Some Studies of Heat Island in Japan—With Special Emphasis of the Climatological Aspects

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The purpose of this report is to make a general view on the recent studies of heat island phenomena, specifically focussed on its climatological aspects, in Japan, and to make a perspective of urban climatology in future. At first, the causative processes of urban climates were shown conceptionally from the viewpoint of urbanizations and this made possible to grasp its significance. Namely, urbanization is expressed to concentration of population, modification of earth's surface constituent materials and expansion of living space onto and into the ground. Also these bring about changes in morphological and physical features, and energetic conditions, which consequently modify radiation, heat and water balance to come out heat island.

Among the processes mentioned above, it is noted on the ones which is being studied or interested in now in Japan. One of climatological interests is to grasp heat island phenomenally. At first distributional character of isolines in heat island and occurrence time of maximum heat island intensity were made clear, and its relation to population was compared with the cases in North America and Europe. Next, the formative factors of heat island were considered from the viewpoints of morphological roughness of a city (roughness parameter, Ohgaki city), sky view ratio (cities along the Tama river) and soil moisture (Kawagoe city), separately. As well as the case of population, these are superficially correlated with heat island and very interested geographically, on the other hand it is also necessary to make connections with its physical structure. Futhermore, it was considered on radiation and heat balance in an urban area. The studies of radiation balance were mainly introduced here on the relationships between nocturnal urban heat island and longwave radiation field. In Japan there are few comprehensive studies on urban heat balance, and its components such as latent and heat flux are taken into considerations separately. A systematic study in an urban canyon must be also waited in future. Finally it is stated about subjects or ways of the study to be expected.

I. Introduction

It is a very well-established fact that the climatic environment of an urban area is markedly different from that of its nearby surrounding area. A city thus produces an unique climatic environment, the so-called urban climate, of which the most typical example is the heat island phenomenon.

The study of urban climates is very important from the geographical viewpoint since cities are man-made and they modify the climate. There are, in addition, scientific interests in the various physical phenomena, that occur within an urban atmosphere. Moreover, it is inevitably necessary from the viewpoint of urban planning, for architecture and landscape gardening, and for the amenities of urban residents.

Urban climatological studies have advanced remarkably during the 1970s, LANDSBERG (1981) made a comprehensive compilation of the investigations to the end of the 1970s and published the results in an excellent book called “The Urban Climate”. The study of urban climates during the 1970s was greatly influenced by the METROMEX project and was focused on simulation studies.

Now in the 1980s, it is time to develop further and deepen our urban climatological knowledge. Many studies associated with urban climates were presented at the Technical Conference on Urban Climatology and Its Application with Special Regards to Tropical Areas (Mexico City, 1984), the 10th International Congress of Biometeorology (Tokyo, 1984), and The 1st International Conference on Atmospheric Sciences and Applications to Air Quality (Seoul, 1985). This reflects the recent tendency for the importance of urban cli-
mate. In this report, the causative factors of heat island phenomena, and some aspects of radiation and heat balance in an urban area are presented.

II. Formation Processes of Urban Climate

The climate which a city produces is called the urban climate. Thus the urban climate does not exist without a city. From a climatic viewpoint, a city is equal to the concentration of population and the existence of building for people. The existence of a city hence produces a modified climate from that of nearby surrounding environs.

The formation processes of urban climate are considered as follows: In general, the processes of becoming urbanized are defined as urbanization, and can be expressed in terms of concentration of population, change in earth's surface constituent materials and expansion of living space onto and under the ground. For specific details, the following points should be noted. Concentration of population produces increasing metabolism and increasing energy consumption. Changes of the earth's surface modifies surface morphology and physical property of its constituent materials. Also, expansion of living space onto and under the ground results in significant increases in energy consumption and changes to the earth's surface morphology. Moreover, increasing metabolism produces emission of heat which in turn leads to modification of the heat budget at the earth's surface. The increase in energy consumption also produces emission of heat and discharge of aerosols, which subsequently modify the heat budget at the earth's surface and the radiation balance of the atmosphere.

The change of earth's surface morphology modifies albedo and roughness, and affects directly the radiation balance and latent heat flux near the ground. The change of surface constituent materials causes modification of its albedo, heat conductivity and permeability. As a result, radiation

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balance, soil heat flux and latent heat flux are greatly influenced.

A change of one element thus produces another change, and this in turn results in further changes and so on. Therefore, the above-mentioned examples are ones which are due to direct changes. Table 1 shows these relations.

