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Does the restoration of an inner-city stream in Seoul affect local thermal environment?

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With 7 Figures

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Summary

Changes in local thermal environment associated with the restoration of an inner-city stream in Seoul, Korea, are investigated using observational data. The stream, called the Cheonggye stream, which had been hidden and covered with cement/asphalt for 46 years, runs 5.8 km eastward through a central region of Seoul. Intensive observations were made in the stream area for a number of summertime periods before, during, and after the stream restoration to detect the effects of the stream on local environment and to quantify them. It is estimated that after the stream restoration the near-surface temperature averaged over the stream area dropped by 0.4 °C, with the largest local temperature drop being 0.9 °C. However, it cannot be stated that this 0.4 °C temperature drop is due entirely to the stream effect only, because synoptic-scale and local-scale weather conditions during the two periods were inevitably not identical. The stream effect on air temperature is also evident in the temperature distribution along a street traversing the stream. In the daytime after the stream restoration, the sensible heat flux was greatly reduced and the ratio of sensible heat flux to net radiative flux dramatically decreased. These first-time results of the restored-stream effects on urban thermal environment could contribute to the scientific basis of urban planning which aims to make a large city comfortable to live in and nature- and environment-friendly.

1. Introduction

Green areas such as parks in cities are cool patches and mitigate urban heat islands (Honjo et al., 2002; Narita et al., 2002; Jansson et al., 2007). Their effect is pronounced in the summer daytime (Oke, 1989; Spronken-Smith and Oke, 1998). In areas with water bodies, two main processes take place. One is evaporation, which acts to decrease air temperature due to the latent heat absorption and increase specific humidity. The other one is sensible heat transfer between the air and the underlying water. If the water is cooler than the air, especially under hot weather conditions, the effect appears as a decrease in air temperature (Munn et al., 1969; Naot and Mahrer, 1991). If the moisture content of the air, say, water vapor mixing ratio or specific humidity, remains unchanged, a decrease in air temperature results in an increase in relative humidity. The rate of evaporation depends on air and water temperatures and moisture content, while that of sensible heat transfer depends on the temperature difference between the air and the water. The wind effect on the evaporation rate and sensible heat transfer rate is rather complex, but those rates increase as the wind speed increases (Arya, 2001). In the hot daytime, the surface temperature of water bodies in urban areas is typically lower than the temperature of street bottom or building roof-top floor. Hence, the magnitude of sensible heat flux over the water bodies is smaller

a b

Fig. 1. Pictures taken (**a**) before and (**b**) after the restoration of the Cheonggye stream

than that over the street bottom or building rooftop floor.

Recently, an ambitious project to restore an inner-city stream in Seoul, called the Cheonggye stream, was undertaken and successfully completed. For a number of periods before, during, and after the stream restoration, intensive meteorological observations were made with the purpose of evaluating the effects of the inner-city stream on local environment. In this paper, we report for the first time changes in local thermal environment associated with the restoration of an inner-city stream in a mega-city with a population of about 10 million (Seoul, Korea). Here, we present the observed changes in near-surface air temperature and sensible heat flux.

2. The Cheonggye stream restoration project

The restoration project of the Cheonggye stream in Seoul was a part of a plan to make the mega-city more nature- and environment-friendly. The stream had been covered with a cement/asphalt pavement, above which an elevated highway ran, for 46 years (Fig. 1a). The restoration project involved demolishing the elevated highway, opening the cement/asphalt pavement, and renewing the stream environment. The restoration project was started in July 2003 and successfully ended in September 2005. The stream now has a water depth of about 40 cm and runs 5.8 km eastward through a central region of Seoul (Figs. 1b and 3a). The green areas and walkways were made just near the stream. The Cheonggye stream has been recognized as an ecological city stream and also as a prototype for the restoration of streams in cities. The restored stream will affect its nearby urban climate, motivating our interest in field observations and the detection of changes in local environment.

