bullard & Herendeen, 1975; Bullard, Penner, & Pilati, 1978; Costanza, 1980; Costanza & Herendeen, 1984). Similar methods are currently intensively applied to studies in the fields of lifecycle assessment, carbon leakage issues in climate change studies and/or trade and the environment studies to measure embodied carbon emissions (for example, Ahmad & Wyckoff, 2003).

With reference to Nansai, Moriguchi, and Tohno (2002), the basic model for specifying the intensity of embodied CO_2 emissions and the carbon balance of an open economy is described as follows. First, using column-wise data obtained from an input-output table, the balance of CO_2 emissions in sector *j* can be expressed in terms of ε_k, the intensity of CO_2 emissions embodied in the products of sector *k*; $x_{i,j}$, the domestic intermediate inputs from sector *i* to sector *j*; X_j, the total output of sector *j*; and D_j, the direct CO_2 emissions from sector *j*:

$$\varepsilon_j X_j = \varepsilon_1 x_{1,j} + \varepsilon_2 x_{2,j} + \cdots + \varepsilon_k x_{k,j} + \cdots + \varepsilon_n x_{n,j} + D_j \quad (1)$$

With introduction of the relations $a_{i,j} = {x_{i,j}}/{X_j}$ and $d_j = D_j/X_j$, equation (1) can be changed to

$$\varepsilon_j = \varepsilon_1 a_{1,j} + \varepsilon_2 a_{2,j} + \cdots + \varepsilon_k a_{k,j} + \cdots + \varepsilon_n a_{n,j} + d_j \quad (2)$$

Using matrix and vector notation to extend entire sectors, equation (2) is expressed as:

$$(\varepsilon_1 \;\; \varepsilon_2 \; \cdots \; \varepsilon_n) = (\varepsilon_1 \;\; \varepsilon_2 \; \cdots \; \varepsilon_n)\begin{pmatrix} a_{1,1} & a_{1,1} & \dots & a_{1,n} \\ a_{2,1} & a_{2,2} & \cdots & a_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n,1} & a_{n,2} & \dots & a_{n,n} \end{pmatrix} + (d_1 \;\; d_2 \; \cdots \; d_n) \quad (3)$$

In the competitive type of input-output table, m_i is an import coefficient to the total supply of products *i* and can be specified using the following formula:

$$m_i = \frac{M_i}{\sum_{j=1}^{n} a_{i,j} X_j + F_i^d} \quad (4)$$

where M_i is the total value of imported product *i*, $\sum_{j=1}^{n} a_{i,j} X_j$ represents the total intermediate demand for product *i*, and F_i^d is the domestic final demand for product *i*.

To differentiate imported products from domestically produced intermediate products, equation (3) can be further extended by introducing λ_k, the intensity of CO_2 emissions embodied in the imported products of sector *k*:

$$
\begin{aligned}
&(\varepsilon_1 \ \ \varepsilon_2 \ \cdots \ \varepsilon_n) \\
&= (\varepsilon_1 \ \ \varepsilon_2 \ \cdots \ \varepsilon_n)\begin{pmatrix} 1-m_1 & 0 & \cdots & 0 \\ 0 & 1-m_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1-m_n \end{pmatrix}\begin{pmatrix} a_{1,1} & a_{1,1} & \cdots & a_{1,n} \\ a_{2,1} & a_{2,2} & \cdots & a_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n,1} & a_{n,2} & \cdots & a_{n,n} \end{pmatrix} \\
&+(\lambda_1 \ \ \lambda_2 \ \cdots \ \lambda_n)\begin{pmatrix} m_1 & 0 & \cdots & 0 \\ 0 & m_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & m_n \end{pmatrix}\begin{pmatrix} a_{1,1} & a_{1,1} & \cdots & a_{1,n} \\ a_{2,1} & a_{2,2} & \cdots & a_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n,1} & a_{n,2} & \cdots & a_{n,n} \end{pmatrix} + (d_1 \ \ d_2 \ \cdots \ \ d_n) \quad (5)
\end{aligned}
$$