Heat island phenomena as manifested in the horizontal distribution of air temperatures are thus considered the result of modifications to the radiation, heat and water balances in an urban area.

III. Some Characteristics of Heat Island and Daily Variations of Heat Island Intensity

The map of horizontal distribution of air temperature in an urban and surrounding areas is similar to a topographical map of an island, so it has been called a heat island. Its general characteristic is that isothermal lines are dense around the boundary of the urban area and sparse in the urban center. Thus, the horizontal gradients of air temperature are gradual within the city and rather abrupt between the city and the surrounding areas. This feature is generally characteristic of cities world-wide.

The physical and ecological characters of a city is remarkably different from region to region, so that the phenomena occurring within cities substantially differs from one to another. A Japanese city has very different landscape, functional structures or energy consumptions compared with other countries. First of all, the above-mentioned feature of air temperature distribution is not always applicable for a Japanese city. Figure 1 shows air temperature distribution in Tokyo at 03:00 hr on Dec. 1, 1980. The most typical feature is the gradual change of nocturnal air temperature from the urban area to the surrounding rural areas. This is mainly due to the obscurity of the city boundary as the Tokyo Metropolitan area expanded sprawl-like into the surrounding rural agricultural areas. A similar feature of the heat island was found during the daytime in a city covered with snow rather than during the nighttime, and was explained by the more active urban convection during the daytime (Ohata et al., 1985).

Heat islands have been generally observed to develop most clearly before sunrise on a calm winter day. Oke (1977) revealed remarkable differences in cooling rates after sunset between an urban and a rural environment. For two to four hours after sunset, the heat island formed rapidly because of this difference in cooling rates, and its intensity became a maximum before midnight. On the other hand, past knowledge still holds true for many Japanese cities. Namely, the heat island develops best around the time of minimum air temperature. Also, large differences in cooling rates were found not only after sunset but also before sunset, and this plays an important role in the formation of heat islands (Yamashita, 1981).

The temperature becomes high, then the relative humidity naturally becomes low without any change of other conditions. Therefore heat island produces dry island. This was investigated in the special new town (danchi in Japanese) by Sakakibara (1982). Diurnal or annual behaviors of heat islands may be different because of the urban structure of the city but also may be different because of climatic divisions or geographical locality where the city is located. This kind of research is progressing, but is not treated here.

Population has been used as a indicator to express the character of a city. It is obvious that this indicator is not essential to solve the urban structure physically, however, it is still interesting as an index to express the total feature of a city geographically. Oke (1973) successfully correlated population with maximum heat island intensity for cities in North America and in Europe. The difference in the slope of the regres-
sion lines reflects the different urban heat island structure in the different geographical regions.

In Japan, FUKUOKA (1983) obtained similar relations from a compilation of the observational data by various authors, and showed two different regression lines for the cities with less than and more than 300 thousand inhabitants. The difference in slope of the regression lines is attributed to structural or functional differences between large cities and small cities. More recently, PARK (1986) considered cities in Korea and concluded the existence of similar features as that found in Japan. Figure 2 shows these relations which are taken from PARK (1986). The regression lines are indicated below.

For North America
\[ \Delta T_{u-r}(\text{max}) = 2.96 \log P - 6.41, \quad r^2 = 0.96 \] (1)

For Europe
\[ \Delta T_{u-r}(\text{max}) = 2.01 \log P - 4.06, \quad r^2 = 0.74 \] (2)

For Japan (less than 300,000 population)
\[ \Delta T_{u-r}(\text{max}) = 0.85 \log P - 2.46, \quad r^2 = 0.84 \] (3)

For Japan (more than 300,000 population)
\[ \Delta T_{u-r}(\text{max}) = 4.83 \log P - 23.81, \quad r^2 = 0.95 \] (4)

For Korea (less than 300,000 population)
\[ \Delta T_{u-r}(\text{max}) = 1.46 \log P - 5.93, \quad r^2 = 0.98 \] (5)

For Korea (more than 300,000 population)
\[ \Delta T_{u-r}(\text{max}) = 3.43 \log P - 16.58, \quad r^2 = 0.98 \] (6)

where \( \Delta T_{u-r}(\text{max}) \) is the maximum heat island intensity, \( P \) is population and \( r \) is the correlation coefficient.

