Effects of Regional Warming due to Urbanization on Daytime Local Circulations in a Complex Basin of the Daegu Metropolitan Area, Korea

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ABSTRACT

Numerical and observational analyses were conducted using realistic and historical three-set land-use data over 40 yr from 1963 to 2002 to evaluate regional warming in the Daegu metropolitan area due to dramatic land-use alterations in the basin area and to quantitatively estimate the influence of nonuniform regional warming on complex local circulation. The results are as follows: (a) The daily mean temperature in the Daegu metropolitan area increased by 1.5 K over 40 yr, and the increase was higher than that of the mean temperature on the Korean Peninsula. (b) A simulated surface wind pattern in 2002 agreed well with the observed data. The rapid urbanization of the Daegu metropolitan area has had a large influence on the local circulation outside of the area. (c) Because of the variation in heat and momentum transfer due to land-use alteration, the prevailing wind has also changed in the central basin in the Daegu metropolitan area. The spatial distribution of the temperature change is very similar to the changes in the wind. (d) The two-dimensional mixed-height theory was applied to local circulations. By this theory, regional warming that occurs as a result of land-use alteration determines a higher critical height, which serves as an index for estimating the mixing intensity induced by a surface sensible heat flux. According to the observational data, this index can be used to quantitatively estimate regional warming in complex terrain.

1. Introduction

In the past decade, concerns about the distribution of the surface sensible heat flux have been increasing because a heterogeneous sensible heat flux is a critical factor in the production and modification of regional circulations such as land–sea breezes, mountain–valley winds, and heat island circulation. Land-use alterations in densely populated areas are especially prone to causing heat island circulation strongly associated with urban air pollution. Urban temperatures are known to increase on a regional scale over long periods. The influence of urban areas on temperature and wind fields as a result of the heterogeneity of land use in large metropolitan areas in China, Japan, and Korea have been thoroughly investigated (Takahashi and Kimura 1991; Lee and Lee 1994; Kusaka et al. 2000; Savijärvi and Jin 2001; Lee et al. 2002; Ichinose 2003).

Kusaka et al. (2000) carried out a comparison study of three cases of land use in the Tokyo metropolitan area for 100 yr. They noted that the summer temperature in Tokyo has increased up to 2° or 3°C in 100 yr, and this increase results in extended sea breezes and changes in the intensity and pattern of sea breezes. Fujibe (2003) showed that the long-term surface wind had changed in the Tokyo metropolitan area in the afternoons on sunny days in the warm season and found that the amount of daytime pressure fall had increased by 0.2–0.3 hPa in the central and northern parts of the Kanto Plain along with a slight change in surface winds, resulting in convergence toward the central Kanto Plain.

Kitada et al. (1998) simulated the local circulation and thermal environment over the Nohbi Plain, and the zone of maximum temperature gradually moved toward the inland suburban area by the coupling between the sea breeze and heat island circulations. This cou-
pling is caused by the increased depth of the mixed layer of the surface boundary. Ohashi and Kida (2002) estimated the variations in the sea breezes induced by a heat island and topographic effects in the Osaka–Kyoto region. They concluded that the incursion of the sea breeze from Osaka Bay into the inland was strongly associated with a heat island effect. These studies focus primarily on urbanization in coastal areas. Because of its familiarity and importance for those people living in coastal regions, sea-breeze phenomena have been frequently and extensively studied in theoretical, observational, and numerical investigations.

Extended urban areas occur not only in coastal areas but also in inland basins in east Asia, especially in China, Japan, and Korea. However, regional circulation in an inland basin tends to be complicated because the effects of topographic and urban heat islands function simultaneously. The importance of topographic effects on local circulation has been demonstrated in previous studies (Kimura and Arakawa 1983; Kondo et al. 1989; Kuwagata et al. 1990; Daul and Pielke 1993; Kimura and Kuwagata 1993; Lee and Kimura 2001). These studies have shown that the mountain–valley structure is strongly related to the modification of the boundary layer flow, which often occurs in conjunction with diurnal heat cycles. Recently, many studies have dealt exclusively with the relationship between the intensity of thermally forced orographic circulation and the horizontal–vertical scale of a mountain. The horizontal scale of the topography has been determined to be one of the most significant factors in the mesoscale transportation of pollutants.

Generally, urbanization tends to influence inland areas as much as it does coastal areas. Thus, the alteration of local circulation due to regional warming as the result of changes in land use must be studied. However, the effect of urban areas on the structure and behavior of the local circulations in inland basin areas, in particular, the Daegu metropolitan area, one of the extensively urbanized inland basin areas in the Korean Peninsula, has not been precisely established. Moreover, most numerical studies have been comparisons of regional circulation with or without urban areas. In this paper, we will investigate the historical change in daytime local circulations due to urbanization and the relationship of the coupling of thermally induced topographic circulation and that produced by land use in an inland basin.

