Effects of changes in land use on the diurnal temperature range: a long-term data analysis

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Abstract
Air temperature is sensitive to changes in local land use. In this study, we investigated the effect of dam lake water on the air temperature based on open climate data. Lake Sayama (and its surroundings), located in Tokorozawa City, 30 km from Tokyo, Japan, was undertaken as the case study. This artificial lake was empty for three years for seismic reinforcement. To remove the effects of time-series changes in the air temperature, nearby observation stations where the air temperature difference did not change from that of Tokorozawa during the analysis period were selected. Analysis of data revealed that the minimum air temperature increased, and the maximum air temperature slightly decreased during the period when the dam reservoir was full throughout the year. Moreover, the reduction in the diurnal range of air temperatures was 1.78 °C in December and 0.46 °C in August. The effect of the lake on the air temperature reflected the size of the lake and the climatic zone. These results highlight the need for maintaining a network of meteorological observation stations, whose data can prove useful for identifying local climate changes due to land use.

1. Introduction
Land use change plays an essential role in climate. Humans have changed the albedo, surface roughness, and evapotranspiration by changing the land use from native vegetation to cropland and areas of urban development (Alkama and Cescatti 2016, Goddard and Tett 2019). Physical change near the ground surface is one of the factors altering temperature, precipitation, and the wind system on a global scale (Pielke et al 2011). Also, as is the case on a global scale, land use changes have affected the local climate. For example, humans have changed land use by storing large amounts of water or changing the flow of rivers for disaster prevention and irrigation. Sacks et al (2009) reported that irrigation changed the local air temperature by increasing evaporation. Additionally, several explanations have been offered regarding the effect of dam lakes on the local climate from observational studies (Stivari et al 2005). In Ghana, downstream of the Akosombo Dam, the air temperature changed as the river flow decreased (Gyau-Boakye 2001). Moreover, in the agricultural sector, Yoshimura et al (1968) reported that dam construction altered the area affected by citrus frost damage in winter. Water evaporation from agricultural reservoirs, which are considerably smaller than dams, has been known to decrease the daytime air temperatures during the summer (Kanda et al 1991).

A sufficient number of studies have demonstrated that a natural body of water influences the local climate at the ground surface. The Great Lakes in North America affect the climate of the lakeshore region, such as the wind system (Weber 1978) and precipitation (Strommen and Harman 1978). A lake breeze blows in the summer at Lake Suwa in Japan, a large lake that is relatively smaller compared to the Great Lakes (Yoshino et al 1970). Many studies have addressed the effects of lakes on air temperatures. The impact of lake water on local air temperature depends on the time of day, season, and location. Takahashi and Itagaki (1980) reported that lake water increases the air temperature, especially in winter. In contrast, the air temperature of the lakeside decreases...
significantly when the lake ice melts in spring at high latitudes (Yang et al 2012), and cooling effects of water are observed during the daytime (Itagaki 1980). These studies clarified the effect of the lake on the air temperature by observing the distribution of the air temperature around the lake.

Another method of investigating the effects of land use on temperature involves examining changes in temperature trends using long-term observational data. Although it is impossible to use this method to investigate the effect of natural lakes on the air temperature, the effect of dam lakes can be clarified by comparing temperature data before and after dam construction. However, few studies have confirmed that artificial lakes change the local climate by comparing parameters before and after dam construction. For instance, an artificial lake promotes the occurrence of fog (Vogel and Huff 1975). Using observational data, it was shown that the Itapúa Dam, located in a subtropical zone, decreased the daytime air temperature and increased the nighttime air temperature five years after its construction (Stivari et al 2005). Chikamori and Kamiî (1993), however, reported that there was no significant air temperature change before and after the construction of a dam located in a temperate region based on temperature data that spanned decades.

Yamaguchi Reservoir (commonly called Lake Sayama) is located in Tokorozawa, Japan. The dam was constructed to supply water to Tokyo. The lake water was drained for seismic reinforcement in 1998 and was empty for approximately three years excluding the transition periods. The lakeside air temperature has been observed for 40 years, including the period in which the lake was empty. The landscape around the lake has been managed as a secondary forest from the start of observation to the present; no changes in local conditions were observed except that the dam lake was drained.