From these results it is interesting to note that not only the slope of the regression lines are different from region to region, but also that the inflection point of the regression lines for Japan and Korea is around the 300,000 population level. This thus shows that the large cities with more than 300,000 population have different functions from those that are smaller. This feature is coincident with that drawn from a human geographical perspective. Namely, a city in Japan is supposed to have special governmental and administrative functions on attaining an urban population of 300,000. This means that the energy loading contributed to heat island per person becomes quite different at the 300,000 urban population level. Just recently PARK (1987) discussed the relationship between city size and heat island intensity for Japanese and Korean cities from the geographical point of view.

![Figure 2](image-url)

Figure 2. Relationships between maximum heat island intensity and population for North American, European, Japanese and Korean settlements (North America and Europe by Oke, Japan by Fukuoka and Korea by Park). (Park, 1986)
IV. Some Considerations on the Causative Factors of the Heat Island

1. Roughness

Urban climate is partly caused by modification of the earth’s surface, which includes changes in surface morphology and changes in constituent materials. The change in surface morphology lead to changes in roughness height which in turn affect significantly the sensible heat flux as shown in Table 1. Building height is initially considered to be an indicator of surface morphology. It is calculated by the method of SEKINE (1981). At first, the number of floors for each building or house are surveyed. For wooden houses, the height of one floor is assumed to be 2.5 m, the base of the building 0.5 m, and the height of roof 1.5 m. For ferroconcrete buildings, the height of one floor is assumed to be 3.0 m and the base of the buildings 1.0 m. With these assumptions, the height(H) of buildings or houses are obtained as follows:

For wooden houses
\[ H = 2.5n + 2.0 \]  
(7)

and for ferro-concrete buildings
\[ H = 3.0n + 1.0 \]  
(8)

where \( n \) is the number of floors.

Next, the average height for each grid is computed. Figure 3 shows the relationship between heat island intensity and average building height. Observations were made in the early morning of Jan. 20, 1980 in Kichijoji, a new urban center within the Tokyo Metropolitan area. The correlation coefficient was good \( (r=0.79) \). There was no data for building heights between 10—13 m because the urban center is composed of high-rise buildings and the surrounding areas are residential with mainly two storied houses. This suggests that the surface morphology of a city is strongly related to the formation of the heat island. The geometrical morphology of the surface can be expressed by the roughness parameter \( (z_0) \). LETTAU (1969) obtained the following equation experimentally for \( z_0 \), namely:

\[ z_0 = \frac{1}{2} \frac{h^*s}{S} \]  
(9)

where \( h^* \) is the average building height, \( s \) the silhouette area, and \( S \) the lot area. SEKINE (1981) applied this equation to Ohgaki city which is located in the central part of Japan, and obtained a map of the distribution of roughness parameter. Since the silhouette area varied with wind direction, the roughness parameter varied with wind direction. In his study, Sekine initially examined each building height individually, and next obtained the grid data of average building heights. From these data, roughness parameters were computed for four wind directions (north-south, east-west, northeast-southwest and northwest-southeast). Mean values were then obtained by averaging \( z_0 \) for these four directions and were used to express the surface morphology of the city.

Figure 4 shows the map of the distribution of average roughness parameter and air temperature observed in the early morning of Oct. 18, 1978 in Ohgaki city.

The roughness parameter and air temperature distributions show good agreement and are apparently related. In addition, \( z_0 \) of 50—80 cm was obtained in the central urban area. This is extremely large from an aerodynamic viewpoint. NAKAGAWA (1983) discussed the relationships between roughness parameter and other causative factors such as house density, areal ratio of surface constituent materials, etc., and proposed the calculation method of \( z_0 \) reasonable from an aerodynamic viewpoint. HAYASHI (1983) also examined the roughness parameter from observational and experimental methods in the area of Tsukuba University.

Although the roughness parameter of a city can
be obtained by the methods mentioned above, this is still an over-simplification as no distinction is made of the physical link between the processes within the urban canyon and those above the urban canopy layer. Thus, the physical aspects of this is yet to be solved. In future, there should be efforts directed towards obtaining $z$ with an aim to understand the physical structure of a city.

2. Sky view fraction

Recently sky view fraction has been used as an useful index of the causative factor of urban heat islands (Oke, 1981; Yamashita et al, 1986 and Park, 1986). However, there are two definitions for sky view fraction. One is defined by Davies et al. (1970), which is successfully applied for urban heat island by Oke (1981). In practice Oke (1981) redefined sky view factor as the ratio of the wall height to the street width for hypothetical urban canyons on infinitely consecutive walls. In a strict sense sky view factor is defined as the fraction of the projected area of the hemisphere occupied by sky to the whole area of an overlying circle.