Therefore, three-dimensional numerical experiments that require simple surface parameterization were conducted to clarify the effects over 40 yr of urbanization (1963–2002) and basin orography on the local circulation in the inland basin of the Daegu metropolitan area.

### Table 1. Basic features of an atmospheric dynamic model.

<table>
<thead>
<tr>
<th>Coordinate</th>
<th>Terrain-following coordinate (z)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic equation</td>
<td>Nonhydrostatic equation</td>
</tr>
<tr>
<td>Planetary boundary layer</td>
<td>Turbulent closure model level 2 (Mellor and Yamada 1974)</td>
</tr>
<tr>
<td>Constant flux layer</td>
<td>Monin–Obukhov similarity theory</td>
</tr>
<tr>
<td>Surface temperature</td>
<td>Two-layer vegetation (Lee and Lee 1994; Lee 1998)</td>
</tr>
<tr>
<td>Soil model</td>
<td>Multilayer model (heat-conduction equation)</td>
</tr>
<tr>
<td>Shortwave radiation</td>
<td>Kimura and Arakawa (1983)</td>
</tr>
<tr>
<td>Longwave radiation</td>
<td>Empirical form (Kondo et al. 1991)</td>
</tr>
<tr>
<td>Top boundary condition</td>
<td>Wave radiation condition (Klemp and Durran 1983)</td>
</tr>
<tr>
<td>Lateral boundary condition</td>
<td>Wave radiation condition (Orlanski 1976)</td>
</tr>
</tbody>
</table>

This paper includes a brief description of the numerical model in sections 2 and 3. Section 4 shows the change of the local circulation. The temperature variation with different historical land use is also discussed in this section. A theoretical evaluation of these mesoscale circulations is reported in section 5. A simple criterion that can be used to estimate the relative importance of the land-use contrast and the orographic forcing on the local circulation is also presented. Section 6 presents the conclusions.

### 2. Numerical model description

#### a. Numerical model

The mesoscale model used in this study is a local circulation model (LCM) developed by Kimura and Arakawa (1983) and Kimura and Takahashi (1991) and modified by Lee and Lee (1994) and Lee (1998). The LCM is based on a nonlinear three-dimensional model with a terrain-following coordinate system. The model includes a turbulent closure scheme in the boundary layer and a prognostic equation for surface temperature. The governing equations and numerical scheme of the model are precisely summarized in Kimura and Kuwagata (1993) and Lee (1998).

The horizontal domain is 45 km × 45 km covered with 126 × 126 grid points at uniform intervals of 360 m. Vertical grids consist of 27 vertical layers with higher resolution near the ground surface. The lowest vertical grid is at a height of 15 m, and the top of the vertical grid reaches 7100 m.

The basic features of the LCM used in the present study are summarized in Table 1. The vertical exchange coefficients of the momentum, heat, and moisture are calculated using the turbulence closure scheme (level 2).
suggested by Mellor and Yamada (1974). Below the lowest vertical grid, a constant flux layer is assumed in order to estimate the sensible and latent heat fluxes using Monin–Obukhov similarity theory.

The top boundary is controlled by wave radiation provided by Klemp and Durran (1983) in order to avoid a wave reflectance and gravity wave. The lateral boundary condition is also the wave radiation condition discussed by Orlanski (1976).

b. Topography and land-use data

This study focuses on the change in regional circulation over a 40-year period in the Daegu metropolitan area, which is located in the center of the Korean Peninsula and is extensively urbanized. The population of the Daegu area is 2.5 million people, according to the 2004 census. The rapid industrialization and urbanization of Korea in the 1960s and 1970s have been accompanied by continuous migration of rural residents into the cities, producing heavily populated metropolises. Because of the basin terrain, Daegu sometimes experiences the hottest summertime temperatures in Korea.

The location and topography in the model domain are shown in Fig. 1. The Daegu metropolitan area is surrounded by two large mountains, Palgong and Bisul, with summits of 1193 and 1084 m, respectively. The eastern part of the area is open, and sea breezes from the East Sea flow through the area when the synoptic weather is stable in the summer. As a result, the Daegu metropolitan area has ideal basin topography.

The land-use data used in this study were provided by the Korean Ministry of the Environment (KME) with 1-km spatial resolution. The original dataset are divided into 16 categories of land uses. To clearly analyze the influence of changes in land use, these classifications were reduced from 16 to 5. Figure 2 shows the land-use pattern maps used in this study for the years (a) 1963, (b) 1975, and (c) 2002. If the area covered with buildings and houses is larger than any other land-use area, the area was designated as urban in this study. The ratios of the urban area in 1963, 1975, and 2002 were 2.36%, 4.45%, and 11.98% of the domain, respectively. Thus, urban areas in 2002 were about five times greater than those of 1963 and three times those of 1975. However, the area of fields for irrigated crops and forests drastically decreased in the 40-yr period. The data shown in Table 2 outline the changes in land use over the 40-yr period.