With a vector of intensities of CO_2 emissions embodied by domestic products ε and that for imported products λ,, a diagonal matrix of import coefficients $\widehat{M}$, an input coefficient matrix A, a vector of direct CO_2 emissions per unit production d and the identity matrix I, equation (6) can be expressed as:

$$\varepsilon = \varepsilon(I - \widehat{M})A + \lambda\widehat{M}A + d. \tag{6}$$

Solving equation (6) with respect to ε yields:

$$\varepsilon = [\lambda\widehat{M}A + d][(I - (1 - \widehat{M})A]^{-1}. \tag{7}$$

Then, using row-wise data from an input-output table with the given intensity of CO_2 emissions embodied by product *i*, the balance of CO_2 emissions of domestically produced products in sector *i* can be obtained:

$$\varepsilon_i X_i = \varepsilon_i(1-m_i)\{x_{i,1} + x_{i,2} + \cdots + x_{i,k} + \cdots + x_{i,n}\} + \varepsilon_i(1-m_i)F_i^d + \varepsilon_i EXP_i$$

$$= \varepsilon_i(1-m_i)\sum_{j=1}^{n} x_{i,j} + \varepsilon_i(1-m_i)F_i^d + \varepsilon_i EXP_i \qquad (8)$$

where EXP_i is the export of product *i* that is produced domestically.

Integrating both sides of equation (8), we obtain:

$$\sum_{i=1}^{n} \varepsilon_i X_i = \sum_{i=1}^{n}\sum_{j=1}^{n} \varepsilon_i(1-m_i)x_{i,j} + \sum_{i=1}^{n} \varepsilon_i(1-m_i)F_i^d + \sum_{i=1}^{n} \varepsilon_i EXP_i \qquad (9)$$

Similarly, in reference to equation (2) using column-wise data from an input-output table:

$$\varepsilon_j X_j = \sum_{i=1}^{n} \varepsilon_i(1-m_i)x_{i,j} + \sum_{i=1}^{n} \lambda_i m_i x_{i,j} + D_j \qquad (10)$$

Integrating both sides of equation (10) once again, we obtain:

$$\sum_{j=1}^{n} \varepsilon_j X_j = \sum_{j=1}^{n}\sum_{i=1}^{n} \varepsilon_i(1-m_i)x_{i,j} + \sum_{j=1}^{n}\sum_{i=1}^{n} \lambda_i m_i x_{i,j} + \sum_{j=1}^{n} D_j \qquad (11)$$

Based on equations (9) and (11) and considering the control totals principle, which is written as $\sum_{i=1}^{n} \varepsilon_i X_i = \sum_{j=1}^{n} \varepsilon_j X_j$, the following balance is obtained:

$$\sum_{j=1}^{n}\sum_{i=1}^{n} \lambda_i m_i x_{i,j} + \sum_{j=1}^{n} D_j = \sum_{i=1}^{n} \varepsilon_i(1-m_i)F_i^d + \sum_{i=1}^{n} \varepsilon_i EXP_i \qquad (12)$$

The left side of equation (12) represents the input, total CO_2 emissions associated with domestic production, whereas the right side indicates the final destinations of the CO_2 emissions embodied in the domestic products.

Equation (12) captures the balance of CO_2 emissions associated with domestic production processes. However, to construct a more comprehensive balance of the CO_2 emissions associated with city activities, two other forms of CO_2 emissions that are not related to domestic production must be considered. One such form of CO_2 emissions is the CO_2 emissions embodied in the imported commodities that are supplied directly to the final demand sector, whereas the other involves direct CO_2 emissions from the final demand sector. Examples of this second form include CO_2 emissions produced by private vehicles and the combustion of fuel for cooking and heating at home.