The purpose of this study was to determine the impact of a water body on the local air temperature. To this end, long-term observational data were used to compare the air temperatures during the period in which the artificial lake was empty to the two periods in which it was filled with water. First, for this comparison, we statistically selected several comparable observation stations. Thereafter, the effect of the artificial lake on the air temperature at a local level is noted. Finally, the impact of the lakes in different climatic zones and the impact of lake size on air temperatures is discussed.

2. Methods

2.1. Study site

2.1.1. Outline of Kanto plain, including Tokorozawa city

Tokorozawa City, Saitama Prefecture is situated at 35°48′00″N and 139°28′11″E and is approximately 100 m above sea level (figure 1). Tokorozawa City is a typical suburban area located approximately 30 km from the center of Tokyo on the western border of a densely inhabited district (figure 2). The average annual temperature of the Tokorozawa AMeDAS (Automated Meteorological Data Acquisition System) is 14.3 °C, and the average annual precipitation is 1481.6 mm. It is hot and humid in summer in the Kanto Plain where Tokorozawa is located (the monthly average temperature is 25.8 °C and the precipitation is 209.7 mm in August); conversely, it is cold and dry in winter (monthly average temperature is 3.6 °C and precipitation is 44.4 mm in January). It lies approximately 35 km from the coastline and is relatively unaffected by the sea breeze.
2.1.2. Location of Lake Sayama and the Tokorozawa AMeDAS
Lake Sayama is located at the southern end of Tokorozawa City. The average altitude of the lake surface is 119 m above sea level. This artificial lake is an earth-type dam with an effective water level of 20 m, a surface area of 189 ha and an effective storage capacity of 19 km$^3$. The lake was constructed as a water supply reservoir in 1934. The dam lake is surrounded by a secondary forest for water source recharge and water quality conservation and has been administered by the Tokyo Metropolitan Government Bureau of Waterworks since its construction. There has been no significant development in the surrounding area in the last 50 years (figures 1(b), (c)). The east side of Lake Sayama was a residential area even before the analysis period, and no noticeable development was observed during the analysis period.

The Tokorozawa AMeDAS was installed by the Japan Meteorological Agency (hereafter, the JMA) on the east shore of Lake Sayama (figures 1(b), (c)). At this station, observations were continuous from 1978 to the present, except for several days of missing data due to the updating of meteorological equipment.

2.1.3. Seismic retrofit
From January 1998 to November 2002, the reinforcement of levees and water intake towers was carried out for seismic strengthening. By December 2002, the water depth had returned to 20 m. During the construction period, there were some areas in which some water was retained to protect the habitat of the northern goshawk (Accipiter gentilis) (figure 1(c)). During this period, the Tokorozawa AMeDAS continued to record climate data.

2.2. Analysis period
The analysis period for this study is from January 1st, 1979 to December 31st, 2018, during which AMeDAS observed daily data. Three periods were defined for the analysis. The period before the seismic retrofit began is termed as the ‘before normal’ period, lasting for 19 years from 1979 to 1997, and is hereafter called the ‘BN-period.’ The ‘empty period,’ for a duration of 3 years from 1999 to 2001 (hereafter called the ‘EMP-period’), was the period in which the lake water was drained for seismic retrofitting. The period after construction when the lake was again filled with water is designated as the ‘after normal’ period, spanning 16 years from 2003 to 2018 (hereafter called the ‘AN-period’). Since there were no severe droughts during the BN-period and AN-period, the volume of the lake water was regarded as constant. The years 1998 and 2002 were excluded from the analysis because the water level fluctuated greatly when construction began in 1998 and again in 2002 when construction was completed.