The surface value parameters used in the numerical simulation are listed in Table 3. The parameters have been estimated and observed by several researchers in Korea and Japan (Kondo and Yamazawa 1986; Garratt 1978; Anthes et al. 1987; Kusaka et al. 2000). Kusaka et al. (2000) also validated these parameters through the application of sea-breeze changes in the Kanto Plain, Japan. However, they did not apply anthropogenic heat
because they focused on the changes in land use. We also concentrate on historical changes in the local circulation in basin topography by the distribution of daytime heterogeneous surface heat due to land-use alteration. Thus, anthropogenic heat is not accounted for in this study.

3. Simulation design and validation

Every numerical simulation starts at 0300 LST. The initial velocity, potential temperature, and specific humidity are assumed to be horizontally uniform. The study does not focus on a specific day but, rather, on an ideal day with a well-developed condition of local circulation. Thus, we adopted atmospheric data on five clear days in August 2005 as the initial data for our numerical simulations.

The criteria for undisturbed summer synoptic conditions are defined as follows: (a) Atmospheric stability is controlled by a vertical potential temperature profile assuming weak atmospheric stability (4 K km$^{-1}$). (b) The specific humidity is assumed to be 15 g kg$^{-1}$, decreasing by 2 (g kg$^{-1}$) km$^{-1}$ with altitude in the lower boundary. (c) The initial wind fields are slightly easterly ($V$, $W = 0$ m s$^{-1}$ and $U = -0.5$ m s$^{-1}$) near the surface. (d) The initial ground surface and deep soil temperatures are based on observations by Doran et al. (1992). (e) The solar radiation parameters correspond to 15 August at 35°N. The solar radiation and other parameters are assumed to be horizontally uniform and change with time.

As reported above, many studies on heat island circulation due to the changes in land use have been conducted. Previous researchers have concluded that obtaining a precise estimation of urban heat island circulation is very difficult since the heat island effect is determined by many factors, including (a) the local surface properties and near-boundary conditions, (b) the urban terrain, and (c) sky conditions related to regional and large-scale circulation. Jin and Shepherd (2005) reported and proposed that the urban area should be

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**Table 2. Changes in land use in the Daegu metropolitan area over a 40-yr period.**

<table>
<thead>
<tr>
<th>Land use*</th>
<th>1963 % (No. of pixels)</th>
<th>1975 % (No. of pixels)</th>
<th>2002 % (No. of pixels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water bodies</td>
<td>2.87 (456)</td>
<td>2.36 (375)</td>
<td>2.19 (348)</td>
</tr>
<tr>
<td>Irrigated crops</td>
<td>30.63 (4864)</td>
<td>27.65 (4391)</td>
<td>16.92 (2687)</td>
</tr>
<tr>
<td>Forests</td>
<td>62.31 (9893)</td>
<td>61.66 (9790)</td>
<td>57.06 (9059)</td>
</tr>
<tr>
<td>Grasslands</td>
<td>1.81 (288)</td>
<td>3.85 (612)</td>
<td>11.84 (1880)</td>
</tr>
<tr>
<td>Urban areas</td>
<td>2.36 (375)</td>
<td>4.45 (708)</td>
<td>11.98 (1902)</td>
</tr>
</tbody>
</table>

* The land-use classifications used in this study have been simplified from 16 to 5 categories. Water bodies include oceans and inland water. Irrigated crops are agricultural crops. Forests consist of narrow leaf and broadleaf evergreens, mixed woodlands, deciduous shrubs, woodland, evergreen needles, and deciduous needles. Grasslands include crop/mixed farming, short grasses, and tall grasses. Urban areas include buildings and roads.
treated as a new type of landscape in urban climate research.

However, since our focus is not on the heat flux process but on the relationship between the heat fluxes on the surface and mesoscale circulation and on the qualitative analysis of the changes in regional circulation, we simplified the parameters of the surface properties in our study of the evolution of the mesoscale circulation with a mixture of surface conditions. Because the moisture availability ($\beta$) and roughness length ($z_0$) (Siebert et al. 1991) are different for rural and urban areas, the simplification of surface properties in this study is based on the control of these two factors. In general, observations indicate great differences in the surface characteristics between urban and rural areas in the surface heat distribution, which depends primarily on evapotranspiration from the surface. The previous studies have shown that the roughness length, which can change the vertical diffusion of the momentum, heat, and moisture, is also important for predicting mesoscale circulation. Therefore, instead of using a full-canopy model, the moisture availability and roughness length are used as the surface parameters for the urban and rural areas in this study.

There are three numerical simulations with different land-use data, one each for 1963, 1975, and 2002, and these simulations are referred to as cases 1, 2, and 3.

