

Relative impacts of increases of solar radiation and air temperature on the temperature of surface water in a shallow, eutrophic lake

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ABSTRACT

We monitored lake surface water temperatures from 1992 to 2019 in Lake Kasumigaura, a shallow lake in Japan. We hypothesized that increases of shortwave radiation had increased surface water temperatures and heat fluxes more than had the increases of air temperature. We used the heat flux analyses and the sensitivity analyses to test the hypothesis. The fluxes of solar radiation gradually increased during the study period in a manner consistent with the phenomenon of global brightening. The increase was especially apparent in the spring. The rate of increase of surface water temperature was especially significant in May. Air temperature did not significantly increase in May, but it increased significantly in June ($0.40\text{ }^{\circ}\text{C decade}^{-1}$). A sensitivity analysis of the heat fluxes at the lake surface (shortwave radiation, longwave radiation, latent heat flux, and sensible heat flux) revealed that surface water temperature was more sensitive to changes of shortwave radiation than to air temperature during the spring. Although other factors such as inflows of groundwater and river water may also have impacted surface water temperatures, the increase of solar radiation appeared to be the major factor responsible for the increase of surface water temperature during the spring in Lake Kasumigaura.

Key words: air temperature, global warming, shallow lake, solar radiation, temperate

HIGHLIGHTS

- We observed water temperatures in Lake Kasumigaura for 28 years from 1992 to 2019.
- The rate of increase of the water temperature was greater than the rate of increase of the atmospheric temperature in spring.
- We clarified that increases of solar radiation had affected the surface water temperature more than the increases of atmospheric temperatures.

1. INTRODUCTION

The International Panel on Climate Change (IPCC) has predicted a global temperature increase of $4.8\text{ }^{\circ}\text{C}$ by 2100 based on scenario RCP 8.0 (Stocker *et al.* 2013). This increase in air temperature could substantially affect lacustrine environments (Woolway *et al.* 2020). Previous studies have analyzed the effects of the climate change on deep lakes, such as changes in stratification pattern, but shallow lakes should also be affected by the climate change. Previous studies have experimentally predicted the effects of increases of surface water temperatures on aquatic ecosystems (Meerhoff *et al.* 2012; O'Reilly *et al.* 2015), such as macrophytes (Feuchtmayr *et al.* 2009) and phytoplankton blooms (Bucak *et al.* 2018).

Global air temperature increase could cause an increase of surface water temperatures, but some studies have already reported that the rate of increase of surface water temperatures has exceeded the rate of increase of air temperature in lakes (Schmid & Köster 2016; Woolway *et al.* 2019). The implication is that the increase of surface water temperatures has been determined by more than the increase of air temperature. A variety of factors affect the flux of heat through the surface water of a lake and hence the temperature of the water (e.g., shortwave radiation, longwave radiation, sensible heat flux, latent heat flux). For example, the global increase of solar radiation (Wild *et al.* 2005, 2007) has increased the flux of shortwave radiation (Schmid & Köster 2016). The direction and speed of the wind associated with, for example,

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local land–sea breezes also change surface water temperature via sensible and latent heat fluxes through the lake surface (Yoshikado 2013). Differences in the changes of lake surface water temperatures have therefore reflected how much and what kind of heat fluxes through the water surface have changed during the last couple of decades.

Shallow lakes with mean water depths of less than 5 m are very common in Japan (78% of the total number of lakes). Whether and how much increases of air temperature are affecting lake surface water temperatures should be clarified because changes of surface water temperature can be expected to have impacts on lake biology [e.g., phytoplankton blooms; Tomioka *et al.* (2011)] and chemistry [e.g., colored dissolved organic matter; Weyhenmeyer *et al.* (2016)]. Previous studies of climatic effects on lake surface water temperatures have focused mostly on subarctic lakes and high-altitude lakes (Fink *et al.* 2014; Schmid & Köster 2016; Niedrist *et al.* 2018). Such lakes are especially sensitive to an increase of surface water temperature because of the associated reduction of ice cover (Benson *et al.* 2012; Magee & Wu 2017; Chikita *et al.* 2019). However, most temperate lakes are ice-free, and little information is currently available about the effect of meteorological changes on heat fluxes.

The objective of the current study was to clarify (1) how surface water temperatures have been changing in a shallow, eutrophic lake and (2) whether heat fluxes during the last 28 years in Lake Kasumigaura, a shallow, eutrophic lake in Japan, have increased more because of changes of solar radiation or air temperature. First, we documented the relationship between surface water temperature in Lake Kasumigaura and meteorological conditions. Second, we calculated heat fluxes (i.e., shortwave radiation, longwave radiation, sensible heat flux, and latent heat flux) through the lake surface. We then analyzed the sensitivity of the heat fluxes to solar radiation and air temperature. Third, because the surface water temperature is also altered by river inflow, ground storage, and groundwater inflow, we analyzed how much changes of the heat flux through the lake surface could explain changes of surface water temperature in Lake Kasumigaura. We have been monitoring the surface water temperature of Lake Kasumigaura and meteorological conditions over the lake since 1992. Because the monitoring data have been obtained at intervals of 1 h, we could carry out detailed analyses of heat fluxes. We tested the hypothesis that increases of solar radiation had affected the surface water temperature more than the increases of air temperatures.