Another is the ratio of the area occupied by sky to the area of the whole hemisphere. This may be better to be called sky view ratio. The large difference between two definitions is the different estimation near the skyline. Any of them is obtained from a photograph of the whole sky using a fish-eye lens.

Oke (1981) pointed out that sky view factor is the appropriate measure of radiation geometry on the assumption of the isotropic radiant flux. As longwave radiation from the buildings or the roads is usually larger than the one from sky, it is very difficult to estimate the contribution of each sky fraction in a proper way. However, as long as
air temperature in the urban canyon is concerned, it may be affected by radiations or heat flows from all directions (sky, walls and roads) and then it is not necessary thought that the surface received energy is horizontal. In this case sky view ratio may be more reasonable measure of heat island phenomena.

Yamashita et al. (1986) concluded that the sky view ratio is more representative of urban areas than the population from an investigations of five cities located in the Tama river basin, 30 km west of Tokyo. One example, shown in Figure 5, is a map of the distribution of percent sky view ratios in Fuchu city. Sky view ratios of 50—60% were found in the urban area, while a minimum of 46% occurred in the eastern part of the city where high-rise residences have been recently built. As a whole, the distribution of sky view ratios coincides well with the urban area.

Sky view ratio can be considered to represent the degree of urbanization at the spot within a city. Figure 6 shows the relationship between heat island intensity and minimum sky view ratio for each city. In this figure, the white circles represent day and the black circles represent night observation, and d, n, and t represent lines adjusted for daytime, nighttime and total values. In general, daytime values of heat island intensity are more related to minimum sky view ratio than nighttime ones.

Geographically it is interesting to consider sky view ratio as an indicator of urbanization, however it is also necessary to relate the sky view to the radiative behaviour within an urban canyon for more physical understanding of the heat island.

3. Soil moisture

Nishizawa et al. (1979) initially found that a heat island appears on the horizontal distribution of the ground temperatures similar to that of the air temperature in an urban area. He examined the reasons for this feature from the viewpoint of heat and water balance and concluded that the most important factor was the soil moisture in an urban area. Yamashita et al. (1983) subsequently observed soil moisture content in a medium-sized city of Kawagoe and considered its distributional coincidence with the ground temperature distribution. Soils at the surface and at depths of 10 cm were collected with a soil sampler of 100 ml, and percentage of soil moisture content and volumetric heat capacity were obtained by drying them after weighing the net volume of solid and liquid. Volumetric heat capacity \( \rho c \) is expressed by the following equation:

\[
\rho c = (\rho c)_s (X_s) + (\rho c)_w (X_w) + (\rho c)_a (X_a)
\]

where \( s \), \( w \) and \( a \) mean solid matters, water, and
air respectively, and $X_s$, $X_w$ and $X_a$ their fraction of the total volume. Observation points were carefully selected to be representative of the spot.

The results obtained by the above-mentioned method are shown in Figures 7—9. The ground temperature was observed at a depth of 50 cm, and soil moisture was at a depth of 10 cm. Investigations were made for all seasons in Kawagoe city. The ground temperature was high in an urban area from spring to summer and low from autumn to winter. These observations were related to the low soil moisture content in an urban area. Namely, the amplitude of the annual variation of the ground temperature at a given depth can be expressed as follows:

$$\Delta T_{30} = (\Delta T_S)_{0} e^{-z/(\pi/\kappa P)^{1/2}}$$  \hspace{1cm} (11)

where $(\Delta T_S)_{0}$ is the amplitude at the depth $z$, $(\Delta T_{30})_{0}$ is the amplitude of the surface temperature, $e$ is the base of the natural logarithm, $P$ is the period, and $\kappa$ is the thermal diffusivity. Thermal diffusivity, on the other hand, is directly proportional to thermal conductivity, and is inversely proportional to volumetric heat capac-

Figure 7. Distribution map of ground temperature at the depth of 50 cm on Aug. 17, 1982 in Kawagoe city, Saitama.

Figure 8. Distribution map of soil moisture at the depth of 10 cm on Aug. 17, 1982 in Kawagoe city, Saitama.