3. Field observations

Intensive observations were made in the Cheonggye stream area in 2003, 2004, and 2005. Ordinary observations were made starting from 19 June 2003. Table 1 lists the meteorological instruments used for the field observations and Fig. 2 shows photos of the instruments installed. The topography of the Seoul metropolitan area, the locations of KMA (Korea Meteorological Administration) operational automatic weather stations within Seoul, and the Cheonggye stream

Table 1. Meteorological instruments used for the field observations

Instrument	Observational element	Data-saving interval (minutes)	Number	Location (see Fig. 3)
T-RH measuring kit	temperature, relative humidity	15	13	P1–P13
			13	along R (1–13)
Automatic weather station	temperature, wind speed and direction, precipitation amount, pressure	10	2	A1, A2
Ultra-sonic anemometer	three components of velocity	30	1	stream
Radiometer	radiative flux	1	1	stream
Scintillometer	sensible heat flux	1	1	stream
Radiosonde	temperature, wind speed and direction	0.2	2	A1

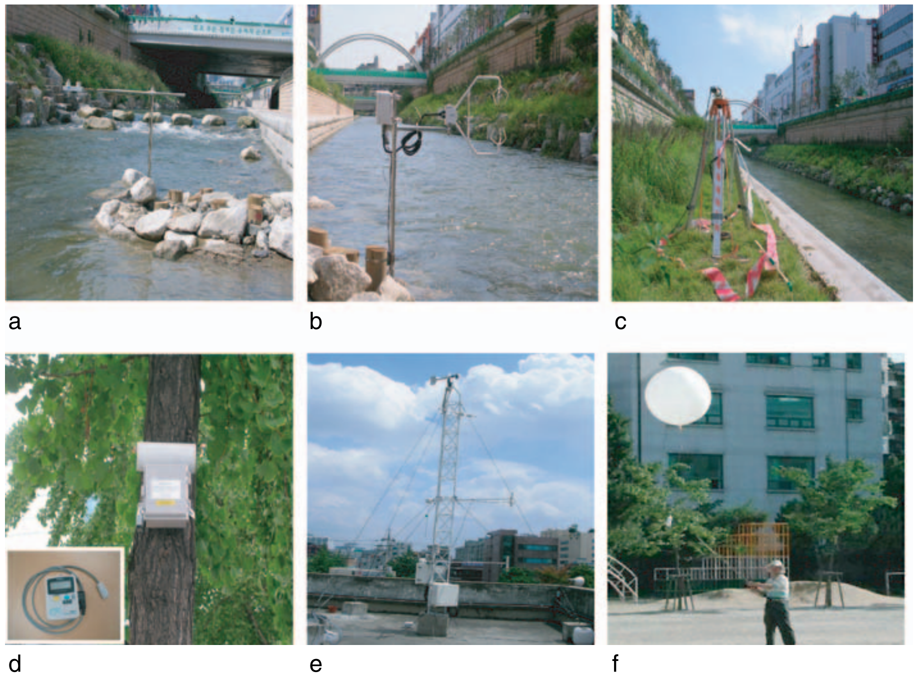

Fig. 2. Pictures of the meteorological instruments used for field observations: (**a**) radiometer, (**b**) ultra-sonic anemometer, (**c**) scintillometer, (**d**) temperature and relative humidity measuring kit, (**e**) automatic weather station (AWS), and (**f**) radiosonde

are shown in Fig. 3a and field measurement locations are indicated in Fig. 3b and c.

Seoul is, overall, flat except for the northern and southern central regions where Mt. Bukhan and Mt. Gwanak are situated, respectively. Seoul belongs to a temperate climate zone, exhibiting distinct daily and seasonal temperature variations. The annual mean temperature is 12.2 °C, the annual mean wind speed is 2.4 m s^{-1}, the annual mean relative humidity is 67%, and the annual precipitation amount is 1344 mm (Korea Meteorological Administration, 2001; Kim and Baik, 2005). In summer, Seoul exhibits hot and humid weather, receiving much of its annual rainfall in a concentrated period.

Twenty-six temperature and relative humidity (T-RH) measuring kits were deployed in the vicinity of the Cheonggye stream (P1–P13, Fig. 3b) over a distance of about 6 km and deployed across the stream (R 1–13, Fig. 3c) over a distance of about 380 m. The region shown in Fig. 3b consists largely of commercial and residential sections. Most of the T-RH measuring kits at locations P1–P13 were installed at a height of 1.2 m above ground level inside meteorological instrument shelters. The T-RH measuring kits at R 1–13 were attached at a height of 2 m above ground level to trees lining the street (Fig. 2d). Two automatic weather stations, measuring temperature, wind speed and direction, precipitation amount, and pressure, were installed on the tops of school buildings (Fig. 2e, A1 and A2 in Fig. 3c).