The model validation should be verified by a comparison between the calculated wind field in case 3 and the observed Automatic Weather System (AWS) data. Figure 3 represents the simulated and observational wind vectors at nine AWS sites around the Daegu basin at 1500 LST for 5 days in August 2005. The level of simulated wind in this figure is 15 m high. This validation was conducted under weak synoptic conditions, and the atmospheric stability corresponds with the initial data used in the numerical simulation. The convergence in central Daegu is clear, and the simulated wind pattern agrees well with the results from this observation. Thus, the simulated results are reasonably accurate and can be used to analyze the influence of regional warming on local circulation in basin topography.

**Table 3. Classification of surface parameters used in our numerical simulations.**

<table>
<thead>
<tr>
<th>Category</th>
<th>Roughness length (m)</th>
<th>Moisture availability (dimensionless)</th>
<th>Heat capacity (cal °C⁻¹ cm⁻¹)</th>
<th>Heat conductivity (cal cm⁻¹ s⁻¹ °C⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water bodies</td>
<td>0.000 015</td>
<td>1</td>
<td>0.49</td>
<td>0.0034</td>
</tr>
<tr>
<td>Irrigated crops</td>
<td>0.075</td>
<td>0.6</td>
<td>0.49</td>
<td>0.0026</td>
</tr>
<tr>
<td>Forests</td>
<td>0.5</td>
<td>0.3</td>
<td>0.49</td>
<td>0.0026</td>
</tr>
<tr>
<td>Grasslands</td>
<td>0.12</td>
<td>0.15</td>
<td>0.49</td>
<td>0.0026</td>
</tr>
<tr>
<td>Urban areas</td>
<td>1.0</td>
<td>0.05</td>
<td>1</td>
<td>10</td>
</tr>
</tbody>
</table>

**Fig. 3.** (top) Simulated and (bottom) observed winds at nine sites at 1500 LST shown as an ensemble average of typical summer days in August 2002. The degree of shading indicates topography.
4. Results

a. Observational analysis of the temperature change

The annual mean temperature variations in Daegu and Chupungnyung over 40 years are shown in Fig. 4. Chupungnyung is located to the east of the Korean Peninsula and is the representative background observation site in Korea (Fig. 1a). The annual variations in the temperature frequency pattern in the two areas are almost identical, but they differ in their rates of increase. Temperature increased more rapidly in Daegu than in Chupungnyung. This difference suggests that warming in Daegu cannot be explained exclusively by the occurrence of background warming in Korea and that another factor plays a role in warming in the Daegu area.

To understand better the relationship between temperature variation and regional warming in several cities located around the Daegu metropolitan area, the annual variations of the daily mean, maximum, and minimum temperatures in Daegu, Gumi, Yeoncheon, and Uiseong were analyzed. Observational data obtained over 31 yr, from 1971 through 2001 were used. The locations of these cities are shown in Fig. 1a. The daily mean, maximum, and minimum temperatures in the Daegu metropolitan area increased by 1.5°C, 1.4°C, and 1.8°C, respectively. These data indicate that the daily minimum temperature has increased rapidly. These results agree well with those from a previous study by Oh et al. (2004). The daily mean temperature in Gumi increased by 1.2°C and the daily minimum temperature rose by 0.7°C. However, the increase in the daily maximum temperature was 1.9°C over 31 yr, and this value is significantly higher than for any other cities on the Korean Peninsula.

However, although the increases in the maximum temperature in Yeoncheon and Uiseong are very clear, the daily minimum temperatures in those two cities decreased during the same period. The daily mean and maximum temperature in Yeongcheong increased by 0.4°C and 0.8°C, and the minimum temperature in the same place decreased by 0.2°C. The temperature in Uiseong also had a similar pattern to that in Yeongcheong. These warming tendencies could be caused by changes in the regional-scale surface heat characteristics as well as by global background warming.

The relationship between the change in population and the warming tendency in the four cities has also been analyzed. Table 4 shows that the populations and annual mean temperatures for the four cities have increased. Decreases in population have been strongly associated with decreases in the minimum temperature in Yeongcheong and Uiseong. This result suggests that the minimum temperature variation tends to correspond with anthropogenic heat due to the increases in population and that the temperature increase in Gumi has been caused by industrialization and an increase in population.

b. Comparison of local circulation caused by historical changes in land use

The horizontal distributions of wind vectors at 1500 LST for cases 1 and 3 are shown in Fig. 5. In case 1, the valley wind induced by the Palgong and Bisul Mountains is predominant throughout the entire domain. Although the synoptic wind is initially calm, the easterly wind is dominant in the eastern part of the basin. The easterly from the open gate of the eastern boundary may be induced by the impact of the two high mountains in the northern and southern parts of the domain and by the existence of the urban area in the central part of the basin. However, the predominant wind in the western part of the basin is different from that in the eastern part. A strong westerly wind appears at 1500 LST and penetrates to the center of the basin.
These two different winds meet and converge over the central downtown area of Daegu. The general wind patterns in cases 1 and 3 are similar. However, the locations of the convergence and wind speed and direction over the extended urban area vary somewhat.