2.3. Comparison stations
2.3.1. Air temperature differences to identify the effects of land use change
The main purpose of this study is to determine the influence of the presence of water in Lake Sayama on the local air temperature. Comparing the three periods using only Tokorozawa data, the average of the annual mean air temperature was 14.0 °C in the BN-period, 14.5 °C in the EMP-period, and 14.8 °C in the AN-period (figure S1 is available online at stacks.iop.org/ERC/2/021001/mmedia). If the analysis uses only one observation dataset, multiple factors, including temperature increases due to global warming and/or urban heat islands, have to be considered. In other words, it is possible that the effect of time-series change is greater than the effect of land use change on local air temperature. Moreover, the period in which the lake was empty is short. The influence of interannual variations such as El Niño–Southern Oscillation (ENSO) events may be included. A La Niña event occurred from the summer of 1998 to the spring of 2000. The air temperature in Japan tends to be warmer in summer and cooler in winter when La Niña occurs, although the effect is not statistically significant.
One way to cancel out the time-series change is to use the temperature difference from neighboring observation datasets. In comparison with nearby stations, where the daily and annual variations in air temperature did not change, we can detect the temperature difference changes that occur when the local scale observation conditions at one station change (Memon and Leung 2010). This is the first study to use the air temperature difference between Tokorozawa and nearby stations for this purpose; therefore, we began by selecting stations for which the site comparison method can be used. We focused on the AMeDAS stations in the western area of the Kanto Plain where Tokorozawa is located. All AMeDAS stations have been maintained and managed by the JMA with the same observation method over time.

2.3.2. Excluding nearby stations from a geographical point of view

There are 12 AMeDAS stations within 40 km of Tokorozawa (figure 2). Among these stations, stations that had different observation conditions from Tokorozawa were excluded as follows:

1. Otemachi (Tokyo), Nerima, and Saitama AMeDAS were excluded because these stations are located in the central part of the city, while Tokorozawa is located outside the Tokyo metropolitan area.

2. Chichibu (232 m above sea level) and Yorii (132 m above sea level) were excluded because they are established in a small basin of approximately 890 km². Similarly, Ogochi (560 m above sea level) was excluded because it is located in the mountains; Tokorozawa is located at the edge of the Kanto Plain.

Consequently, the six remaining stations with the same geographical characteristics as Tokorozawa (hereafter called ‘TKR’) were Fuchu, Hachioji, Koshigaya, Kuki, Ome, and Hatoyama (hereafter called ‘FCH’, ‘HCJ’, ‘KSH’, ‘KUK’, ‘OME’, and ‘HTY’, respectively). Moreover, the rate of the mean annual air temperature increase at the comparison stations during the analysis period is almost the same as that at TKR (figure S1).

2.4. Climate data

2.4.1. Calculation of the air temperature difference in hourly data

Figure 3 shows the comparative analysis flow in this study. We used the hourly air temperatures of TKR and six comparison stations from January 1, 1979 to December 31, 2018. We defined the air temperature difference between TKR and each comparison station as follows:

\[
\Delta T_{\text{sta.}} = T_{\text{TKR}} - T_{\text{sta.}},
\]

where \(T_{\text{TKR}}\) is the hourly air temperature (°C) of TKR, and \(T_{\text{sta.}}\) is the hourly air temperature (°C) of each comparison station. The three-letter acronym of the comparison point is assigned to the superscript ‘sta.’. Taking FCH as an example, the population of air temperature differences between TKR and FCH can be calculated using the following formulas:

\[
\Delta T_{\text{FCH BN}(m,h)} = \sum_{y=1979}^{1997} \sum_{d=1}^{d} \Delta T_{\text{FCH BN}(y,m,d,h)} (1979 - 1979 + 1) \times d,
\]

\[
\Delta T_{\text{FCH EMP}(m,h)} = \sum_{y=1999}^{2001} \sum_{d=1}^{d} \Delta T_{\text{FCH EMP}(y,m,d,h)} (1999 - 1999 + 1) \times d,
\]

\[
\Delta T_{\text{FCH AN}(m,h)} = \sum_{y=2003}^{2018} \sum_{d=1}^{d} \Delta T_{\text{FCH AN}(y,m,d,h)} (2003 - 2003 + 1) \times d,
\]

where \(y\) is the year (1979 to 2018), and \(d\) is the number of days in a month (28, 29, 30, or 31). This calculation was similarly performed at the other five comparison stations. The mean of the population average at each station during the BN-period was expressed as follows:

\[
\Delta T_{\text{sta. ALL BN}(m,h)} = \frac{\Delta T_{\text{FCH BN}(m,h)} + \Delta T_{\text{HCJ BN}(m,h)} + \Delta T_{\text{KSH BN}(m,h)} + \Delta T_{\text{KUK BN}(m,h)} + \Delta T_{\text{OME BN}(m,h)} + \Delta T_{\text{HTY BN}(m,h)}}{6}.
\]

By the same calculation method as in equation (5), we defined the average of the results of all comparison stations as \(\Delta T_{\text{EMP}(m,h)}\) and \(\Delta T_{\text{AN}(m,h)}\). Finally, \(\Delta T_{\text{LAKE}(m,h)}\), which indicates the influence of the presence or absence of water on the temperature, was defined as follows:
D = D + D - D

T

mh

mh

mh

LAKE

sta.