An ultra-sonic anemometer was installed to measure the three components of velocity at 1.2 m above the stream surface (Fig. 2b). A radiometer was installed to measure the net radiative flux at 1.2 m above the stream surface (Hill, 1997), as pictured in Fig. 2a. A scintillometer was installed to measure the integrated sensible heat flux over the stream (Fig. 2c), with an 85 m optical path traversing the stream. The ultra-sonic anemometer, radiometer, and scintillometer had operated during the intensive observing periods (see Table 3). To examine the thermal structure of the urban boundary layer over the Cheonggye stream area of Seoul, radiosonde observations were made twice on 14 August 2003.

Table 2 lists the main land use in the vicinity of each measurement location P1–P13 (see Fig. 3b). The central business district with high-rise buildings is largely located near the upstream part of the Cheonggye stream and the residential area is largely located near its downstream part. Since the study region is a central part of Seoul, it is a good region for detecting changes in local thermal environment associated with the stream restoration.

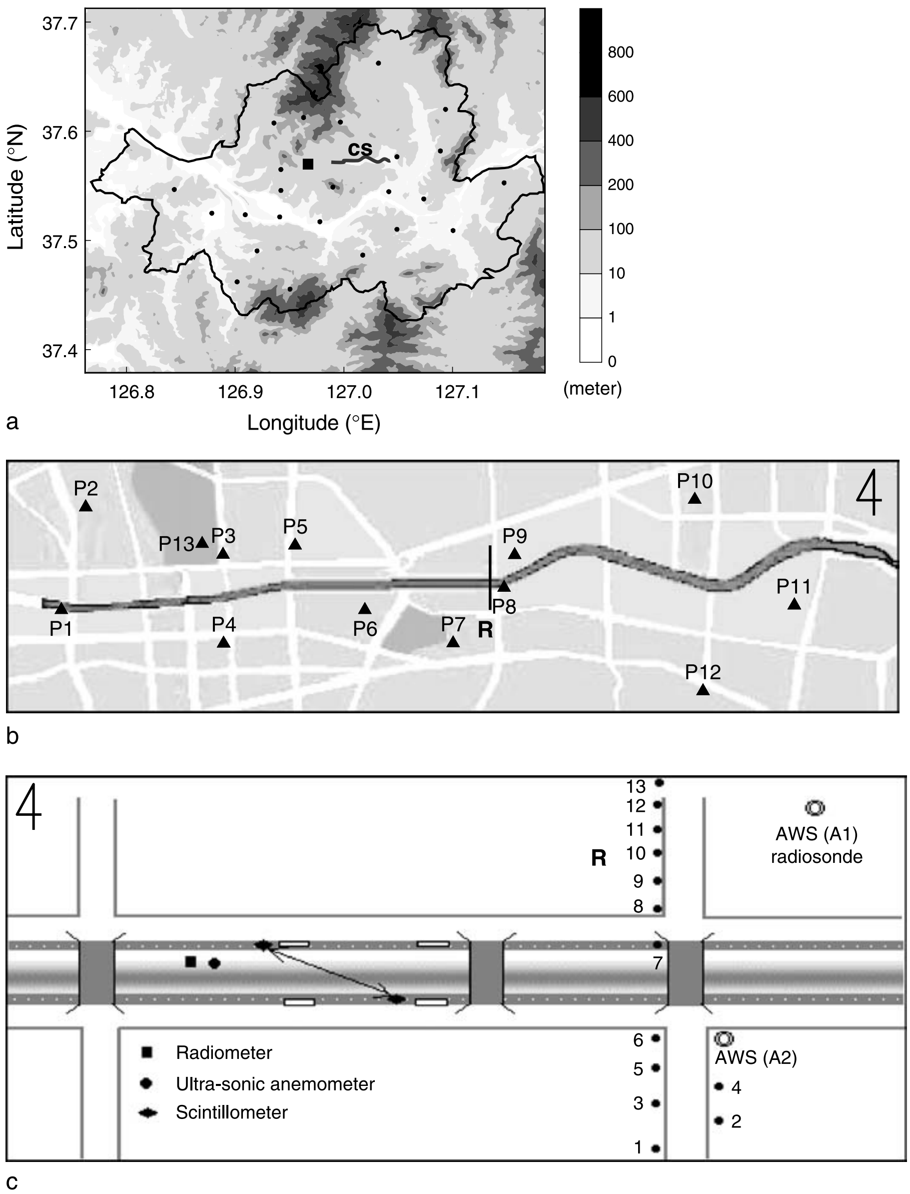

Fig. 3. (**a**) Topography of the Seoul metropolitan area. The locations of automatic weather stations (AWS) are marked by ●, the location of Seoul meteorological observatory is marked by ■, and the Cheonggye stream is marked by gray line (CS). (**b**) and (**c**) depict measurement locations in the Cheonggye stream area