To clarify the change of wind direction due to urbanization, the vectors of case 3 minus case 1 are presented in Fig. 5c. Significant differences in wind vectors over the western urban area are easy to find in the 2002 land-use data. The difference vectors point westward in the western part of urban area. The same tendency was observed on the western boundary of the domain. However, while there were changes in the patterns in both the western and eastern parts of the urban areas, they were different.

The area with the greatest change in wind direction and intensity coincided with an expanded area of urban land use in 2002. In contrast, the changes in wind direction and intensity were less significant in the eastern than in the western urban areas. Therefore, these differences in the patterns have been caused by urban changes in the surface heat conditions over the 40-yr period, namely, the discontinuity of the surface heat and momentum transfer process.

Differences in wind patterns occur on the boundaries of urban areas as well as in the foothills of mountains. These differences indicate that the change in the urban heat conditions is strongly associated with that in the regional circulation in the mountainous areas. In section 4c, theories concerning the changes in the mountain valleys that have occurred as a result of the winds from urbanization are presented.

Some difference vectors near the southern boundary far from the Daegu metropolitan area also appear. The difference vectors may have been caused by the land-use alteration from forest to irrigated field as shown in Fig. 2. Because the magnitude of difference over the boundary is not stronger than that over the Daegu metropolitan area, we mainly focus on the change in local circulation due to the alteration of land use in the great metropolitan area.

The difference in wind speed between cases 1 and 3 is shown in Fig. 6. Thick (thin) solid line indicates the decrease (increase) in wind speed from case 1 to case 3. An area with a reduction in wind speed was generally

![Fig. 5. The horizontal distribution of wind vectors calculated for (a) case 1 and (b) case 3 at 1500 LST and (c) the difference. The degree of shading indicates the topography. The thick solid lines in (a) and (b) indicate the main urban areas in 1964 and 2002, respectively.](image-url)
found along the central basin in an east–west direction except for the urban areas in 1964. To discuss the precise changes in wind speed in the central basin, we classified four blocks along the centerline of the urban basin according to the variation in wind speed. Each block shows good correspondence with the changes in land use over the 40-year period. Blocks A and D are newly urbanized areas. Block B corresponds better to a traditional urban area.

The wind speed tends to decrease in blocks A and D, where urban expansion occurred, as indicated by the land-use data from 2002. This may have been caused by the urban changes in the total heat budget and surface momentum transfer. Although land use in the west exceeded that in block A, the wind over the area decreased. This outcome may have been caused by an effect that the penetration of western circulation is restricted due to high roughness length from urbanization.

In block B where strong convergence appears in case 1, wind speed becomes stronger in comparison to that in case 1. This difference caused the change in convergence reported above. Because the convergence area moved westward in 2002, the wind over convergence area in 1963 was strong. However, the change of wind speed in the traditional urban area (block C) was not larger than that in the other blocks. On the other hand, the wind speed in the area surrounding the central basin tended to increase, and the wind direction pointed toward the urban area, as shown in Fig. 5. The great sensible heat flux and high mixed layer of the urban area due to urbanization resulted in this wind pattern in the area surrounding the central basin.

Figure 7 is identical to Fig. 6 except for surface temperatures. The differences in air temperature are similar to those in wind speed. The maximum difference in the temperature in the urban center of the Daegu metropolitan area is 1.61 K. However, although the rate of increase varies depending on location, the air temperature over the entire basin area has a clear tendency to increase.

To clarify the relationship between the wind speed
and air temperature, the line drawn through the four blocks in Fig. 6 was specifically analyzed.

Figure 8 shows the spatial variations in the temperature and wind speed differences on the east–west horizon along 28 km of the y axis. The solid (dotted) line indicates the wind speed (air temperature) difference. The low wind speeds in blocks A and D reported above can be seen in this figure, and the increase in wind speed is also noted in block B. These variations in the patterns of wind and temperature tend to have a negative correlation. The higher correlation between wind speed and temperature anomalies may be strongly associated with the heat transfer process on the urban surface through the planetary boundary layer and also with the bulk coefficient of the surface roughness.

Wind speeds in blocks A and D were accompanied by larger sensible heat flux due to the land use rapidly changing from irrigated paddy field to urban surface over the 40-yr period of study. In addition, the high roughness length of the new urban surface also leads to the decrease in horizontal wind speed over these blocks. On the other hand, the wind speed on block C increased in case 3, because of the slight movement of convergence over the block. In 1964, convergence was located over block C, but the convergence in the urban area moved toward block A in 2002 (Fig. 5). This movement caused the wind speed over block C to increase. Therefore, the changes in sensible heat and roughness length, which are directly associated with the variations

![Fig. 7. As in Fig. 6, but for surface air temperatures (K).](image)

![Fig. 8. Spatial variation of the difference in wind speed and surface air temperature along a centerline of the four blocks shown in Fig. 6. The dotted and thick solid lines illustrate the differences in temperature and the difference in wind speed, respectively. The arrows indicate the width of the four blocks used in this analysis.](image)
in surface heat and momentum transfer due to the land-use alteration, induced the change in wind patterns over the basin metropolitan area.

