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Cities and Heat-island

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1. Introduction

While global warming problem is widely recognized as an important subject to be solved, it is also noticeable that the temperature of urban area rises in recent years. It was cool in the morning and evening even in summer in the metropolises such as Tokyo. However, people are hit by the record heat wave every year, and the temperature stops falling down even if night comes. Walking in the town of tall buildings in the daytime of summer, most people will feel that the aggravation of urban environment proceeds, because the narrow street space is polluted by heat emissions from buildings and automobiles, by the concentration of them, and by the multiplex reflection of heat from roads and buildings. The reports about the number of victims of heat stroke are seen frequently these days. Air conditioners are always indispensable in such cities to get along comfortably. People continue to use air conditioners even though they notice that the waste heat from air conditioners is one of the factors of the temperature rise, and then they are falling into a vicious circle. In addition to summer, the number of the days whose daily lowest temperature is below 0 ºC decreases in winter.

The temperature of the center of Tokyo rose at about 3 ºC in the past 100 years, as we see it in detail in the next section. Various influences such as health damage and the localized torrential downpour in summer arise to our life from this phenomenon. As for global warming problem, according to the IPCC (Intergovernmental Panel on Climate Change) 3rd report, the average earth's surface temperature will rise to 1.4-5.8 ºC from 1990 through 2100. The unstabilization of climate condition and the bad influences to mankind associated with it are being expected. The temperature change of Tokyo in the past 100 years might as well be expressing and anticipating exactly the average temperature change of the whole earth in the 21st century. Therefore, it can be said that even the various influences that have occurred in urban regions at present are the precious data suggesting the figure of the future earth. If no countermeasure is touched from now on, it seems that urban environment becomes worse all the more with the influences of global warming.

The various phenomena associated with the rise of urban temperature are known

as "heat-island phenomenon" these days. This phenomenon is also observed in many cities of the world, and thought to originate in the advancement of urbanization and in waste heat associated with the intensive energy consumption in cities.

The quantity of energy which mankind uses is said about 0.01% of the energy which the ground surface receives from solar radiation, and therefore the direct influence of the waste heat from energy consumption is not so much if we see it with the scale of the whole earth. As it is well known, it is not heat emissions from cities but greenhouse gasses by fossil fuel combustion and so on that influence on global warming. The influences of artificial exhaust heat, however, cannot be disregarded when discussing urban regions limitedly, because energy consumption is carried out in local places such as cites. Thinking of a unit area, the central districts of Tokyo and New York are said to radiate the energy which is close to the quantity they receive from the sun. Therefore the situation will be not too much to say with "the heat contamination of city." However, it has not been recognized as an important problem very much, partly because there were little concrete damage and influence so far.

The purpose of this paper is to consider the problem of urban warming, focusing on the heat antipollution measures for the solution of the urban problem rather than the prevention measure of greenhouse gases. We will recognize the heat contamination of cities called heat-island phenomenon as an important problem that equals to urban pollution problems, and then we will examine it comprehensively.

2. Heat-island Phenomenon

As for the scientific aspects of heat-island phenomenon, many researchers are proceeding with the clarification vigorously. In this section, we will survey the characteristic points of heat-island phenomenon such as the situations, causes and influences, based on the existing research results.

2.1 What is Heat-island Phenomenon?

"Urban climate" is a climate as a conclusion of the climate change caused by the advancement of urbanization. Heat-island phenomenon is one of the characteristics of the urban climate. Heat-island phenomenon is a phenomenon that the temperature of an urban region becomes higher in comparison with the suburban area. When we draw the

isotherms of temperature about the area where an urban region and a suburban area are combined, the form of the distribution becomes the state of closed-shaped curve around the center of the city. It looks like the contour lines seen in the map of an island on the ocean, and then has come to be called heat-island by the analogy.

It has known that the temperature of urban region becomes higher in comparison with suburbs since the old days. Howard (1833) was the first research which showed the fact using the observation of the climate data during 1807-1816 in London. In London at the beginning of the 19th century, the progress of urbanization was remarkable with the development of industries and the concentration of population by the Industrial Revolution. Therefore, it is inferred that not only the natural environment and ecosystem but also the climate of the urban region was changing very much. After that the temperature rise in urban region seems to be observed even in the big cities in Europe such as Berlin, Vienna, and Paris at the beginning of the 20th century. It is said that Duckworth and Sandberg (1954), the meteorologists of the United States, were the first paper which named this phenomenon "heat-island" and have come to collect the concerns. Heat-island phenomenon is being observed in many cities in the world these days, and making the life in urban region uncomfortable. Because of this, the accumulation of observations and researches is carried out as one of the fields of urban environmental problems in Europe and America. In Japan the occurrences of it are confirmed in not only big cities but also small and medium sized cities. The researches are advanced vigorously among meteorologists, geographers, urban engineering scholars and architecture scholars.