ALL

EMP

sta.

ALL

sta.

ALL

Figure 3. Procedure for the calculation of $\Delta T_{\text{LAKE}}^{\text{sta.}}$. Based on equation (1), the difference in air temperature between Tokorozawa and the comparison station was calculated for each period. Equations (2) to (4) were used to calculate the differences at all stations and the average values for each. Since $\Delta T_{\text{EMP}}^{\text{sta.}}$ is the difference in air temperature between the EMP–period and the normal periods when the lake was filled, a positive value indicates that the air temperature was higher during the latter.

$$\Delta T_{\text{LAKE}}^{\text{sta.}} = \frac{\Delta T_{\text{ALL} \text{BN}}^{\text{sta.}} + \Delta T_{\text{ALL} \text{BN}}^{\text{sta.}}}{2} - \Delta T_{\text{EMP} \text{BN}}^{\text{sta.}}$$

$\Delta T_{\text{LAKE}}^{\text{sta.}}$ is a value obtained by subtracting the value of the EMP–period from the average value of the two normal periods. A positive value indicates that the temperature is higher during the normal periods. Conversely, negative values indicate that the temperature is higher in the EMP–period. In other words, a positive value indicates that the lake water increases the local air temperature, and a negative value indicates that the lake water decreases the air temperature.

2.4.2. Calculation of the air temperature difference in extreme air temperatures

We also focused on extreme temperatures. The daily maximum and minimum air temperatures were sensitive to land use around the station (Nishimori et al. 2009). We used the daily maximum (defined as $T_{\text{max} \text{sta.}}$) and minimum air temperature (defined as $T_{\text{min} \text{sta.}}$) of all stations as well as hourly data. As with hourly data, the calculation used the air temperature difference obtained by subtracting each comparison station from TKR. The equations are as follows:

$$\Delta T_{\text{max} \text{sta.}} = T_{\text{max} \text{TKR}} - T_{\text{max} \text{sta.}}$$

$$\Delta T_{\text{min} \text{sta.}} = T_{\text{min} \text{TKR}} - T_{\text{min} \text{sta.}}$$

2.5. Two-sample test

Normality was first confirmed using the Shapiro Wilk test, and the significance level was 5%. If the two groups to be compared both followed a normal distribution, a t-test was performed, otherwise the Wilcoxon rank sum test
was used. The levels of significance were 5%, 1%, and 0.1%. Supporting information (SI 1 and SI 2) explains the random sampling for two-group comparisons and elaborates on the sample size selection.

3. Results and discussion

3.1. Determination of comparable stations with TKR

As we selected comparison points with the same geographical conditions as TKR, it can be assumed that comparisons between periods during which the lake water was filled are not significantly different.

First, we sampled two sets of 90 samples from the BN–period without duplication and examined whether there was a change in the air temperature difference within the same period at each station. Both \( \Delta T_{\text{max}}(\text{a}_{\text{BN}}) \) and \( \Delta T_{\text{min}}(\text{a}_{\text{BN}}) \) were not significantly different for all monthly and hourly patterns at the 5% level. This result was true for all comparison stations. This test was also performed for the AN–period, with no significant differences for all patterns. Thereafter, a two-group comparison between the BN–period and AN–period was made (table 1). At four stations (FCH, HCJ, KSH, KUK) there were no significant differences at the 5% confidence level in most of the months for both maximum and minimum air temperatures. In contrast, the temperatures at the OME and HTY had significant differences in most cases.