Table 2. Main land use in the vicinity of each measurement location P1–P13

Location no.	Land use
1	high-rise commercial buildings
2	high-rise commercial buildings, primary school
3	high-rise commercial buildings, park
4	high-rise commercial buildings, middle school
5	commercial buildings, primary school
6	high-rise commercial buildings, hospital
7	high-rise commercial buildings, high school
8	low-rise commercial buildings, high school
9	low-rise commercial buildings, primary school
10	residential, primary school
11	residential, primary school
12	residential, primary school
13	park

4. Results and discussion

4.1 Meteorological conditions

Intensive observations were made during four periods: 11–17 August 2003, 9–15 August 2004, 7–16 August 2005, and 22–30 September 2005. Table 3 shows the average temperature, daily maximum and minimum temperatures, precipitation amount, average wind speed, average relative humidity, and average cloudiness observed at Seoul meteorological observatory for each day of the four intensive observation periods. Cloudiness is expressed as values of 0–10, 0 indicating no clouds and 10 indicating completely overcast skies or rainy weather. The Korea Meteorological Administration provides four weather (sky)

Table 3. Meteorological conditions in Seoul during the intense observation periods. NPH and MA in the last column denote the North Pacific high and migratory anticyclone, respectively

Date	Temperature (°C)	Maximum temperature (°C)	Minimum temperature (°C)	Precipitation amount (mm)	Wind speed ($m\,s^{-1}$)	Relative humidity (%)	Cloudiness	Weather type
2003.8.11	23.8	28.3	20.9	3.5	1.3	78	6	cloudy
2003.8.12	24.8	30.0	20.4	0.0	1.6	64	4	partly cloudy, NPH
2003.8.13	24.7	30.0	20.6	0.0	0.7	61	5	partly cloudy, NPH
2003.8.14	24.9	29.7	19.8	0.0	1.3	52	1	clear, NPH
2003.8.15	24.7	30.2	19.9	0.0	1.7	51	4	partly cloudy
2003.8.16	23.5	26.5	21.4	0.0	1.4	62	9	overcast
2003.8.17	23.0	25.1	21.1	0.2	1.0	68	10	overcast
2004.8.9	28.6	33.0	25.0	0.0	2.1	71	4	partly cloudy
2004.8.10	30.2	36.2	25.2	0.0	1.7	67	1	clear, NPH
2004.8.11	30.4	35.7	25.6	0.0	2.1	53	0	clear, NPH
2004.8.12	29.6	34.7	25.6	0.0	2.3	61	1	clear, NPH
2004.8.13	28.7	32.7	26.0	0.0	2.7	69	3	partly cloudy, NPH
2004.8.14	26.3	29.2	24.0	3.0	1.7	75	9	overcast
2004.8.15	26.7	31.0	22.8	0.0	1.9	67	8	cloudy
2005.8.7	26.9	30.1	24.3	0.0	2.1	72	9	overcast
2005.8.8	26.2	30.2	23.7	16.0	2.8	80	9	overcast
2005.8.9	26.4	29.5	24.3	15.0	4.5	76	9	overcast
2005.8.10	25.1	28.2	23.5	57.5	2.2	86	10	overcast
2005.8.11	25.2	27.5	23.2	25.0	2.8	85	9	overcast
2005.8.12	26.0	26.8	24.6	1.0	3.2	85	10	overcast
2005.8.13	27.2	30.1	25.1	0.5	2.8	78	8	cloudy
2005.8.14	27.3	31.1	25.2	0.0	2.8	75	5	partly cloudy, NPH
2005.8.15	27.2	31.3	25.0	0.5	2.3	79	5	partly cloudy, NPH
2005.8.16	28.3	33.0	25.2	0.0	2.1	74	4	partly cloudy, NPH
2005.9.22	17.1	19.0	14.8	0.5	1.7	87	9	overcast
2005.9.23	20.1	23.2	16.6	0.0	1.8	72	6	cloudy
2005.9.24	20.9	25.7	17.1	0.0	2.4	66	5	partly cloudy, MA
2005.9.25	20.5	24.7	16.6	0.0	2.1	66	5	partly cloudy, MA
2005.9.26	21.0	25.6	17.5	0.0	1.4	66	5	partly cloudy, MA
2005.9.27	21.0	26.1	17.8	0.0	1.5	67	5	partly cloud, MA
2005.9.28	20.8	26.5	16.3	0.0	1.4	64	2	clear, MA
2005.9.29	20.8	25.2	15.8	0.0	1.9	59	7	cloudy
2005.9.30	17.7	21.2	16.0	104.5	2.3	91	10	overcast