2.2 Characteristics of Heat-island Phenomenon

Heat-island phenomenon is thought generally to distinguish from global warming since the causes are different each other. However, both of them have many common points at the same time. The remarkable feature of heat-island phenomenon is that it combines the nature of global warming problem and the nature of air pollution problem. The similarities with global warming are, firstly, that the pollutants themselves are not harmful. Most of greenhouse gases such as carbon dioxide do not bring harm to mankind, animals and plants as chemical substances. As well as greenhouse gases, "heat," which is the pollutant bringing heat-island phenomenon, does not cause fatal damage to the life and living of citizens to the amount of some extent.

Secondly, both of them are the problem of climate change caused by economic activities of human, and also the problem that the polluters are the victims at the same time.

The victims by global warming are mankind, and the emissions of greenhouse gases which are the cause of it are also associated with human activities. As seen in the following subsection, the cause of heat-island phenomenon is the waste heat discharged by anonymous people in cities, and the sufferers from unpleasantness are also the urban residents. That is, both of them are caused by the increase of energy consumption associated with economic activities.

On the other hand, the first point in common between heat-island phenomenon and air pollution problem is that the damage from a unit of contamination differs by time and space. Nitrogen oxides and sulfur oxides are the flow pollutants from the viewpoint of time, because they are purified in several hours or several days after they are discharged into the atmosphere. Heat also has the similar pattern to them. In addition, the extent of damage differs at daytime and night, and depends on the season. It is contrastive with the damage by greenhouse gases which are the stock pollutants and remain in the atmosphere for a very long period to keep the bad influences going on.

From the viewpoint of space, heat-island phenomenon becomes a serious problem just in an urban region, in other words, the polluted range is limited in a particular area. This point is similar to the air pollution caused by nitrogen oxides and sulfur oxides. Heat-island phenomenon is a problem in a domestic, moreover, a limited urban region, and its causes are clear to some extent. Consequently, if we see it from a different angle, this suggests there are comparatively few obstacles to promote measures.

In contrast, the mechanism of global warming is very complex and there are many to elucidate, although the primary cause of it is thought to be the accumulation of greenhouse gasses into the atmosphere. As for global warming, the estimated rise of temperature and the influences on mankind are uncertain. Therefore, it is the subject to think for a very long period of a few hundred years, and it is necessary to tackle the measure with international cooperation. But it is not necessarily easy to promote effective measures because of the political, economical and social differences among nations.

The second point in common is that the damage increases sharply when the level of pollution exceeds a critical value. The appropriate environmental standards are set up and the discharge regulation is carried out so as not to exceed it, because nitrogen oxides and sulfur oxides do harm to human health directly through air pollution. Heat-island phenomenon causes the increase of health damage such as heat stroke when the temperature exceeds a critical point.

2.3 Situation of Temperature

We start to see the transition of the temperature of cities in order to confirm the actual condition of heat-island phenomenon. According to the Meteorological Agency (1999), the annual average temperature rise of the Japanese metropolises for the past 100 years is 2.9 ºC in Tokyo at the maximum, 2.1 ºC in Sendai at the minimum, and 2-3 ºC in general. Also as for the big cities, the rise of temperature is higher in winter than in summer, and the rise of the lowest temperature at night is higher than that of the highest in daytime on average (Table 1). On the other hand, the rises of the annual average temperature, the average temperatures in January and August in small and medium sized cities where the effect of urbanization is relatively not so much are lower than those in big cities. They are about 0.9-1.0 ºC, and there is little difference among seasons. The rise of the daily lowest temperature is 1.4 ºC, which is low in comparison with 3.6 ºC of the average of big cities. As seen from the above observations, the characteristics of heat-island phenomenon are that it is more obvious in winter than in summer, more distinct at the lowest temperature at night than at the highest temperature in the daytime, and more notable in big cities. This phenomenon is seen not only in Japan but also in the cities of the world in common.

<Table 1 is around here.>

Table 2 shows the annual change of the number of "tropical days" on which the temperature rises above 30 ºC, "ice days" on which the temperature stays below 0 ºC, and "sweltering nights" on which the temperature does not fall below 25 ºC, from 1951 to 2000. The number of ice days shows a tendency to decrease in Sapporo and Sendai. Especially in Sapporo, it decreases greatly from 1991 through 2000 compared with the former years, and we are able to infer the temperature rises in winter. There is a tendency to increase in the number of tropical days in the big cities such as Tokyo, Nagoya and Osaka, and more than 50-70 tropical days are observed every year from 1991 through 2000. The number of sweltering nights is also in an increasing trend, and the pace to increase is faster than that of tropical days. This shows that temperature at night is hard to fall down.