When the above-mentioned two types of CO_2 emissions are added for both the inputs and the distribution of the carbon balance of the economy without altering anything, equation (13) is obtained:

$$\sum_{j=1}^{n}\sum_{i=1}^{n}\lambda_i m_i x_{i,j} + \sum_{j=1}^{n} D_j + \sum_{j=1}^{n}\lambda_j m_j F_j^d + D_F$$

$$= \sum_{i=1}^{n}\varepsilon_i(1-m_i)F_i^d + \sum_{i=1}^{n}\varepsilon_i EXP_i + + \sum_{i=1}^{n}\lambda_i m_i F_i^d + D_F \tag{13}$$

where $\sum_{j=1}^{n}\lambda_j m_j F_j^d$ and $\sum_{i=1}^{n}\lambda_i m_i F_i^d$ are the CO_2 emissions embodied in the imported commodities for both the inputs and the distribution, respectively. D_F represents the aggregate direct CO_2 emissions in the final demand sector.

4.2 Boundary setting and model application

This paper applies common alternative simplified methods to establish boundaries between countries and cities, for which the embodied carbon intensities are computed separately.

This paper then applies the above-mentioned methodology to both countries and cities as a simplified input-output approach to capture the virtual flows of carbon emissions of cities. First, the CO_2 emissions embodied in goods and services or by sector are measured using the input-output model at the national level to capture indirect CO_2 emissions. Note that the influxes of goods and services into a city from domestic and overseas sources cannot be easily differentiated, due to the limitations of the data. Therefore, national average intensities of embodied CO_2 emissions are used as the best available proxy indicators to capture the indirect CO_2 emissions embodied in the goods and services imported by cities.

4.3 Data

Two primary sources of data, input-output tables and energy balance tables of study cities, are used in the empirical analysis presented in this paper.

Input-output tables are collected directly from each local government as paper-based documents and converted into digital format[7]. The number of endogenous sectors in the original input-output tables used in the analysis are summarized in Appendix A. In the energy input-output analysis, these numbers are usually constrained by the availability of per-sector data on energy consumption, which is much less detailed. The availability of energy data is summarized in

[7] Some has been published online or paper-based and some are internal documents of local governments. However, we collected all these input-output tables in the form of paper-based documents.

Appendix B, and regional energy balance tables for the 6 cities are generated using available data sources. The energy balance tables of cities are generated mainly based on digital archives of "Current Survey on Market Structure of Petroleum Products (in Japanese) (Ministry of Economy, Trade and Industry of Japan. (various years)) as these surveys include not only prefectural data but those of the GODLCs. Other supplementary materials used for completing energy balance tables are various paper-based documents and books, including data books that compile information on household energy consumption and statistical data on power stations (Office of Gas Market Development, Agency for National Resources and Energy, Ministry of Economy, Trade and Industry (ed.). (1980, 1985, 2000), Electricity and Gas Division, Agency for National Resources and Energy, Ministry of Economy, Trade and Industry of Japan (ed.). (1980, 1985, 2000), Jyukankyo Research Institute Inc. (2009)).

Considering the availability of data on sectoral energy consumption, a common unified sector classification of input-output tables is established to permit coherent empirical analysis among the 6 cities (see Appendix C). The input-output tables from all of the selected cities are separated and combined to create twenty-four compatible sectors.

For the national level analysis, the input-output tables and energy balance tables are both available with much more detail information (Administrative Management Agency (1980), Management and Coordination Agency (2000), Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry of Japan. (various years)). We then edited national data to be consistent with city level analysis.

5 Results

5.1 Emission inventories produced using the four system boundaries approach

Per capita emission inventories produced using the four system boundaries approach are estimated for the selected cities in 1980 and 2000, and cross-city and historical comparisons are made (see Appendix D for detailed results). Industrial cities, such as Kitakyushu, demonstrate higher per capita emissions when SB-1 and SB-2 are used. This indicates the suitability of utilizing these two system boundaries for capturing the responsibilities imposed by the direct emissions associated with the production activities. On the other hand, those cities with relatively larger-scale economies, such as Yokohama and Kitakyushu, show large per capita carbon footprints as measured using the SB-3. The consumer cities with relatively smaller economies show greater amounts of per capita emissions when the SB-4 is used, compared to the emission values obtained using the SB-1 and SB-2.