2. METHODS

2.1. Lake Kasumigaura

Lake Kasumigaura, the second-largest freshwater lake in Japan, is 60 km northeast from the Tokyo metropolitan area (Figure 1; 36° 00.22'N, 140° 22.85'E). The water depth of the lake averages 4 m, and the maximum water depth is 7 m. The lake has a surface area of 172 km² and a watershed area of 1915 km². Water retention time in Lake Kasumigaura is about 200 days. More than 944,000 people in 2018 live in the watershed. The lake is a source of drinking water and is used for fishing and recreation. Lake Kasumigaura is ice-free even in winter; its minimum recorded surface water temperature has been ~4 °C since 1992. The water level of the lake is controlled and is almost constant. Lake Kasumigaura is very turbid; Secchi depths in the lake are ~50 cm. Our research team from the National Institute for Environmental Studies has been monitoring Lake Kasumigaura for more than 40 years as a part of the Global Environmental Monitoring System Water Trend Monitoring Program.

2.2. Data collection and analyses

The hourly monitoring data are available at the website of the Lake Kasumigaura Water Research Station of the National Institute for Environmental Studies (Figure 1). The water depth at the study site was ~1.7 m. We collected hourly surface water temperature, wind speed, and air temperature data at the monitoring station (Figure 1); temperature and humidity data were collected at an adjacent weather station on the rooftop of our laboratory at a height of 13 m above the ground. Surface water temperatures were collected at a depth of 0.2 m. The data are opened online at National Institute for Environmental Studies (<http://www.cger.nies.go.jp/db/kasumi/index.html>). If data were missing for more than 60 h during a given month, monthly averages were not calculated for that month.

Concentrations of suspended particulate matter (SPM) in the atmosphere were collected from the database of the Atmospheric Measurement and Experiment Laboratory (Air Quality Research Station), National Institute for Environmental Studies (NIES; Figure 1). Solar radiation and atmospheric pressure data were collected from the website of the Japan Meteorological Agency (<https://www.jma.go.jp/jma/menu/menureport.html>). We used data from the Japan Meteorological Agency

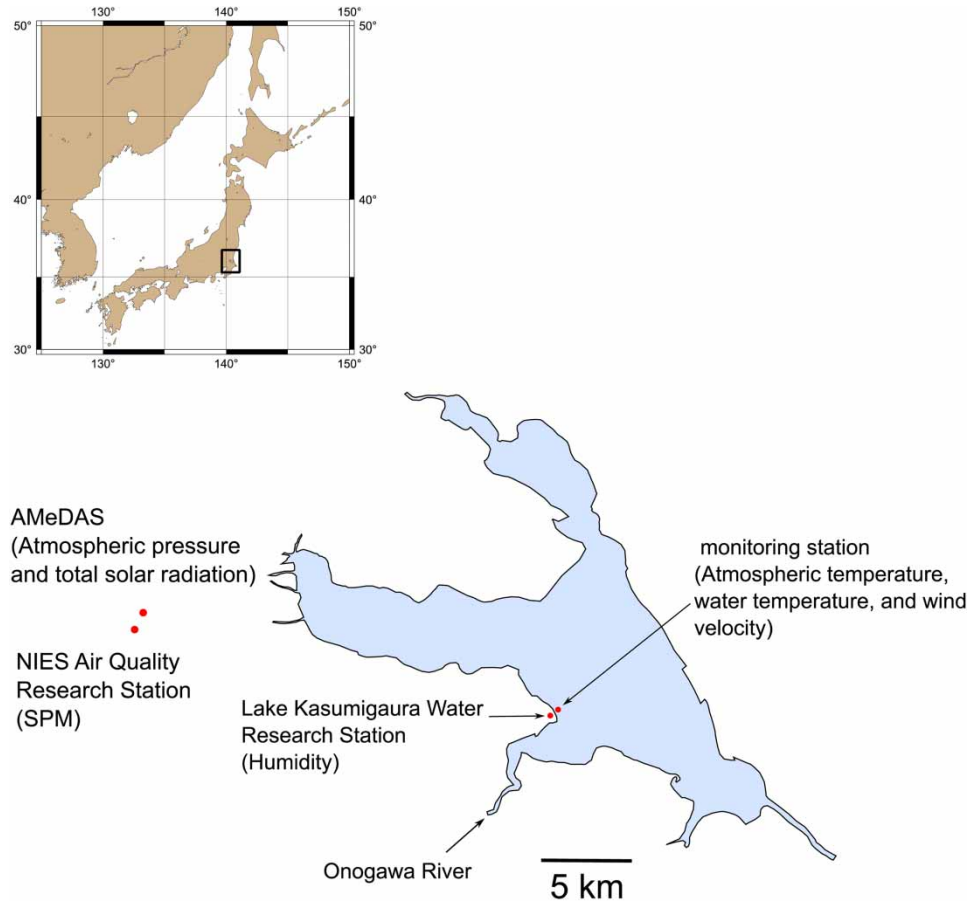


Figure 1 | Map of Lake Kasumigaura and meteorological stations. The measurements that were made are indicated in parentheses.