<Table 2 is around here.>

The point we must pay attention on evaluating the change of urban temperature is that it is necessary to distinguish the influence caused by urbanization from the influence caused by global warming. However, it is very hard in general to calculate the influence

caused by urbanization strictly, because urbanization has progressed to a greater or less extent in the long run in cities of any kinds of scale.

The Meteorological Agency carried out a minute analysis for the temperature rise in Japan excluding the elements of urbanization (Meteorological Agency, 1999). The estimated rise of average temperature for the past 100 years in Japan was approximately 0.7 ºC.

The Ministry of the Environment (2001) introduced some temperature distribution maps on the typical summer days (fair and weak wind days covered with a Pacific high pressure, from June to September in 1997-1999). According to the maps of the Kanto region, a high temperature area of above 30 ºC appears from Nerima-ward over the southeast part of Saitama Prefecture around 10 a.m. This area expands all over the Kanto plains around 2 p.m., and still remains from the northern part of Saitama Prefecture to the southern part of Gunma Prefecture even in the evening at 6 p.m. The temperature does not fall down very much even at night in the center of Tokyo compared with the suburbs, and the condition of high temperature continues until dawn. We can see easily that heat-island phenomenon is formed (Figure 1).

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Another characteristic point reported on it is that the total number of hours exposed to the high temperature of above 30 ºC from July to September is increasing sharply. Based on the analysis, it increases three times in Sendai, twice in Tokyo and Nagoya when comparing 1980 and 2000. In addition, more serious matter as a condition of heat contamination is the expansion of the areas where the total number of hours of above 30 ºC increases. The reasons such a high temperature continues for a long time are inferred as follows. First, the air warmed in the center of Tokyo is carried to the inland by the sea wind from Tokyo Bay or Sagami Bay in the Kanto region. Second, the cool wind from the Echigo region flows into the Kanto region during the middle of the night but does not reach the southeast part of Saitama Prefecture.

2.4 Influence

The influences associated with heat-island phenomenon are, firstly, the effects caused by climate change on our daily life. It is temperature to be obvious. The high temperature of the daytime in summer, especially the one above 35 ºC, gives people unpleasantness.

Heat-island phenomenon brings a sleeping difficulty, because it appears at night remarkably and especially increases the number of sweltering nights in summer.

It is pointed out that there may be the relevance between the short time torrential downpour in summer observed recently and heat-island phenomenon. Some people died due to the house inundation and so on by a local downpour. The frequency of heavy rain of 10 mm and more per hour has a tendency to increase. Especially the number of the heavy downpour of over 100 mm per hour was ten times in 1999, six times in 2000, whereas it was zero-twice in the first half of the 1990s in Japan. According to some researches, it is thought that cumulonimbi grow easily in urban areas. The mechanism is that urban atmospheric convection meets the wet air current from the ocean and becomes an active updraft due to the urban high temperature. As for the time zone when heavy rain falls, the share of the evening (5 p.m.-8 p.m.) decreases to about 40%, and instead of this the share of the middle of the night (9 p.m.-12 a.m.) and early afternoon (1 p.m.-3 p.m.) increases to about 20% each by the observation at Otemachi in Tokyo. These observed facts meet with the characteristics of heat-island phenomenon which temperature in cities rises to high even in the morning and does not fall down easily even at night.

The second influence is much increase of energy demand. Cities are huge energy consumption places, and radiate enormous waste heat at the same time. Heat-island phenomenon has a close relation with the energy consumption in cities. The more rise of urban temperature by artificial exhausted heat brings the excessive energy consumption especially for air conditioning. This forms a vicious circle. The increasing number of severe heat days and sweltering nights in midsummer pushes up the demand of electric power for air conditioning. It is easy for us to imagine that the increase of energy consumption becomes enormous quantity as a city total even if it is very little for each office and residence.

The third influence, which is the most anxious about, is the damage to human health. Human health condition is fragile against an extreme climate change rather than a stable climate. The severe heat in midsummer is considered as a typical case of the extreme climate change. More serious damage to human body we should be anxious about is the increase of heat stroke though unpleasantness and sleeping difficulty at a sweltering night. The number of persons carried by ambulances with the symptom of heat stroke has a tendency to increase year by year (Figure 2). The relation with the rise of temperature by heat-island phenomenon is suspected. According to the research by Ando with the cooperation of the Tokyo Fire Defense Agency (Ando, 1998), it is reported that there is an obvious positive correlation among the daily average temperature, the daily highest

temperature and the number of sufferers of heat stroke when the temperature exceeds a certain level. Sufferers begin to appear with the highest temperature of around 29 ºC, and have a tendency to increase sharply with that of around 31 ºC in Tokyo (Figure 3). Considering the number of sufferers of heat stroke per 1 million of population, it is one person at around 33 ºC, and two persons and more when the temperature reaches 34 ºC. The very characteristic point is that the speed of the increase is like an exponential function. It is forecasted that the temperature rise of only 1 ºC brings too many sufferers after it exceeds 34 ºC. Seeing the sufferers by age, they are distributed to all the age classes of over 15 years. But it is known that the occurrence rate is extremely high for elder people of over 80 years.