Figure 9 is a vertical cross section of the potential temperatures in cases 1 and 3 at 1500 LST. The cross-section line is a west–east horizontal line crossing the y axis at 28 km. Few differences occur in their distributions over 1.5-km height. The surface temperature in case 1 was about 29.5°C over the urban area with a width of 7 km wide and a mixing height of 1 km. However, in case 3, the region over 29°C is expanded to a 15-km width, and the mixing height is slightly higher than that in case 1.

Figure 10 shows the vertical profile of the potential temperatures in cases 1 and 3 as a time variation at 3-h intervals from 0600 LST. After sunrise, convection begins to develop in both cases, and the surface temperature increases over time. However, its increasing rate in case 1 was smaller than that in case 3, and the mixed layer in case 1 at 1500 LST was also lower than that in case 3. These differences in the vertical potential temperature were caused by the differences in land use. Namely, the increase of the sensible heat flux induced by the alteration of land use from irrigated crop fields to urban areas determined the changes to the vertical heat environment.

As can be seen, the time when the maximum surface
temperature appeared has changed dramatically. The maximum temperature in case 1 was reached at a later time than that in case 3. The maximum surface temperatures in cases 1 and 3 were observed at 1430 and 1250 LST, respectively. The fact that the maximum temperature was observed at an earlier time in case 3 is thought to be due to a strong westerly wind that brought in slightly colder air from the rural area. The analysis point in this figure is in the center of block A in Fig. 6, where a westerly wind was dominate after noon. The intensity of the westerly wind in case 3 was stronger than that in case 1. Thus, the strong westerly in case 3 carried slightly cold air from the rural area at an earlier time, and the surface temperature at 1500 LST was lower than that at 1200 LST in case 3. It would appear that regional warming is strongly associated with changes in land use and that these relations become more important at the small regional scale than at the global scale.

c. Theoretical analysis of the intensity of local circulation

The area where the wind speed decreased in case 3 was mainly located along the central basin mentioned above as well as at the foot of the Palgong and Bisul Mountains. Typical changes in the local circulation around these mountainous areas were induced both by topography and the discontinuity in surface heating. In general, regional circulation patterns over the mountainous areas are simultaneously induced by topography and heat island effects (Lee and Kimura 2001; Ohashi and Kida 2002). Thus, it is necessary to estimate the change of the two effects as a result of land-use alteration. To evaluate the changes in the local circulation quantitatively, the available vertical potential energy associated with the mixing height was used in this study. The conceptual model of the available vertical potential energy was introduced by Lee and Kimura (2001). They proposed a simple two-dimensional criterion for determining the predominant circulation between an anabatic wind and a land to land breeze induced by surface land-use heterogeneity in complex terrain. The criterion is a simple equation of the mountain height, the ratio of the heat flux from the different land-use patterns, the atmospheric static stability, and the time-integrated heat flux. The criterion of Lee and Kimura also requires the use of some assumptions. These are 1) a constant potential temperature gradient at the initial stage, 2) a vertically uniform potential temperature in the mixed layer, 3) a negligible entrainment at the top of the mixed layer, and 4) a sensible heat flux dependent only on the surface properties. It has been shown by numerical experiments and observations that assumptions 2 and 3 are almost correct in the late afternoon, when the mountain is less than 2 km high (Kimura and Kuwagata 1993, 1994).

A criterion for the two-dimensional topography is described below based on Lee and Kimura (2001). Figure 11 is a simple schematic diagram explaining the criterion. Lee and Kimura assumed that the flat surface would be bare soil, but, in this study, the flat area is assumed to be an urban area. The mountainous area is assumed to be covered by vegetation both by Lee and Kimura (2001) and in this study.

First, the mixed layer over flat ground surface is estimated. The respective accumulated sensible heat \( Q_h \) in the atmospheric column is defined as

\[
Q_h(x, y, t) = \int_0^{z_m} \theta(x, y, z, t) - \theta_0 \, dz, \tag{1}
\]

where \( \rho \) is the air density, \( z_m \) is the mixing height over ground assumed to be infinitely flat, and \( \theta_0(z) \) is the initial profile of the potential temperature.

The time-integrated sensible heat flux \( Q_0(x, y, t) \) is defined as

\[
Q_0 = Q = 0.5 \rho\gamma z_m^2, \tag{2}
\]

where \( \gamma \) is the vertical gradient of the initial profile of the potential temperature.