Figure 2 displays the per capita emissions obtained using each of the carbon accounting methods in 1980 and 2000 as boxplots. In general, the cross-city variance decreases slightly from 1980 to 2000. During this period, all of the cities have shifted towards being consumer cities with service-oriented industrial structures. Furthermore, the largest cross-city variation is found using the measurements based on the SB-3, whereas that obtained using the SB-4 is fairly small, indicating that the emission inventories obtained using the SB-4 are homogeneous across the different cities and are stable over time.

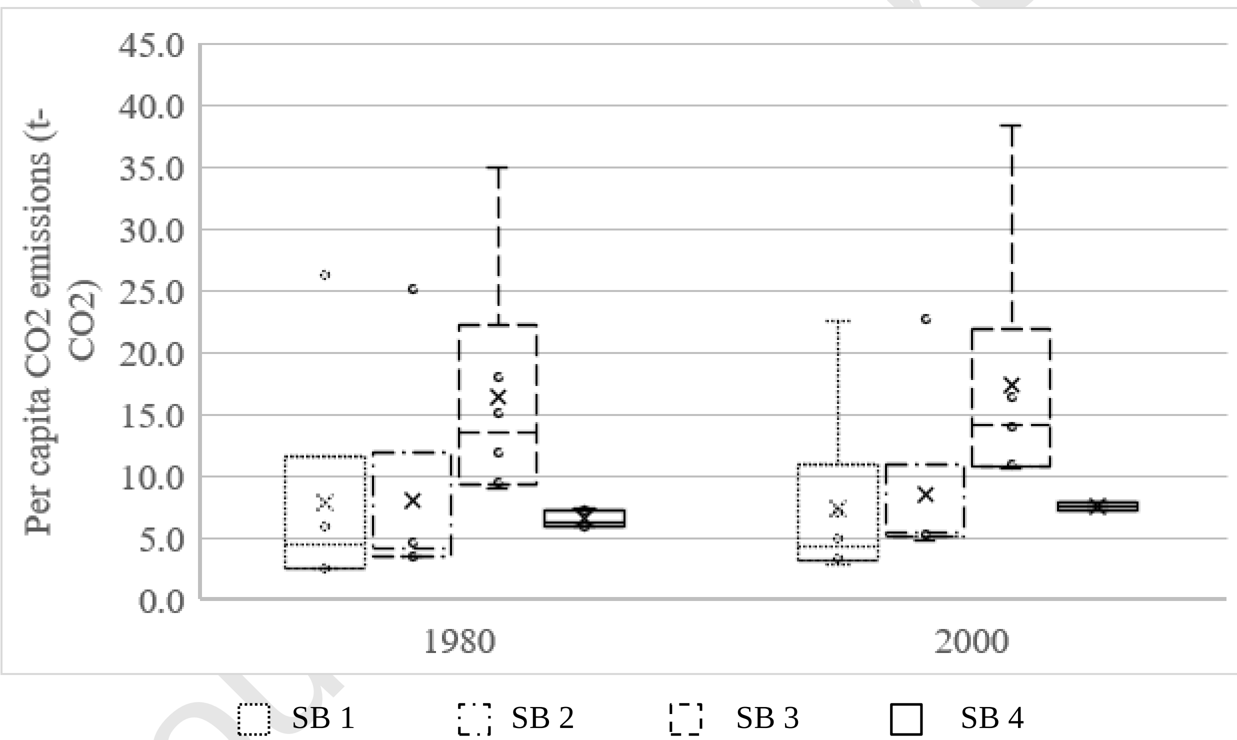
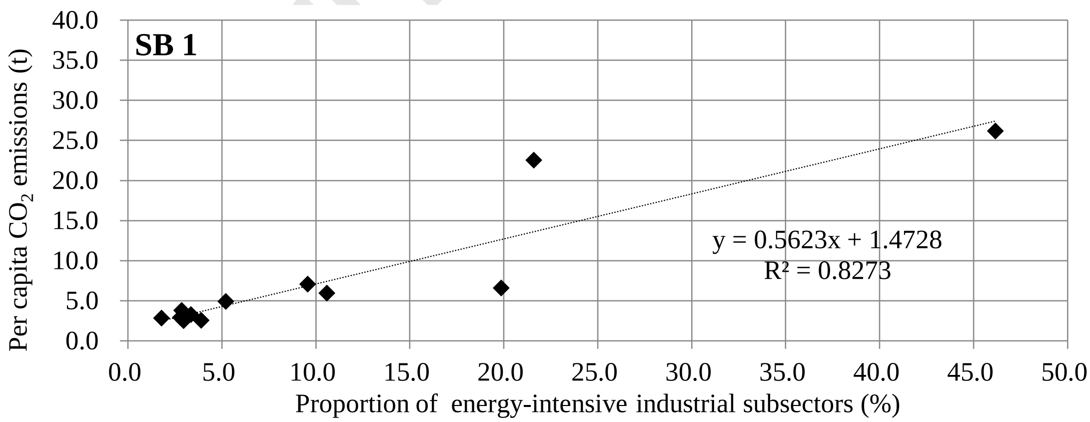