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3. Causes, Measures and Problems

3.1 Causes

It is artificial exhaust heat and the change of city form that generally pointed out as main factors which influence the formation of heat-island. In fact, it seems that these factors are acting compositely. We examine them in the following.

It is needless to say that the artificial exhaust heat is the result of energy consumption such as petroleum, gas and electricity. The input energy is distributed and consumed for the use of industries, transportations and other private sectors with the form of electricity and so on. However, the energy used effectively is only 30-40% of all the input energy, and the rest is discharged into the atmosphere as waste heat in Japan. Moreover, the energy used effectively is 37.5% of all the input energy in 1975, and it became worse to 33% in 1994.

The energy such as petroleum, gas and electricity is finally radiated in the form of thermal energy into the atmosphere. The sources of waste heat are buildings (residences and offices), business activities such as factories, automobiles and so on. By investigating the change of the energy consumption in Tokyo Metropolitan area, we are able to understand that the transportation sector and the business sector are contributing to the increase of the energy consumption very much. The reasons in the transportation sector

are the increasing number of automobiles and the deterioration of fuel efficiency by the enlargement of automobile size. In the business sector, the reasons are the increase of floor space by the occurrence of higher office buildings with wide basement space, the increase of energy consumption per unit floor area by air conditioning and electronic equipment for business, the diffusion of vending machines, and the extension of business hour of service industries such as convenience stores and food restaurants. In the household sector, the reasons are the increase of the number of household itself, and the increase of energy consumption per household by the widespread of electronic goods.

One more important factor giving the influence to urban temperature is the change of ground surface. The decrease of water and green areas due to urbanization causes the loss of the mechanism that latent heat of evaporation drops the urban temperature. Most of green areas in Tokyo are small while the supply of parks is in progress. Many small rivers disappeared along with the urbanization, and the rest of the rivers are hardened with concrete walls or became culverts. The characteristic point in urban area is that most part of ground surface is covered with such materials as concrete constructions or asphaltic paving, whereas the surface in suburban area is covered with soil. Even if it rains on such a concrete surface, it returns to dry with little ground permeation, and then the amount of water evaporation from the surface decreases. As a result, most of energy from solar radiation and artificial exhaust heat becomes sensible heat, and raises urban temperature directly.

Moreover, concrete and asphalt have big heat capacity in comparison with soil, and have the nature that they are hard to get cold easily once they warm up. By this nature of heat storage, buildings and asphaltic roads radiate the heat saved in daytime slowly during night, and then raise urban temperature at night.

Building high constructions expands the surface area of city, therefore it affects negative on the thermal environment of the city. In addition, it is known that heat is easy to be concentrated near the ground surface in the urban region where constructions of various heights line up.

As mentioned above, the waste heat associated with economic activities and the change of ground surfaces (the decrease of green spaces and the increase of artificial surfaces) are conceivable as main factors of the rise of urban temperature. These factors are acting compositely. It is difficult to evaluate them indiscriminately because their importance varies in city scale, the structure of blocks and geographical features. The observations by remote sensing method and simulations by models are advanced in order to solve these problems.

3.2 Measures and Problems

Heat-island phenomenon has come to attract attention recently as an urban environmental problem, and has more opportunities to be reported on the media. The Ministry of the Environment and some local governments including Tokyo have started the consideration for the measures. Many scholars and researchers are tackling scientific studies toward the elucidation of the phenomenon and promoting more detailed studies using remote sensing and model simulation methods as well as climate observations. These research results, however, are on the way of accumulation at present.

It is hard to say that heat-island phenomenon is heading for the improvement because administrative agencies have just begun the measures. We are able to imagine easily that the influences and the damages by heat-island phenomenon are getting more serious for the near term. We hope that some measures are taken promptly before the present situation is gets worse. It is because there is a fear that heat-island phenomenon brings health damage to the city inhabitants when the temperature exceeds a certain critical level and because causes are comparatively definite. As for several measures, the efficacy is confirmed to a certain extent by the simulations.

One of the problems is, however, these measures are whether or not cost-effective. The cost of them is not necessarily definite. Especially, the confirmation of the cost and benefit is indispensable as for measures the public sector manages. Furthermore, it is necessary to give priority which measure should be taken based on the evaluation of these measures, but such a work is delayed at present. The accumulation regarding the cost and benefit evaluation is hastened because there is a possibility that high cost measures are implemented without these evaluation and examination.