The accumulated sensible heat flux over a flat urban area and a mountainous area is as follows:

\[
Q_1 = \int_0^t H_1 \, dt = 0.5 \rho\gamma Z_1 \quad \text{and} \tag{3}
\]

\[
Q_2 = \int_0^t H_2 \, dt = 0.5 \rho\gamma Z_2(x, y), \tag{4}
\]

where \( H_1 \) and \( H_2 \) are the sensible heat fluxes over a flat urban area and a mountainous area, respectively, and \( Z_1 \) and \( Z_2(x, y) \) are the heights of the mixed layer measured from a flat ground surface and a mountainous surface, respectively (Fig. 11).

Since the height of the mixed layer measured from the ground surface is assumed to depend solely on the surface characteristics regardless of the elevation of the
measuring position, then \(Z_2(x, y)\), shown by the dashed line in Fig. 11, can be assumed to be the same value everywhere as follows:

\[
Z_2(x, y) = \bar{Z}_2. \tag{5}
\]

From Eqs. (3) and (4), \(Z_1\) and \(Z_2\) are written as

\[
Z_1 = \left( \frac{2 \int_0^t H_1 \, dt}{c_p \rho \gamma} \right)^{1/2} \quad \text{and} \quad \bar{Z}_2 = \sqrt{\alpha} Z_1, \tag{6}
\]

where \(\alpha (= H_2/H_1)\) is the ratio of the sensible heat flux of a mountainous area to a flat urban area.

Therefore, the predominant local circulation is determined by comparing the top height of the mixed layer in the urban and mountainous areas. The difference of the mixed layer heights indicates the excess of available potential temperature; thus, this excess value plays a role in the induction of local circulation.

The criterion is summarized as follows:

\[
\begin{align*}
&Z_1 < \bar{Z}_2 + \bar{h}, \quad \text{anabatic wind} \\
&Z_1 > \bar{Z}_2 + \bar{h}, \quad \text{land – land breeze}.
\end{align*} \tag{7}
\]

If \(Z_1\) is higher than \(\bar{Z}_2 + \bar{h}\), a great amount of available potential energy over the urban area flows toward the mountainous area. When the opposite case is true, the excess available potential energy is transported by an anabatic wind. The critical value of height \((h_c)\) is defined as \(Z_1 - \bar{Z}_2\) and rewritten as follows:

\[
h_c = (1 - \sqrt{\alpha}) \left( \frac{2}{c_p \rho \gamma} \int_0^t H_1 \, dt \right)^{1/2}. \tag{8}
\]

Figure 12 shows the distribution of the increase of the surface potential temperature during the 40-yr period of our study. The increase in the potential temperature occurred mainly over the urban area. The strong sensible heat flux over the urban area resulted in a high mixing height. Thus, the change in the surface heat flux over the plain basin determined the critical height in Eq. (8). The mountainous area and the urban basin

![Figure 12. Distribution of the differences in potential temperature between case 3 and case 1. Points A–D are quantitative analysis positions in Fig. 13. The contour interval is 0.25 K, and the degree of shading indicates the topography. The thick solid line indicates the urban areas in 2002.](image-url)
area on the plain are shown at points A and C and B and D, respectively. The potential temperatures at points B and D increased by 0.56 and 1.1 K, respectively. On the other hand, the surface air temperature did not change at points A and C. Thus, the variations of the regional circulation may be attributed to the changes in the mixed layer over the plain basin area.

Figure 13 shows the critical height \( h_c \), which is dependent on the integrated sensible heat flux. The relation is estimated by Eq. (8). The initial lapse rate of the atmosphere is 0.004 K km\(^{-1}\), the same value as for the initial condition used in the numerical simulation. The critical height can be easily found depending on the heat balance when there is heterogeneous land use, as the following example shows. If the integrated sensible heat is 4 MJ and \( \alpha = H_2/H_1 \) = 0.5, the critical height becomes 412 m high. Thus, if the mountain height is over 412 m, an anabatic wind is predominant in the area; however, if the mountain is less than 412 m high, a land–land breeze from the mountainous area to the urban area prevails. From the example, it is reasonable to conclude that the present criterion makes it easy to determine the predominant circulation and predict variations.

This criterion has been used to estimate the data at two sites at the bases of the Palgong and Bisul Mountains. The mountain sites are located at points A and C in Fig. 12, and the two urban area sites are located at points B and D in the same figure. In case 3, the time-integrated heat fluxes at points A and B around Palgong Mountain at 1500 LST are 2.5 and 4.0 MJ, respectively. Whereas their values at points A and B in case 1 are 2.4 and 2.7 MJ, respectively. In comparison with the flux at point B, the significant difference in the time-integrated heat flux at point A in cases 1 and 3 is caused by the land use changing from an irrigated paddy field in 1963 to an urban area in 2002. Moreover, the ratios of the sensible heat between A and B in cases 1 and 3 are 0.89 and 0.63, respectively. Therefore, the change of the local circulation during the 40-yr period can be quantitatively estimated using these values and Eq. (8). The critical heights calculated by this criterion in cases 1 and 3 are 57 and 264 m, respectively. Accordingly, the critical height increased by 207 m.