Figure 9. Distribution map of volumetric heat capacity investigated on Aug. 17, 1982 in Kawagoe city, Saitama. (unit: cal·cm⁻¹·°C
Heat Island in Japan

ity. This relation can be expressed as follows:

\[ \kappa_s = \frac{k_s}{C_s} \]  \hspace{1cm} (12)

where \( k_s \) is the heat conductivity and \( C_s \) is the volumetric heat capacity. This thermal diffusivity varies with soil moisture, is a maximum at some water content (\( w \)) and decreases quadratically on both sides of \( w \). With increase of water content, volumetric heat capacity increases linearly. On the other hand, increase of thermal conductivity is gradual over some range of water content.

From equation (11), \( (\Delta T)^{\kappa_s} \) is dependent of the value of \( \kappa_s \). If \( \kappa_s \) is assumed to be larger in an urban area than in a rural area, \( e^{w(K/K_s)^{\alpha}} \) becomes larger with increasing \( \kappa_s \). Also, since the water content of the surface layer is small in an urban area, \( (\Delta T)^{\kappa_s} \) should be larger in an urban area than in the rural area due to the larger specific heat of water. Thus, the annual amplitude of the urban ground temperature is probably larger than that for rural areas. This is also confirmed from the observational results of the ground temperature in Kawagoe city. Furthermore, this leads to large thermal diffusivity in an urban area due to the decrease of water content. It is concluded that, in this case, water content decreases with urbanization in the domain over the value of \( w_p \). This causes the characteristic ground temperature distribution noted previously.

IV. Radiation and Heat Balance in an Urban Area

1. Radiation balance

OKE (1984) proposed a possible framework for urban climatological studies, consisting of five urban units; building, canyon, block, landuse zone and city. This should be of interest and importance for a systematic understanding of the urban climate. However, Japanese cities are complicated and somewhat disordered so that this framework is not directly applicable, especially since the idea of block and landuse zones are not common in Japanese cities.

In view of this, urban climatological studies of radiation and heat budget in Japan are mainly confined to special aspects.

Solar radiation in an urban area is considerably attenuated by air pollution. For example, the annual average value of the reduction index is less than 10% in Tokyo, however this is not so large compared with that about 20 years ago when it amounted 20% (YAMASHITA, 1983). Albedo in an urban area is usually low due to the multiple reflection of solar radiation. This was examined by AIDA et al. (1978) both experimentally and mathematically.

Downward longwave radiation in an urban area is increased due to the additional radiation emitted from the polluted urban atmosphere. This was observationally proved for the Metropolitan Tokyo area by Aida and Yahi (1979). These studies, however, can not be directly connected to the physical formation of the heat island within the urban canopy layer, and hence it is necessary to investigate the radiative character inside urban canyons.

Although an urban surface is typically composed of roof-levels and ground surfaces, the so-called heat island is a phenomena observed near or on the ground surface. Thus, it is necessary to obtain the downward longwave radiation at the ground surface within an urban canyon to explain the heat islands. Kobayashi (1979) obtained the results shown in Table 2. According to these findings, net longwave radiation at the ground surface is consistently half that at the roof-level because the downward longwave radiation at the ground surface is greater than that as the urban roof-level. The increased downward longwave radiation at the urban ground surface is explained by screen effects due to the buildings. Namely, the downward longwave radiation at the urban ground surface (\( L_{L_u} \)) is expressed by the following equation:

| Table 2. Longwave radiation of urban surfaces at night (17:00—06:00) (Kybayashi, 1979) |
|---------------------------------|---------------------------------|---------------------------------|
| Radiation amount (mJy/min)     | Oct. 30—31                      | Oct.31—Nov.1                    | Average           |
| Roof-level                     | Oct. 30—31                      | Oct. 31—Nov.1                   |                   |
| 402.3                          | 422.6                           | 412.5                           |
| 500.2                          | 511.2                           | 505.7                           |
| 97.9                           | - 88.6                          | - 93.3                          |
| Wall-surface                   | Oct. 30—31                      | Oct. 31—Nov.1                   |                   |
| 497.2                          | 508.0                           | 502.6                           |
| Ground-surface                 | Oct. 30—31                      | Oct. 31—Nov.1                   |                   |
| 445.2                          | 463.2                           | 454.2                           |
| 494.5                          | 501.3                           | 497.9                           |
| 49.3                           | - 38.1                          | - 43.7                          |
\[ L_{\text{ir}} = \psi L_{\text{ir}} + (1-\psi) L_{\text{ir}} \]  
(13)

where \( L_{\text{ir}} \) is the downward longwave radiation at the roof-level, \( L_{\text{ir}} \) is the downward longwave radiation from the walls of buildings and \( \psi \) is the sky view factor. Furthermore, the effect of warm-moist polluted atmosphere on longwave radiation has been examined on the basis of the observational data, and it has been shown that the urban increase of \( L \) is mainly due to the additional radiation from the polluted atmosphere rather than urban increased water vapor (KOBAYASHI, 1982).