4. Urban Atmosphere and Social Common Capital

4.1 Urban Atmosphere as Social Common Capital

Social common capital presented by Uzawa (1994, 2000, 2005) provides members of a society with those services and institutional arrangements that are crucial in maintaining human and cultural life. Social common capital in principle is not appropriated to individual members of the society but rather is held as common property resources to be

managed by the commons in question, without, however, precluding private ownership arrangements. Nor is it to be controlled bureaucratically by the state (Uzawa 2005). It is generally classified into three categories: natural capital, social infrastructure, and institutional capital.

Natural capital consists of the natural environment and natural resources such as forests, rivers, lakes, wetlands, oceans, water, soil, and the earth's atmosphere. Social infrastructure is consists of roads, bridges, public mass transportation systems, communication and postal services, and public utilities. They are the facilities forming a city. Therefore a city is considered as the accumulation of social common capital which provides urban inhabitants with services.

Urban atmosphere can be placed on one of the components of social common capital when we think of it as a part of natural environment in a city.

4.2 Improvement of Artificial Ground Surface: Recovery of Water and Soil

The measures for heat-island have a role to restore urban atmosphere. The main policy to do them is considered to revive the "water" which increases latent heat, and the "soil" which includes green spaces. This is nothing else but the improvement of artificial ground surface in urban region. It is considered as a trial to recover the natural state.

The restoration of water is to improve the water circulation of cities. One of the causes of heat-island phenomenon is the expansion of the impermeable ground surface such as concrete and asphaltic surface. This has led to the collapse of natural water circulation systems in cities. There are two types of water circulation in cities, one is natural circulation and another is artificial circulation of waterworks and sewer. The water environment in cities is consists of both of them with the mutual relevance. Under the natural circulation, rainfall infiltrates into underground and is reserved. The part of it evaporates from ground surface and the rest forms water veins. The part which does not infiltrate completely streams on ground surface and then flows into rivers. The evaporation from ground surface drops the temperature near there. The expansion of impermeable surface associated with urbanization, however, reduces the water around the ground surface and underground water, and increases the flow to rivers. Thus, it became difficult to keep the natural water circulation.

Rivers have come to play the big role of drainage path together with the expansion of impermeable ground surface; that is, it became general that river walls turned

to concrete and that waterways were repaired to straight lines. Rainfall in a city flows out from the city in a short time in such a way. The quantity of the flow is increasing year by year. It often excesses the capacity of rivers and causes floods inside the city because there is no process of water reservation on the way. The flood damage after the torrential downpour in summer is considered to be a phenomenon related to urbanization and heat-island.

In addition to the usual water resource policies such as flood control and waterworks, the importance of the recovery and preservation of the environment is rising in recent years. Especially the preservation and improvement of natural water circulation attract people's attention. This is the conversion from the former idea of the speedy exclusion of rainfall outside of city to the new idea of the enlargement of the quantity of infiltration and reservation inside city. In order to make use of the water retention capability of ground, it is considered to use rainfall permeation facilities as the technology of improvement in water circulation, to recover river walls, and to improve the water environment in parks. Rainfall permeation facility is the one to restore water to ground as before urbanization. Water permeable paving is a type of it, for example. It is expected that the stock water in city leads to mitigate the heat-island phenomenon by making use of it as measures of latent heat supply.

The recovery of ground surface plays an important role as well as natural water circulation. Heat-island phenomenon is a problem arising from the change of land use in city, that is, the change from soil to artificial surface. Therefore, an effective measure is the revival of the former land use from the artificial surface in the city as much as possible. Practically speaking, it is almost impossible to restore to the original land condition in the city. Adopting water permeable paving or other water retention materials as measures is, however, a trial to recover the ground surface with the water retention capability. This is, so to speak, to try to replace natural capital with artificial capital similar to it. Rooftop gardening and wall surface greening as well as the improvements of green spaces are considered to be the restoration of ground surface or soil inside city.

Green space has a close connection to both of water and soil. It is needless to say that the capability of green space is effective for the mitigation of heat-island phenomenon. Although rooftop gardening is promoted as one of the measures for urban tree-planting, it is necessary to secure the sufficient water supply as a precondition to it. As for roadside trees and greenbelts, it is difficult to take full advantage of their capability without the sufficient water supply when there is much impermeable ground surface around them.

4.3 The Improvement of City Form

As city has an irreversible nature, it is difficult to change the form. The restoration of water and soil is a trial to improve the form, and the efforts such as water permeable paving and rooftop gardening are being carried out. But they have only limited effects in the whole improvement of the city.