types according to cloudiness: clear (0–2), partly cloudy (3–5), cloudy (6–8), and overcast (9–10). The weather types are given in the last column of Table 3. Noticing that the urban heat island is pronounced under clear skies (Yague et al., 1991), data from days with cloudiness below 5 were used to detect changes in local thermal environment associated with the stream restoration and quantify them. On rainy days, the influence of the stream on its nearby thermal environment would be negligible or small compared to that on clear days. Excluding most those days, the analysis periods are 12–14 August 2003 (I), 10–13 August 2004 (II), 14–16 August 2005 (III), and 24–28 September 2005 (IV). The Korean peninsula was under the influence of the North Pacific high during periods I, II, and III and under the influence of migratory anticyclones during period IV. These conditions typically give clear weather over the Korean peninsula.

Notice that the Cheonggye stream environment in August 2003 was still that before any restoration had begun and also that the stream restoration was already completed in August 2005, although the official announcement of its completion was not made until September 2005. Therefore, for analysis purposes, period I can be considered as a before-restoration period and periods III and IV as after-restoration periods. Period II belongs to a during-restoration period.

Table 4 shows period-averaged meteorological variables (temperature, daily maximum and min-

Table 4. Period-averaged meteorological variables in Seoul during the analysis periods

Analysis period		Temperature (°C)	Maximum temperature (°C)	Minimum temperature (°C)	Wind speed ($m\,s^{-1}$)	Relative humidity (%)	Cloudiness
period I	2003.8.12–14	24.8	29.9	20.3	1.2	59	3.3
period II	2004.8.10–13	29.7	34.8	25.6	2.2	62	1.3
period III	2005.8.14–16	27.6	31.8	25.1	2.4	76	4.7
period IV	2005.9.24–28	20.8	25.7	17.1	1.8	66	4.4

imum temperatures, wind speed, relative humidity, and cloudiness) observed at Seoul meteorological observatory during periods I, II, III, and IV. Periods I, II, and III experienced hot weather under the influence of the North Pacific high. During period I, the average temperature was 24.8 °C, the average daily maximum temperature was 29.9 °C, and the average cloudiness was 3.3. During period III, the average temperature was 27.6 °C, the average daily maximum temperature was 31.8 °C, and the average cloudiness was 4.7.

4.2 Temperature

Figure 4 shows the vertical profiles of potential temperature at 1500 and 1800 LST (local standard time) 14 August 2003. At 1500 LST, the lowest ~20 m layer is unstable due to the strong surface heating by solar radiation. From that height to 1.65 km, the potential temperature is almost constant with height, that is, a well-mixed planetary boundary layer exists with a thickness of 1.65 km. Above 1.65 km, the potential temperature increases with height, that is, the atmosphere is statically stable. The vertical profile of potential temperature at 1800 LST resembles that at 1500 LST, but the planetary boundary layer at 1800 LST (1.8 km) is slightly thicker than that at 1500 LST, meaning that the planetary boundary layer grew between 1500 and 1800 LST. Figure 4 indicates that the observed planetary boundary layer height in the hot summertime afternoon in Seoul can be ~2 km. This is similar to the planetary boundary layer height at the city center of Philadelphia simulated using a mesoscale model (Otte et al., 2004).

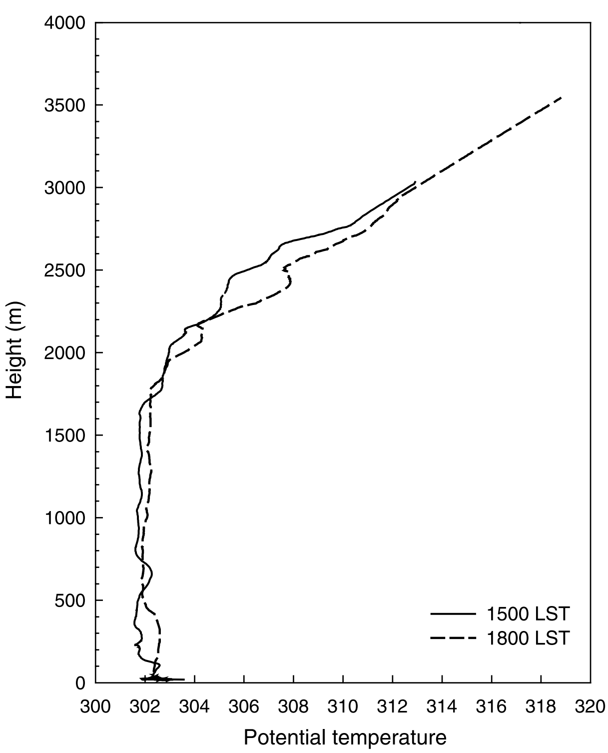

Fig. 4. The vertical profiles of potential temperature at 1500 and 1800 LST 14 August 2003