The site comparison method uses nearby stations with the same geographical conditions as comparison stations. However, the data from the comparison stations may include a small bias related to the differences in local observation conditions and observation methods. HTY is considered to have different climate characteristics from TKR because it is located at the bottom of a small basin, where a temperature inversion layer develops during winter nights (Konno et al. 2013). OME, which is the closest station to TKR in straight line distance, is installed in a park in the factory area, but no changes in local observation conditions have been confirmed in the last 40 years. However, the observation time interval was changed in 2008 during the AN–period. Several studies have reported that time-series observation data are affected by artificial changes, such as changes in observation methods (e.g., Caussinus and Mestre 2004). The \( \Delta T_{\text{max}}(\text{OME}) \) appears to have changed rapidly since 2008, as can be seen from figure 4(a), showing the behavior of the monthly mean \( \Delta T_{\text{max}}(\text{OME}) \) over a 40-year period. From these results, it is suggested that the nonuniformity of the observation data, especially due to the change in the observation time interval, produced a significant difference in the temperature differences between OME and TKR. Thus, the stations FCH, HCJ, KSH, and KUK can be regarded as stations at which the air temperature was in a parallel relationship with that of TKR.

3.2. Two-group comparison of the extreme air temperature

We used the air temperature differences between TKR and the four selected comparison stations to compare the EMP–period with the BN–period and the EMP–period with the AN–period (table 1). While the maximum air temperature was hardly significant, the minimum air temperature was significantly different in all periods. Similarly, when the two groups were compared using the air temperature differences between the comparison stations, there were no significant differences except for the comparison between the BN–period and the AN–period of the maximum air temperature difference between FCH and HCJ (table 2). As a result, it is revealed that only the minimum air temperature in TKR during the EMP–period had changed.

We also analyzed whether the minimum air temperature changed to positive or negative. The temperature during the EMP–period tended to be lower by approximately 1.0 °C compared to that in the previous and subsequent periods as \( \Delta T_{\text{min}}(\text{FCH}) \), regardless of the season (figure 4(b)). This tendency was similar not only in FCH but also in HCJ, KSG, and KUK (figure S2). These results indicated that the minimum air temperature of TKR had decreased only during the EMP–period, as calculated using equation (8). In other words, the minimum air temperature increased owing to the water of Lake Sayama during the normal period in which water is stored therein. In the next section, we used hourly data to confirm the tendency of the increasing effect of the lake water on the air temperature during this minimum temperature observation.

3.3. Seasonal changes in diurnal range

Diurnal changes in the influence of lakes on air temperature were analyzed. The nighttime was defined from 19:00 to 07:00 the next morning, and the daytime was defined from 09:00 to 17:00. The daily minimum air temperature was often observed from 04:00 to 05:00, and the daily maximum air temperature was observed from 13:00 to 14:00 throughout the year. Figure 5 shows \( \Delta T_{\text{min}}(\text{OME}) \); the nighttime air temperature increased year-round. The air temperature increase from May to September was smaller than the significant increase of 1.0 °C or more from October to April. The nighttime air temperature from October to April during the normal periods was also significantly different compared to that in the EMP–period, although the air temperature difference was small. On the other hand, there was no significant difference between the normal and EMP periods during most of the daytime. During the time frame in which there was a significant difference in February and November, the
Table 1. Two-group comparison results for the three periods using the air temperature difference between TKR and the comparison stations. OME and HTY were not compared with TKR during the EMP–period because the comparison results showed air temperature changes due to long-term variability. Although there was no significant difference in maximum temperature, there was a significant difference in the minimum temperature in all patterns.

(a) Maximum Air Temperature

|            | BN–AN  | Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|------------|--------|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| FCH        | n.s.   |       | n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.|
| HJC        | n.s.   | n.s.  | n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.|
| KSH        | n.s.   | n.s.  | n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.|
| KUK        | n.s.   | n.s.  | n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.|
| OME        | ***    | ***   | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| HTY        | n.s.   | n.s.  | n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.|

|            | BN–Emp | Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|------------|--------|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| FCH        | n.s.   | n.s.  | n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.|
| HJC        | n.s.   | n.s.  | n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.|
| KSH        | n.s.   | n.s.  | n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.|
| KUK        | n.s.   | n.s.  | n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.|

|            | AN–Emp | Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|------------|--------|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| FCH        | n.s.   | n.s.  | n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.|
| HJC        | n.s.   | n.s.  | n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.|
| KSH        | n.s.   | n.s.  | n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.|
| KUK        | n.s.   | n.s.  | n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.| n.s.|
| AN–Emp     |        |       |     |     |     |     |     |     |     |     |     |     |     |     |

|            | BN–Emp | Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|------------|--------|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| FCH        | ***    | ***   | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| HJC        | ***    | ***   | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| KSH        | ***    | ***   | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| KUK        | ***    | ***   | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |

|            | AN–Emp | Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|------------|--------|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| FCH        | ***    | ***   | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| HJC        | ***    | ***   | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| KSH        | ***    | ***   | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| KUK        | ***    | ***   | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |

|            | AN–Emp | Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|------------|--------|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| FCH        | ***    | ***   | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| HJC        | ***    | ***   | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| KSH        | ***    | ***   | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| KUK        | ***    | ***   | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |

n. s. no significant change
* Significant change at p ≤ 0.05
** Significant change at p ≤ 0.001
*** Significant change at p ≤ 0.0001

daytime air temperature showed a decreasing trend of approximately 0.3 °C. Although there is no significant difference, the temperature tends to decrease from October to May. From June to September, when there was a slight upward trend, the maximum temperature increase was 0.2 °C.

Thus, in can be inferred that the decrease in the diurnal range of air temperature occurred throughout the year. Additionally, the intensity of the decrease in the diurnal range was stronger in winter than in summer (figure 5). To show that the diurnal range decreased, $\Delta T_{(m,h)}^{\text{LAEK}}$ at the time at which the daily minimum temperature was observed was subtracted from $\Delta T_{(m,h)}^{\text{LAEK}}$ at the time at which the daily minimum temperature
was observed each day. When the calculated values were averaged monthly, the reduction in the diurnal range of air temperatures was 1.78 °C in December and 0.46 °C in August (figure 6).

3.3.1. Increase in the nighttime air temperature
Although the influence of the lake on nighttime air temperatures was stronger in winter than in summer, it is assumed that no seasonal change had occurred due to heat storage. The result indicating that the effect is particularly strong in winter agrees with the results of Takahashi and Itagaki (1980) on Lake Toya. The most important factor pertaining to the lakes that influences the local air temperature is the difference between water temperature and air temperature (Itagaki 1980, Kondo 2000). Comparing the monthly minimum water temperature of Lake Tama, which is adjacent to Lake Sayama and almost the same in size, with the monthly minimum air temperature of TKR, the difference between the lake water temperature and air temperature in winter is greater than in summer (figure 7).

One of the factors that disturbs the development of radiation cooling is a large water body such as a lake (Kondo 2000). The Kanto Plain, where Sayama Lake is located, provides radiative cooling on sunny days throughout the year (Konno et al. 2013). The difference between the lake water temperature and the air temperature supplies heat from the lake surface. In addition, the air is disturbed, and the layer of cold air does not develop for the same reason. Several studies reported that the dam affected the cold air flow generated at night. For example, the number of foggy days increased after the dam construction (Vogel and Huff 1975), and there are slopes in which frost damage to oranges declined as the water warmed the cold air stream flowing into the dam (Yoshimura et al. 1968). In particular, radiation cooling in the Kanto Plain exists from November to February when the winter monsoon develops. This period coincides with the period in which the effect of Lake Sayama on increasing the air temperature became stronger (figure 4).

From the point of view of the impact of land cover on temperature, most studies focus on the impacts of land use changes from forest and grassland to cropland or urban areas on local air temperature. For example, Goddard and Tett (2019) reported that urbanization increased the minimum air temperature by approximately 1.5 °C, and Alkama and Cescatti (2016) reported that the removal of forest cover in temperate and tropical zones increased the mean air temperature by approximately 1.0 °C. The intensity of an increase in winter nighttime air temperature at Lake Sayama was similar to these studies. Thus, the impact of constructing new dams and reservoirs, and conversely, land cover changes from inland water bodies, such as lakes and wetlands, to cropland and urban areas on local air temperatures is suggested to be similar as compared to that of deforestation and urbanization.

3.3.2. Slight decrease in the daytime air temperature
Many studies that reported the increase in minimum air temperature due to lake water concluded that the diurnal range became smaller and the maximum air temperature decreased (Stivari et al. 2005, Hinkel and Nelson 2012). According to the results of these studies, there was no significant change in the maximum air temperature (table 1), and the daytime air temperature was slightly decreased throughout the year (figure 5).