The point that an examination is needed on the relations between heat-island phenomenon and city form is the handling of automobiles in city. The exhaust heat from cars is considered to be controllable by raising the cost of using cars through the environmental tax, and moreover, by introducing fuel cell cars in the future. But it is expected to take much time for the diffusion.

Cities depending on automobiles are not necessarily desirable from the viewpoint of not only heat-island phenomenon but also global warming. Public transportation systems are appropriate rather than automobiles in the center of a city with the high density. On the other hand, automobiles are still effective traffic means in the suburbs and low density areas. The role of automobiles inside city is different from outside, and therefore, it is desirable to use them with the understanding of the effectiveness. In this sense, there seems to be a point to be improved in the present form of the city where automobile transportation systems are highly developed.

The conventional urban planning including zoning or floor-area ratio restrictions has a lot of limits when we try to improve the city form in our country by the restoration of water and soil, and by the control of automobiles. Making synthetic policies is general in Europe on the occasion of the urban planning instead of such a conventional one. The policies such as a strategic vision of city, a fund-raising means, a tax system, a standard for environmental protection, employment, an income distribution, and so on are treated together in it. In other words, the point of view that city is an object of the management with the various measures is dominant. The density in the central part of a city is high in many European cities. Therefore, they think automobile traffic is not suitable. They implement the exclusion of the through traffic, the yield of the right-of-way to pedestrians, and the control of the parking area in the center of the city, by using the combination of various measures. They also practice urban tree-planting and create open spaces. These efforts are based on the idea of "sustainable city." There are some cases that good urban environment increases the asset value of the land and buildings. In this way, the good urban environment yields a good circulation with the improvement of the city form.

References

Ando, M. (1998), "The Effects of Global Warming on Human Health: Heat Stress and Heat Stroke," *Global Environment*, Vol. 2, No. 2, pp. 119-126. (in Japanese)

Duckworth, F. S. and J. S. Sandberg (1954), "The Effect of Cities upon Horizontal and Vertical Temperature Gradients," *Bulletin of American Meteorological Society*, Vol. 35, pp. 198-207.

Howard, L. (1833), *Climate of London deduced from Meteorological Observations*, 3rd edition, in 3 volumes, Harvey & Darton.

Meteorological Agency (1999), *Abnormal Weather Report '99*. (in Japanese)

Ministry of the Environment (2001), *A report on the Analysis of Current Status and the Measures for Heat-Island Phenomenon*. (in Japanese)

Uchiyama, K. (2003), "Heat-island Effects in City," in Uzawa, H., Kuninori, M. and K. Uchiyama (eds.) *Reflections on the City in the 21st Century: City as Social Overhead Capital 2*, pp. 249-284, Tokyo: University of Tokyo Press. (in Japanese)

Uzawa, H. (1994), "The Concept of Social Overhead Capital," in Uzawa, H. and A. Mogi (eds.) Social Overhead Capital: Cities and the Commons, pp. 15-45, Tokyo: University of Tokyo Press. (in Japanese)

Uzawa, H. (2000), *Social Common Capital*, Tokyo: Iwanami Shoten. (in Japanese)

Uzawa, H. (2005), *Economic Analysis of Social Common Capital*, New York: Cambridge University Press.

Table 1: Trends of Average Temperature (Annual, January, August), Daily Highest Temperature (Annual Average), and Daily Lowest Temperature (Annual Average) of Big Cities in Japan.

City	Changes during 100Years (ºC/100 Years)				
	Average Temperature			Daily Highest	Daily Lowest
	Annual	Jan.	Aug.	(Annual Average)	(Annual Average)
Sapporo	+2.3	+3.1	+1.3	+0.9	+4.1
Sendai	+2.1	+3.4	+0.5	+0.4	+3.0
Tokyo	+2.9	+3.8	+2.4	+1.6	+3.7
Nagoya	+2.4	+3.5	+1.6	+0.6	+3.6
Kyoto	+2.3	+3.1	+2.2	+0.4	+3.6
Fukuoka	+2.3	+1.8	+1.9	+0.9	+3.8
Average of Big Cities	+2.4	+3.1	+1.7	+0.8	+3.6
Average of Small and Medium-sized Cities	+1.0	+0.9	+0.9	+0.6	+1.4

(Note) 1. The trend is calculated by regression analysis and converted to the changes of 100 years.

2. The sample period is 1900-97 for Sapporo, Tokyo and Fukuoka, 1927-97 for Sendai, 1923-97 for Nagoya, 1914-97 for Kyoto, and 1990-97 for small and medium-sized cities.

3. Big cities: Cities with the population of more than 900 thousand, and with continuous and appropriate observations since at least 1931.