Figure 2. Changes in cross-city comparison on per capita CO_2 emissions estimated using different accounting methods (t-CO2)

5.2 Industrial structures and emission inventories for individual cities

During the 1980s and 1990s in Japan, the common direction of the industrial transformation of cities was toward consumer cities or service-oriented industrial structures. Likewise, the 6 selected cities have shifted in the same direction. Consequently, the decline in industrial sectors, especially energy-intensive subsectors (EISSs), is a common and visible phenomenon (see Table 2). In this study, we define five industrial sectors, “chemistry”, “petroleum and coal products”, “ceramics, stone and clay products”, “iron and steel”, and “electricity, gas and water”, as the EISSs. Figure 3 shows the relationship between the share of EISSs in the industrial sector, as measured by value added and different boundaries of carbon accounting (from SB-1 to SB-4). The carbon accounting methods for the SB1 to SB-3 are largely explained by their linear correlation with the share of EISSs, whereas the carbon accounting of the SB-4 is not related at all. This result confirms that the SB-4 represents a method of assessing consumption-based emissions performance that is not affected by production-related factors.



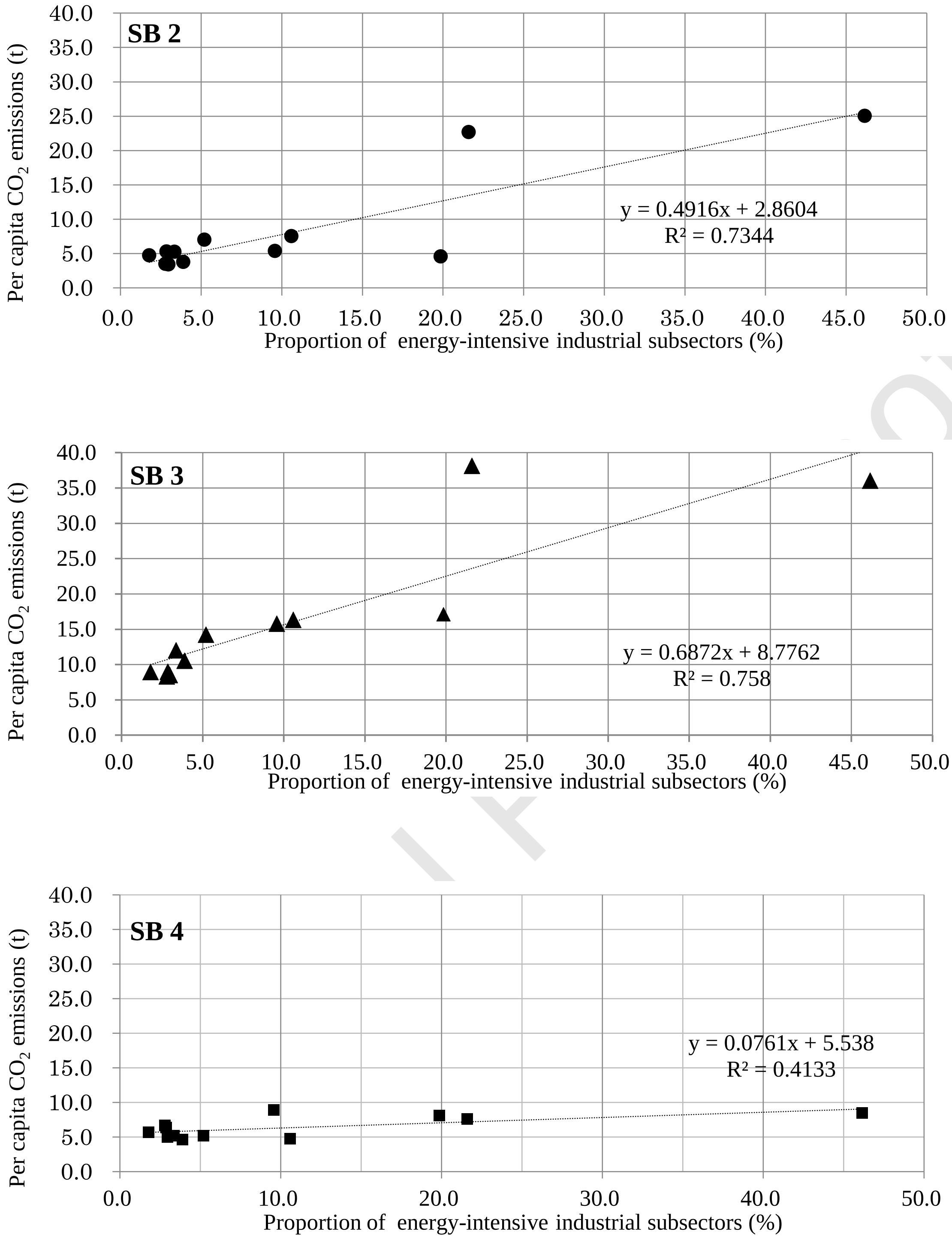


Figure 3. Per capita CO_2 emissions and share of energy-intensive subsectors

Table 2. Share of energy-intensive subsectors (EISSs) in the industrial sector

	Average annual change					
	Chemical products	Petroleum and coal products	Ceramics and stone and clay products	Iron and steel	Electricity, gas and water	Total
Sapporo	0.047	-0.034	-0.077	-0.034	0.008	0.002
Yokohama	-0.050	-0.035	-0.045	-0.106	-0.010	-0.036
Kobe	0.018	-0.045	-0.017	-0.078	0.011	-0.035
Hiroshima	-0.045	-1.000	-0.034	0.000	0.002	-0.007