The critical height can be calculated at points C and D around Bisul Mountain in cases 1 and 3 using the same method. The values for cases 1 and 3 are 111 and 409 m, respectively (note that the difference is illustrated by open and closed rectangles in Fig. 13). The critical heights at points C and D also increased by 298 m (the difference is illustrated by open and closed circles in Fig. 13). Although the critical height in case 3 increased, the estimated critical heights at points A and B and points C and D are smaller than those at the Palgong and Bisul Mountains. Thus, an anabatic wind flowing from the flat area to the mountainous area is predominant in these areas. However, the increase of the critical height means that the mixing height increased over the flat area because of a land-use alteration. For this reason, the potential intensity of land–land breezes has increased in case 3. Because of this higher land–land breeze potential, the anabatic wind in case 3 is weaker than that in case 1, and the decrease in wind speed around the foot of the mountains can be explained by the increase of the mixing height due to urbanization in the Daegu metropolitan area. Although advection in this metropolitan area has caused some errors in estimating the local circulation, the quantitative change of its intensity can be evaluated by the proposed criterion, and this criterion is deemed to be a reasonable method for understanding regional warming induced by the urbanization.

5. Conclusions

The influence of urbanization in the Daegu metropolitan area on local circulation was estimated through the realistic land-use data collected over a period of 40 yr. The Daegu metropolitan area, which has developed rapidly over this period, is extensively urbanized, and regional warming in that area has been more rapid than that in the other areas in Korea. Local circulation in this area is very complicated and differs from that of other metropolises in Korea because of its typical basin to-
pography. To evaluate the regional warming due to the dramatic change of land use in the basin and to estimate the influence of nonuniform regional warming on the complex local circulation qualitatively, numerical and observational analyses were conducted using realistic and historical three-set land-use data collected over 40 yr from 1963 through 2002.

The following results were found:

1) The daily mean temperature in the Daegu metropolitan area increased by 1.5 K over 40 years, and this increase is higher than that of the mean temperature in Korea. The significant increase in the mean temperature was caused by the rapid urbanization. However, some differences exist in the regional warming gradient within Daegu.

2) The simulated surface wind pattern in 2002 agreed well with the observed data associated with summer synoptic conditions. In addition, there is strong convergence at the center of the downtown area in 1963, 1975, and 2002, except for a slight difference in the center's location. The discrepancy in the convergence was due to the changes in the urban area that have taken place over the 40-yr period. The simulated intensity of the wind speed outside of the Daegu metropolitan area in 2002 was stronger than that in 1963, and little variation in the wind speed was observed in the traditional downtown area. Thus, rapid urbanization strongly influenced the local circulation outside of the metropolitan area.

3) The higher correlation between temperature and wind speed anomalies may be strongly associated with the heat and momentum transfer process on the urban surface through the planetary boundary layer and also with the bulk coefficient of the surface roughness, especially in the Daegu metropolitan area, and, therefore, the spatial distribution in the temperature change caused by the changes in land use is very similar to that caused by wind. The increase of heat in urban areas resulted in variations in wind in rural areas. The maximum differences in the values of temperature variation and accumulated heat between cases 1 and 3 are 1.6 K and 1.8 MJ, respectively, at 1500 LST.

4) The decrease in wind intensity occurred primarily in the foothills of the Palgong and Bisul Mountains. In other words, anabatic winds were weaker in 2002 than they were in 1963. The decrease in the strength of the anabatic winds in the vicinity of the Palgong and Bisul Mountains was analyzed using the mixed-height theory developed by Lee and Kimura (2001). According to this theory, regional warming caused by land-use alteration results in a higher critical height, an index for estimating the mixing intensity induced by the surface sensible heat flux. The critical height in 2002 indicated that the intensity of the land–land breeze became stronger against the anabatic wind. This index is used for quantitatively estimating regional warming in complex terrain.

In this study, a simple parameterization of the urban area was used to analyze urbanization qualitatively. In recent years, more precise parameterization techniques, such as satellite data, have been proposed (Jin and Shepherd 2005). Therefore, further studies on urban climate should be conducted using more precise models that include urban parameters. Anthropogenic heat has a significant influence on local circulation. However, because the focus of this study was on the urbanization effect due to the land-use alteration, we did not consider anthropogenic heat, which is more important for nighttime than daytime circulation (Kimura and Takahashi 1991; Ichinose et al. 1999). Cloud cover is also an important aspect of global warming from a climatological point of view. In the present study, more attention is given to regional and local circulation than global circulation. Thus, those two factors were addressed. However, the estimation of anthropogenic heat and the influence of cloud cover also remain as subjects of the future research.

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