The simplest approach to quantifying temperature mitigation due to the Cheonggye stream restoration would be to subtract the temperature after the stream restoration from the temperature before the stream restoration. The average temperature in the stream area (13-location average, Fig. 3b) was 25.6 °C before the stream restoration and 28.7 °C after the stream restoration. This gives a temperature increase of 3.1 °C in the stream area (not a temperature mitigation but a temperature rise). This approach cannot be used in this study. In fact, this approach would be acceptable if weather conditions during the observation periods before and after the stream restoration were very similar. However, weather conditions during periods I and III were different from each other, although both periods were in mid-August and generally exhibited clear and hot days under the influence of the North Pacific high. The average temperature during period III was 2.8 °C higher than that during period I (Table 4). The

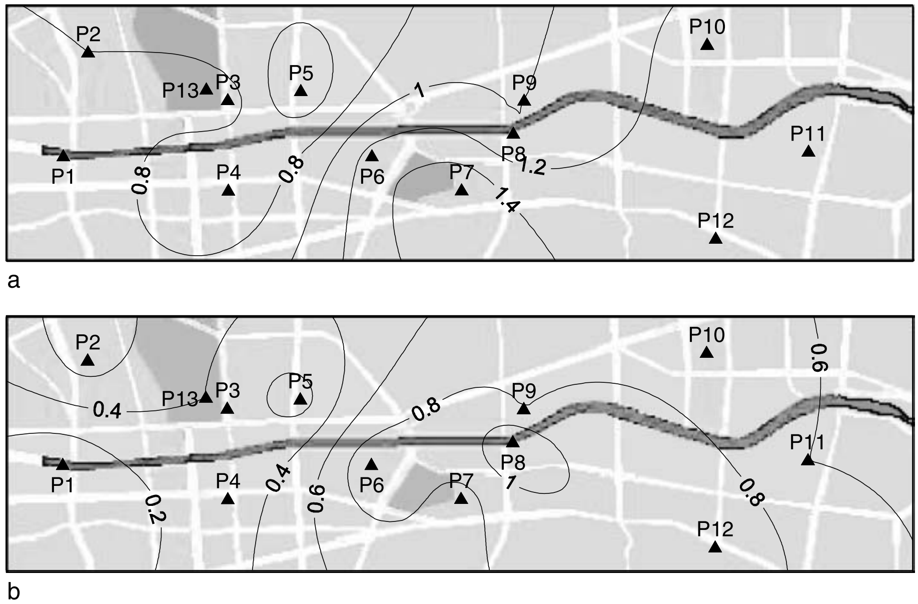

Fig. 5. The spatial distribution of temperature at each location P1–P13 minus average temperature over Seoul. The temperatures are time-averaged over the period of (**a**) 12–14 August 2003 and (**b**) 14–16 August 2005. The contour interval is 0.2 °C

average daily maximum and minimum temperatures during period III were also higher than those during period I. The average wind speed was stronger during period III (2.4 m s^{-1}) than during period I (1.2 m s^{-1}) (Table 4). The magnitude of temperature mitigation due to the stream restoration would be larger on hotter days if other meteorological conditions were similar. On the other hand, days with stronger wind would mitigate temperature less, taking into account that the urban heat island intensity decreases as the wind speed increases (e.g. Sundborg, 1950; Kim and Baik, 2002). To overcome the problem implicit in the simplest approach and reduce synoptic-scale and local-scale weather effects, the temperature deviation from a reference temperature averaged over a larger area during period I and that during period III are considered in this study.