For future work, it is necessary to estimate how much of this increased downward longwave radiation takes part in the formation of the heat island.

### 2. Heat balance

Leading studies of energy balance in an urban area are divided into two groups: one is observational researches within an urban canyon introduced by OKE (1978) and the others are simulation studies originally developed by SUMMERS (1965), MYRUP (1969) and ATWATER (1972). In Japan, similar modelling studies have been done by many authors (for example, OJIMA, 1976), however the principle of the idea similar to SUMMERS was developed by FUKUI (1956) some 30 years ago. The simulation studies are mainly focussed on engineering solution of the urban climatic environment and essentially the model is treated as a black box. Furthermore, there is no systematic observation of heat balance in an urban canyon in Japan.

FUKUOKA (1980) carried out general studies on the heat balance in an urban area in conjunction with heat island observation. Namely, latent and sensible heat fluxes are expressed as follows:

\[ Q_L = k_\gamma \frac{\Delta e}{\Delta z} = k^* (e_0 - e) \]  
(14)

\[ Q_H = k_\theta \frac{\Delta \theta}{\Delta z} = h^* (\theta_0 - \theta) \]  
(15)

where \( k^* \) and \( h^* \) are transfer coefficients, \( e \) and \( \theta \) are water vapor pressure and air temperature, respectively. The method used for this study was moving observations of dry- and wet-bulb temperatures at two heights, and surface temperatures in Hiroshima city by automobiles, and estimation of latent and sensible heat fluxes were obtained from equations (14) and (15). The effects of water area on the heat balance were considered, and it was concluded that \( \Delta e \) was relatively large and \( \Delta \theta \) was rather small along the river in the city.

YAMASHITA (1981) also did similar studies in Nishio city, and found that the daily average vertical gradient of air temperature was positive in an urban area and negative in a rural area as shown in Fig. 10. This means that sensible heat flowed upward into the air in an urban area and vice versa in a rural area and was due to the heat island absorbing more solar energy in the urban man-made surfaces than in the rural agricultural surfaces. The vertical gradient of water vapor pressure was not so consistent and was very unstable because of the complicated conditions of water in an urban area. Without rain, this value should basically be zero over an artificial surface such as paved concrete or asphalt. On the other hand, various human activities release water into an urban atmosphere like air conditioners, etc. In any event, the vertical gradient of water vapor pressure itself was low in the urban area.

Bowen ratio is very useful to understand the relationship between latent and sensible heat fluxes, and is usually defined as follows:

\[ \beta = \frac{Q_L}{Q_H} = \gamma \frac{T_1 - T_2}{q_1 - q_2} \]  
(16)

**Figure 10.** Distribution map of daily average air temperature gradient observed on May, 11-12, 1980, in Nishio city, Aichi. (unit: °C/0.5 m)
where $T_1$, $T_2$, $q_1$ and $q_2$ are air temperatures and specific humidity at the heights of $z_1$ and $z_2$ respectively, and $\gamma$ is $c_p/L$ which is equal to $4.2 \times 10^{-4}$ °C and in this case, $K_H=K_W$ is assumed. Figure 11 shows the horizontal distribution of Bowen ratios in Nishio city that were observed on May 11—12, 1980 (YAMASHITA, 1981). In general this value was positive in the urban area and negative in the rural agricultural areas. However, the ratios were partly negative west of the urban center, where temples and gardens were located. This was mainly caused by the unstable condition in the latent heat flux which readily changes sense of direction depending on the existence or absence of water. Sensible heat fluxes were positive throughout the day and night because of the high surface temperatures in the urban area as mentioned previously. This kind of study is very interesting for its geographical aspect, but it is almost impossible to get an insight into the physical structure of the heat island phenomena.