Since Japan is an island country, the sea breeze prevails in the daytime while the land breeze prevails at night. In the Kanto Plain including TKR, the sea breeze blows from the Pacific Ocean from the south to southeast during the daytime when the maximum air temperature is observed. Conversely, the land breeze from north to northwest prevails at night. As a consequence, it is assumed that there is no water body on the windward side in the daytime to influence the maximum air temperature on the southeastern coast where the TKR AMeDAS is
Table 2. Comparison among four locations where the air temperature difference from TKR does not change over the long-term. There was no significant difference in the minimum air temperature when the two groups were compared. Therefore, a significant difference in the minimum temperature in table 1 (b) indicates that only the temperature in Tokorozawa changed.

### (a) Maximum air temperature

| Location | Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|----------|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| **FCH–HCJ** | *** | * | * | * | * | n.s. | n.s. | n.s. | * | *** | ** | *** | n.s. |
| **FCH–KSH** | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
| **FCH–KUK** | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | * | n.s. | n.s. | n.s. |
| **HCJ–KSH** | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | * | n.s. | n.s. | n.s. |
| **HCJ–KUK** | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | * | n.s. | n.s. | n.s. |
| **KSH–KUK** | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |

| Location | Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|----------|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| **BN–Emp** | FCH–HCJ | * | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | * | n.s. | n.s. | ** |
| **FCH–KSH** | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
| **FCH–KUK** | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | * | n.s. | n.s. | n.s. |
| **HCJ–KSH** | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
| **HCJ–KUK** | n.s. | * | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | * | n.s. | n.s. | n.s. |
| **KSH–KUK** | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |

| Location | Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|----------|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| **AN–Emp** | FCH–HCJ | n.s. | * | n.s. | n.s. | n.s. | n.s. | n.s. | * | n.s. | n.s. | ** |
| **FCH–KSH** | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
| **FCH–KUK** | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
| **HCJ–KSH** | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
| **HCJ–KUK** | n.s. | * | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | * | n.s. | n.s. | n.s. |
| **KSH–KUK** | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |

### (b) Minimum air temperature

| Location | Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|----------|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| **FCH–HCJ** | n.s. | * | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
| **FCH–KSH** | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
| **FCH–KUK** | n.s. | * | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
| **HCJ–KSH** | n.s. | * | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
| **HCJ–KUK** | n.s. | * | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
| **KSH–KUK** | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |

| Location | Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|----------|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| **BN–Emp** | FCH–HCJ | n.s. | * | n.s. | n.s. | n.s. | n.s. | n.s. | * | n.s. | n.s. | ** |
| **FCH–KSH** | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
| **FCH–KUK** | n.s. | * | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
| **HCJ–KSH** | n.s. | * | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
| **HCJ–KUK** | n.s. | * | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
| **KSH–KUK** | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |

| Location | Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|----------|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| **AN–Emp** | FCH–HCJ | n.s. | * | n.s. | n.s. | n.s. | n.s. | n.s. | * | n.s. | n.s. | ** |
| **FCH–KSH** | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
| **FCH–KUK** | n.s. | * | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
| **HCJ–KSH** | n.s. | * | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
| **HCJ–KUK** | n.s. | * | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |
| **KSH–KUK** | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |

n. s. no significant change
* Significant change at $p \leq 0.05$
** Significant change at $p \leq 0.001$
*** Significant change at $p \leq 0.0001$
installed. However, the observation point is susceptible to the wind coming from over the lake surface from night to morning when the minimum air temperature is usually observed. Yoshino et al. (1970) have shown that the temperature during the daytime in summer becomes lower in the area in which the lake wind blows, and there is almost no change in temperature on the windward side. Studies showing that the influence of a lake on air temperature is larger on the leeward side for lakes larger than Lake Sayama have also been reported for urban reservoirs (Fukagawa et al. 2008). Regardless of the size of the water body, these studies have revealed that the intensity of the decrease in daytime air temperature is smaller on the windward side than on the leeward side.