Figure 5 shows the spatial distribution of differences between temperature at each location P1–P13 and average temperature over Seoul during periods I and III. The average temperature over Seoul is the temperature averaged over 24-automatic weather station locations within Seoul (Fig. 3a). The temperatures are time-averaged over periods I and III. Before the stream restoration (Fig. 5a), the temperature difference was larger in the eastern part of the area than in the western part. The average temperature difference (13-location average) is 1.0 °C. The positive difference means that the temperature in the stream area is higher than the averaged temperature over Seoul. In fact, the Cheonggye stream area is one of the areas of strong urban heat island intensity in Seoul, although KMA operational automatic weather stations are not installed yet in that region (Park, 1986; Kim and Baik, 2005). After the stream restoration (Fig. 5b), the temperature difference was smaller at all 13 locations. The average temperature difference is 0.6 °C. This apparent 0.4 °C reduction might have been caused by the stream restoration. The largest temperature drop is 0.9 °C at locations P1 and P7.

The degree of temperature decrease after the stream restoration depends on synoptic-scale and local-scale weather conditions during each August and the above approach cannot completely eliminate weather-dependent effects. Thus, it cannot be stated that the 0.4 °C mitigation of summertime temperature in the vicinity of the Cheonggye stream is due entirely to the stream effect only. In addition, it should be mentioned that the value of the temperature mitigation can differ according to the selection of the reference temperature (in Fig. 5, it is the average temperature over Seoul). This requires further investigation.

Figure 6 shows the distribution of temperature along the street traversing the Cheonggye stream (Fig. 3c) on 15 August 2005. Location 7 is a measurement site within the stream. Data from the T-RH kit at location 8 were not used for analysis in Fig. 6 because the temperature data there were contaminated by pedestrians and cars. The temperature data at location 10 were not used in the

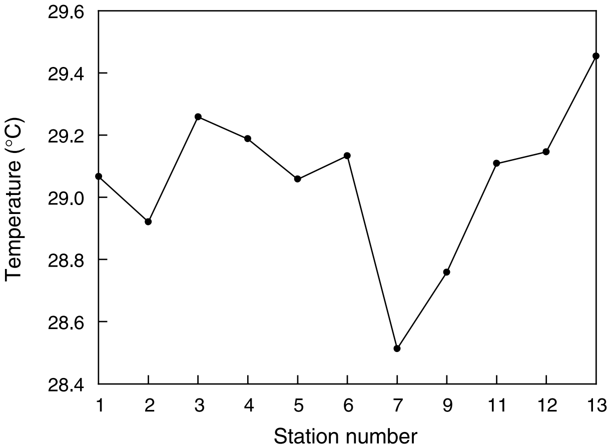

Fig. 6. The distribution of temperature across the Cheonggye stream (R line in Fig. 3b) on 15 August 2005

analysis because of cooking-related heat emitted from a small outdoor tent restaurant in the proximity of location 10. After the stream restoration, the temperature tends to decrease as one goes southward from locations 13 to 7. The Cheonggye stream is obviously responsible for this temperature decrease. The temperature difference between locations 13 and 7 is 1 °C. South of the stream (locations 1–6), the temperature changes very little. The asymmetric pattern of temperature distribution across the stream is associated with wind direction as well as urban morphology. Although Fig. 6 shows the stream effect on temperature over distance, it cannot be estimated that to what horizontal distance the Cheonggye stream influences near-surface air temperature. To examine this, a long-term monitoring of temperature would be needed with a longer measurement line than the R line (Fig. 3b).

4.3 Sensible heat flux

Figure 7 shows the time variations of net radiative flux and sensible heat flux. During the period of 12–14 August 2003, the net radiative flux shows a distinct diurnal variation with its maximum at noon. The daily maximum net radiative flux was 580 W m^{-2} on 12 August. The sensible heat flux also shows a diurnal variation, but with its daily maximum at ∼1500 LST. The sensible heat flux was as large as 393 W m^{-2} at 1500 LST 13 August. This value is larger than the average daily maximum summertime sensible heat flux for cities summarized in Grimmond and Oke (2002), which typically varies between 200 and