4. Small and medium-sized cities: Following 15 cities with the little influence of urbanization.

Abashiri, Nemuro, Ishinomaki, Yamagata, Mito, Iida, Fushiki, Hamamatsu, Hikone, Sakaiminato, Hamada, Tadotsu, Miyazaki, Naze, Ishigaki.

(Source) Meteorological Agency (1999).

Table 2: Ice Days, Tropical Days, and Sweltering Nights

(Days/Year)

Ice Days	Average 1951-80	Average 1961-90	Average 1971-00	(Average 1991-00)
Sapporo	51	51	48	35
Sendai	2	3	2	1
Tokyo	0	0	-	-
Nagoya	0	0	-	-
Osaka	-	-	-	-
Fukuoka	0	0	-	-

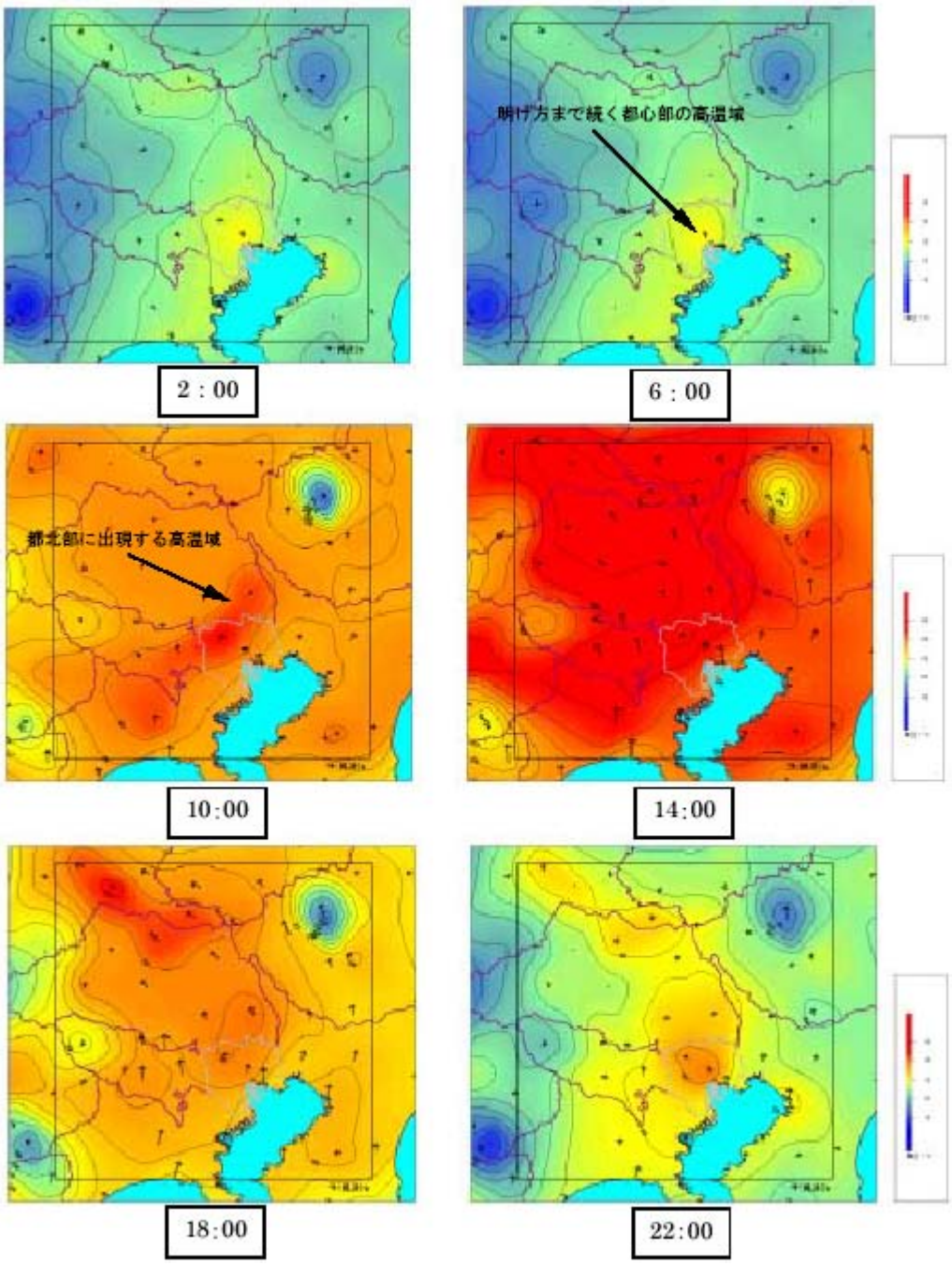
Tropical Days	Average 1951-80	Average 1961-90	Average 1971-00	(Average 1991-00)
Sapporo	7	7	8	7
Sendai	17	17	17	19
Tokyo	45	45	46	51
Nagoya	57	57	58	63
Osaka	63	66	68	72
Fukuoka	53	54	53	54