Furthermore, figure 8 shows the $\Delta T_{\text{sta,ALL}}$ during the time at which the highest temperature was observed based on the wind direction. It was found that the air temperature of TKR is lower in the west wind than in the east wind in summer. Lake Sayama and a secondary forest lie on the west side of the TKR station, while, on the east side, a built-up area is present (figures 1(b), (c)). In the area adjacent to Lake Sayama, Yokobori and Ohta (2009) reported an air temperature difference between the secondary forest and the residential area even in the narrow area due to evapotranspiration. Taking these results into account, it is suggested that the effect on the temperature by the lake is masked by cooling due to evapotranspiration from the secondary forest surrounding the lake. It has been reported that the maximum air temperature does not change under the influence of a dam constructed in a mountainous area covered with a temperate evergreen forest (Chikamori and Kami 1993).
Lake Sayama is located in a temperate zone and stores a very small volume of water compared to natural lakes. We compared the year-round observational studies on Lake Sayama and other lakes in different climatic zones. In tropical dams, the increase in the minimum air temperature and the decrease in the maximum air temperature follow the same trend, although the diurnal range remains almost constant throughout the year (Stivari et al 2005). In the subarctic Great Lakes, the minimum air temperature increased throughout the year, although the winter maximum air temperature decreased, and the diurnal range was larger in summer than in winter (Hinkel and Nelson 2012). Biwa Lake, the largest lake in Japan that is also located in a temperate zone, has a minimum air temperature increase and a clear decrease in the winter maximum air temperature (Edagawa 1986). The daily minimum air temperature increased by almost 5.0 °C, which was higher than that recorded in this study. Moreover, from spring to summer, the maximum air temperature of Lake Biwa decreases. The influence of Lake Sayama on the temperature is consistent with the previously reported influence of temperate lakes on air temperature (Edagawa 1986). However, the change in temperature observed in our study was clearly small; this may be attributed to the small size of Lake Sayama.

On the other hand, the physical characteristics of a deep lake such as Sayama Lake and a shallow pond are different. Agricultural ponds near the center of Tokyo, approximately 40 km away from Sayama Lake, have been reported to have a temperature mitigating effect of approximately 2.0 °C in the summer daytime (Kanda et al 1991). In the same area of Japan, the air temperature in the summer daytime when the water is stored in a pond with a shallow water depth was approximately 1.5 °C lower than when the water was drained (Ishi et al 1991).
These results suggest that the difference between the land surface temperature and the water surface temperature is the cause of the decrease in air temperature, rather than the effect of the water body on the air temperature.

3.5. Effect of changes in local observation conditions on long-term observation data

Since air temperature is sensitive to a change in observation conditions at a local scale, the time-series of long-term observations include not only global climate change but also local climate effects. Thus, a temperature change due to a local factor is an obstacle for accurately understanding global warming (Griffiths et al. 2005). Runnalls and Oke (2006) reported that the deforestation and irrigation around an observation station caused heterogeneity in long-term temperature data. However, the land cover in the TKR station near Lake Sayama has remained unchanged for the most recent 50 years, except during the EMP-period. Therefore, our results described above have been able to clarify the effects of water bodies without being biased by secular changes in land use patterns. In this study, it was possible to investigate the causes of local climate change by using long-term observation data appropriately.

4. Conclusion

Long-term observation data were used to clarify the effect of the dam lake, Lake Sayama, on air temperature. We used the unique method of comparing periods in which the lake was empty and those in which the lake was filled with water. The main findings and conclusions are as follows:

(1) The minimum air temperature was significantly different throughout the year between the period in which the lake was filled and the period in which the lake was drained. The lake water increased the night air temperature throughout the year. The increase in the air temperature changed seasonally from approximately 1.7 °C in winter to approximately 0.3 °C in summer.

(2) The maximum and daytime air temperatures were not significantly influenced by the lake water. However, the diurnal changes suggested that these temperatures decreased slightly throughout the year. In the study area, $\Delta T_{\text{LAKE}}$ by wind direction showed that the effect of the lake water on the air temperature was less than that of evapotranspiration from the secondary forest around the lake.

In conclusion, the present study demonstrated that a small dam lake in a temperate zone decreases the diurnal air temperature range throughout the year. The reduction in the diurnal range of air temperatures was 1.78 °C in December and 0.46 °C in August. Using long-term observation data appropriately, we were able to gain novel insights into the local climate. This study shows that the development and maintenance of meteorological observation networks are necessary and effective for monitoring climate change not only on a global scale but also on a local scale.

Acknowledgments

We would like to express our great appreciation to Kaori Terao, Manami Sato, and Tsuyoshi Minami, who were our laboratory students from 2010–2011 and provided the opportunity to start this research. This paper is a part of the outcome of research performed under a Waseda University Grant for Special Research Projects (Project number: 2010A-088, 2011A-079).

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