Another type of study is to observe latent and sensible heat fluxes separately. NARITA (1984) obtained thermal properties of artificial materials (asphalt blocks) experimentally and found larger thermal diffusivity for asphalt pavement than soil, which was consistent with the hypothesis advanced in the previous section. The heat balance for asphalt pavement was discussed and it was concluded that a significant amount of heat was redistributed into the asphalt layer, about one third of the net radiation. This is one of the important factors of the nocturnal heat island, i.e. small heat capacity. It is also in accord with the previous result shown in Fig. 9 that the volumetric heat capacity is smaller in an urban area than in a rural agricultural area. More recently, MATSUURA et al. (1987) estimated the heat transfer coefficient experimentally by means of a transducer.

Latent heat flux at an urbanized surface was also experimentally investigated by NARITA (1987). The subject treated were the effects of advection, roughness of the urban surface, and desiccation of evaporative surface on a discussion of transfer coefficient and calculation equation hypothetically adopted in numerical simulation studies.

Another aspect of heat island study is that related to the use of remote sensing technology (for example, KAWASHIMA, 1986). This makes it possible to obtain the fluxes over a wide area including the surrounding rural area, and also to see the heat island visually on a micro-scale. Insights into the detailed structure of the urban heat island, are however not possible.

VI. Concluding Remarks

The contents treated in this study are somewhat limited on the urban heat island phenomena. For example, no attempts were made to include the following aspects: the effects of heat island on precipitation and urban air pollution, mathematical models of heat island and air flow over a city, applications of urban climates to urban planning and gardening and energy consumption in an urban area. On the causative mechanism of the heat island, there is an interesting study which discusses heating from the bottom of the urban surface and mechanical mixing of warm air within inversion layer (TAMIYA et al., 1981). From observations in small towns, it is concluded that mechanical mixing is more important than heating from the bottom, and this also makes it possible to explain the dense isoline of temperature around the boundary of a specified city. Another important study was made by SAITO, et al. (1987) who analysed three dimensional behavior of pollutants and road particles in
the urban atmospheres and made clear of pollution island caused by urban circulation under the influence of heat island.

From a geographical perspective, it is necessary to do the following researches on urban climate: the effects of locality conditions such as latitude, altitude and topographical state on the urban heat island, bioclimatological aspects such as effects on respiratory or infection disease, amenity in an urban environment, historical reconstruction of urban climate, and utilization of the urban heat island phenomena for environmental education. The last subject was recently tried by using the urban heat island as a teaching material for understanding global thermal pollution (HARA, et al., 1986).

In any event, cities are increasingly advancing and expanding, and more people live in cities. It thus becomes more and more important to study urban climatic environments and to apply the knowledge to people’s living in a city properly. This report is mainly focused on the climatological aspects of heat island in Japan. In future, a comprehensive study of a single city like METROMEX may be needed to be undertaken in Japan too.

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日本におけるヒートアイランドの研究
—特にその気候学的側面を中心にして—

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本報告の目的は最近の日本におけるヒートアイランド現象に関する研究を、特にその気候学的側面を中心にして概観し、展望することである。先ず、都市化という観点から都市気候の形成プロセスを概念的に把握し、研究の位置づけを可能にした。つまり、都市化は人口の集中、地表面構成物の改善、生活空間の地上・地下への拡大で表現できる。そして、これらが地表面における幾何的・物理的特性や熱的条件を変化させる、その結果が放射収支・熱収支・水収支の変更となり、ヒートアイランドの誕生となる。

以上のプロセスのうち、現在わが国で研究されているものや、とくに関心が寄せられているものについて触れただ。気候学的関心としてはまず現象としてのヒートアイランドの把握である。分布の特徴と最大ヒートアイランド強度の出現時刻を述べ、人口との関係についてアメリカや西ヨーロッパとの違いを明らかにした。次にヒートアイランドの形成要因について、都市表面の幾何的凹凸（ラフネスパラメーター、大垣市）、天空率（多摩川流域の都市）、土壌水分（川越市）の面から考察した。しかし、これらはいずれも人口の場合と同様相関の関係であり、地理的関心が高いヒートアイランドの物理的構造へと結びつけていく必要もある。さらに都市の放射収支と熱収支について概観し、考察した。放射収支については夜間のヒートアイランドと長波長放射場との関連について主として小林（1979, 1982）の研究を紹介した。熱収支の体系的研究はわが国ではなされておらず、顕熱や潜熱を個別に扱っているにすぎない。また、都市キャニオン内での熱収支の体系的観測も今後に待つほかない。最後に今後の研究課題・方向について言及した。

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