Kitakyushu	-0.025	-0.089	-0.008	-0.046	-0.011	-0.037
Fukuoka	-1.000	0.000	-0.045	-1.000	-0.019	-0.025

6 Conclusion and policy implications

The two major findings of this empirical study are summarized below.

1) The per capita CO_2 emissions obtained using the SB-4 exhibit very small cross-city variations amongst large cities in Japan. This is despite the fact that these cities feature different industrial structures ranging from industrial cities to service-oriented ones. In contrast, per capita emissions calculated using the SB-1, SB-2 and SB-3 are significantly affected by the industrial structure of cities.

2) The per capita CO_2 emissions obtained using the SB-4 are stable over the 20-year study period (1980-2000). Over this period, the selected cities have reduced their shares of EISSs to different degrees.

Most Japanese cities employ emission inventories obtained using System boundary 2 to set targets and goals for climate action plans. They are also shifting their industrial structures toward those of consumer cities. Consequently, the climate action plans seem to be successful in meeting climate change mitigation targets. However, the consumption-based emissions measured by carbon inventories obtained using the SB-4 have not changed in large cities in Japan over the 20 years from 1980 to 2000. Althouh a number of challenges remain regarding the acquisition of data and methodological advancements to permit practical application of the measurements made using the SB-4 so that it is sufficiently sensitive to grassroots actions, such as energy-saving behavior and green purchasing and procurement, this study suggests the significance of moving in that direction.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declarations of interest

None.

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