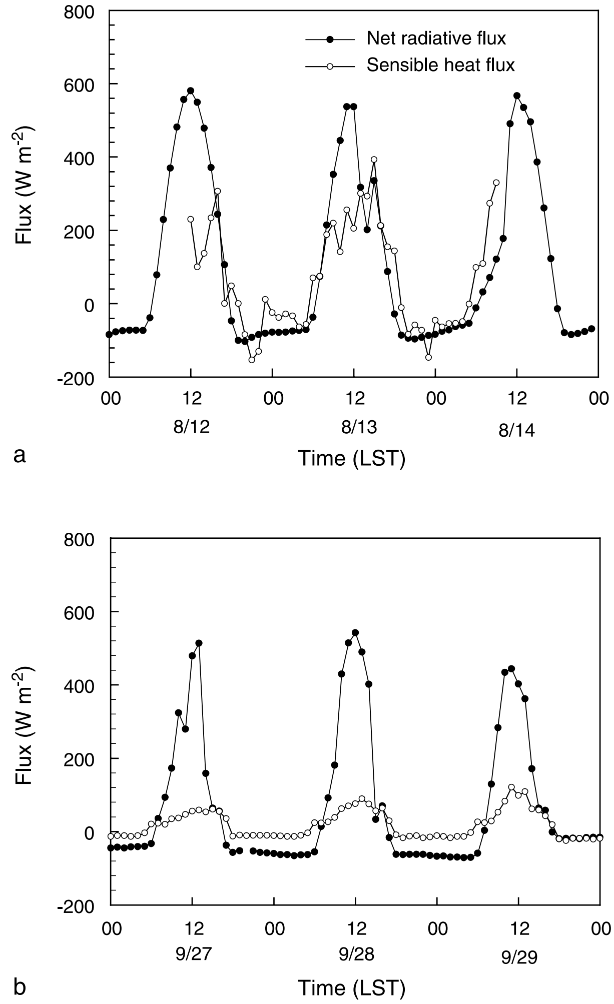

Fig. 7. The time variations of net radiative flux and sensible heat flux during the period of (**a**) 12–14 August 2003 and (**b**) 27–29 September 2005

300 W m^{-2}. The larger daily maximum sensible heat flux in this study is mainly attributed to the fact that the measurement before the stream restoration was made using a scintillometer over a line crossing over a road with heavy traffic, whose bottom temperature is very high in the hot summertime afternoon. Also, notice that the surroundings of the measurement location consist of highly built-up and commercial sections. In the nighttime, the sensible heat flux is negative. The ratio of the daily maximum sensible heat flux to the daily maximum net radiative flux was 0.53 on 12 August and 0.73 on 13 August, giving an average ratio of 0.63. This average ratio is similar to the ratios obtained at the canyon floor and top in a N–S oriented urban canyon in Vancouver, B.C. (Nunez and Oke, 1977; Oke, 1987).

The time variation of the net radiative flux during the period of 27–29 September 2005 is similar to that during the period of 12–14 August 2003, but with reduced net radiative flux in September. The magnitude of the sensible heat flux was greatly reduced after the stream restoration. The daily maximum sensible heat flux was $121\,W\,m^{-2}$ on 29 September, about 0.3 of that before the stream restoration. The reduced daytime sensible heat flux is due partly to lower temperatures in September (Tables 3 and 4), but the Cheonggye stream is largely responsible for that. The ratio of the daily maximum sensible heat flux to the daily maximum net radiative flux was 0.12 on 27 September, 0.16 on 28 September, and 0.27 on 29 September. This gives an average ratio of 0.18 over the three-day period. This average ratio over the Cheonggye stream is smaller than the ratios at suburban and rural sites (Cleugh and Oke, 1986).

Figure 7 indicates that the change in land cover from concrete/asphalt to stream surface significantly influences surface sensible heat flux and hence surface energy balance. In the Cheonggye stream restoration case, the ratio of sensible heat flux to net radiative flux dramatically decreased in the daytime after the stream restoration.

5. Conclusion

It is speculated that an inner-city stream or river will modify its nearby urban climate. However, to the authors' knowledge, there is no study of urban climate changes associated with a large inner-city stream or river restoration. In this study, changes in local thermal environment associated with the restoration of an inner-city stream, the Cheonggye stream, in Seoul were investigated for the first time. For this, intensive observations were made in the stream area over several summertime periods before, during, and after the stream restoration. Through the analysis of the observational data, we found that the restored stream affects local thermal environment, including temperature mitigation and changes in sensible heat flux. In this study, only four periods were considered for data analysis and the impact of variations in weather patterns among the periods could not be quantified. A long-term monitoring of meteorological elements is needed to examine stream effects for different weather patterns, seasons, and years. Also, a numerical modeling study is needed to understand interactive physical processes and mechanisms responsible for changes in local thermal environment associated with the stream restoration. In addition, high-resolution surface temperature data derived from satellites would be useful to identify thermal environmental changes in the vicinity of the stream. A long-term monitoring of meteorological elements in the vicinity of the Cheonggye stream will enable us to detect and quantify changes in local urban climate associated with the stream restoration. The present study is expected to provide a scientific basis for urban planning.

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