Sweltering Nights	Average 1951-80	Average 1961-90	Average 1971-00	(Average 1991-00)
Sapporo	-	0	0	-
Sendai	0	0	1	1
Tokyo	14	18	23	30
Nagoya	5	8	13	20
Osaka	26	28	32	38
Fukuoka	19	23	27	34

(Note) 1. Ice Day: Day on which the maximum temperature drops below 0 degrees.
Toropical Day: Day with temperatures exceeding 30 degrees.
Sweltering Night: Day with the minimum temperature exceeding 25 degrees.
2. As for Osaka, the figures are average from 1969 (average 1969-80 and 1969-90), because of the moving of observation point.
3. "0" shows there is at least one observation during the period. "-" shows there is no observation during the period.

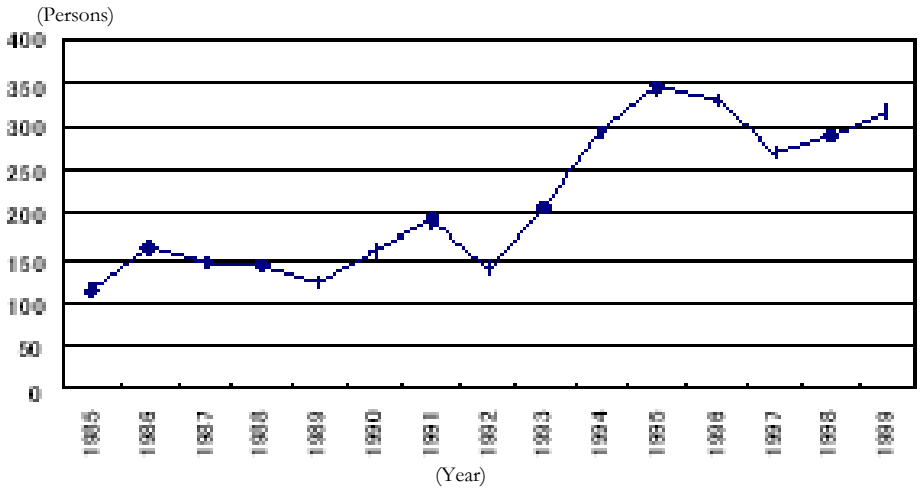
(Source) Japan Weather Association, *Weather Almanac*.

Figure 1: Air Temperature Distribution



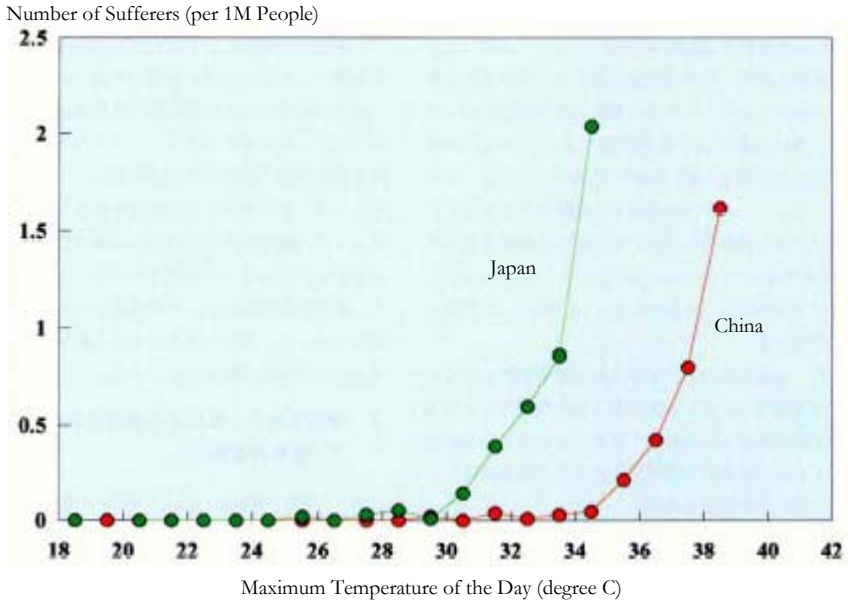
(Source) Ministry of Environment (2001).

Figure 2: The Number of People Taken to Hospital by Ambulance for Heat Stroke: 1985-1999 (3-Year Moving Average)



(Note) The original data is from Tokyo Fire Department.
(Source) Ministry of Environment (2001).

Figure 3: Relation between Daily Maximum Temperature and Ratio of Sufferers of Heat Stroke (per 1Milion People)



(Source) Ando (1998).