(JMA) Automated Meteorological Data Acquisition System at Tsukuba for solar radiation and atmospheric pressure. Long-wave radiation data were also checked from the website of the JMA. The data were downloaded from the website of JMA and used for the analyses.

2.3. Heat flux model at the lake surface

We analyzed heat fluxes at the water surface from 1992 to 2019. Positive values indicate downward fluxes, and negative values indicate upward fluxes. The net heat flux through the water surface was expressed with the following equation:

$$R_n = R_s + R_l + R_{la} + R_{sn} + R_{prec} \quad (1)$$

where R_n is the net heat flux through the water surface (W m^{-2}), R_s is the flux of shortwave radiation (W m^{-2}), R_l is the flux of longwave radiation (W m^{-2}), R_{la} is the latent heat flux (W m^{-2}), R_{sn} is the sensible heat flux (W m^{-2}), and R_{prec} is the heat flux associated with precipitation (W m^{-2}).

The shortwave radiation was calculated with the following equation:

$$R_{sd} = (1 - \text{ref})S_d \quad (2)$$

where ref is albedo, and S_d is the flux of solar radiation (W m^{-2}). We calculated ref based on the zenith angle (Kondo 1994; Woolway *et al.* 2015).

The flux of longwave radiation was calculated with the following equation:

$$R_l = R_{ld} + R_{lu} \quad (3)$$

where R_{ld} is the flux of downward longwave radiation (W m^{-2}) and R_{lu} is the corresponding upward flux (W m^{-2}).

Downward longwave radiation was calculated by using the following equation:

$$R_{ld} = \varepsilon_a \sigma T_a^4 \quad (4)$$

where ε_a is emissivity, σ is the Stefan–Boltzmann constant ($=5.67 \times 10^8 \text{ W m}^{-2} \text{ K}^{-4}$), and T_a is air temperature (K). Emissivity (ε_a) was calculated with the following equation (Yajima & Yamamoto 2015; Hipsey *et al.* 2019):

$$\varepsilon_a = (1.0 - \text{CC}^{2.796}) \times 1.24 \left(\frac{e_a}{\text{AT} + 273.15} \right)^{1/7} + 0.955 \text{CC}^{2.796} \quad (5)$$

where CC is the cloud cover function (0–1), e_a is the air vapor pressure, and AT is the air temperature ($^{\circ}\text{C}$). The values were also verified with data collected by the JMA. Cloud cover (CC) was calculated with the following equation (Quaas 2012):

$$\text{CC} = 1 - \left(\frac{1 - \bar{r}}{1 - r_c} \right)^{1/2} \quad (6)$$

where \bar{r} is relative humidity (0–1), and r_c is the critical relative humidity ($=0.1$).

Upward longwave radiation was calculated by the following equation:

$$R_{lu} = -\varepsilon \sigma T_w^4 \quad (7)$$

where ε is emissivity [$=1.0$; dimensionless; Sugita *et al.* (2020)], and T_w is the surface water temperature (K). Sensible and latent heat fluxes were calculated with the following bulk formulae:

$$R_{sn} = -c_p \rho_a C_H U (T_w - T_a) \quad (8)$$

$$R_{la} = -\rho_a l C_E U (q_{\text{sat}} - q) \quad (9)$$

where c_p is specific heat under constant pressure ($\text{J kg}^{-1} \text{ K}^{-1}$), ρ_a is the density of air (kg m^{-3}), C_H and C_E are the bulk coefficients for sensible and latent heat (dimensionless), respectively, U is wind velocity (m s^{-1}), l is latent heat (J kg^{-1}), q_{sat} is saturation-specific humidity (dimensionless), and q is specific humidity (dimensionless).

The bulk coefficients of the latent (C_H) and sensible heat fluxes (C_E) were calculated in accord with (Kondo 1994) as follows:

$$C_H = \begin{cases} 1.2 \times 10^{-3} & (U \leq 5.0 \text{ ms}^{-1}) \\ 1.5 \times 10^{-3} & (U > 5.0 \text{ ms}^{-1}) \end{cases} \quad (10)$$

$$C_E = C_H \quad (11)$$

The heat flux associated with precipitation was calculated with the following equation (Chikita *et al.* 2019):

$$R_{\text{prec}} = \rho_w c_w d (T_p - T_o) \quad (12)$$

where ρ_w is the density of water (kg m^{-3}), c_w is the specific heat of water ($\text{J kg}^{-1} \text{ K}^{-1}$), d is precipitation (m s^{-1}), T_p is the temperature of the rainwater, and T_o is the standard temperature. The temperature of rainwater was assumed to be the same as the air temperature, and the standard temperature was the annual mean air temperature, 15°C .

2.4. Sensitivity of heat fluxes through the lake surface on solar radiation and air temperature

We used a sensitivity analysis to determine how solar radiation and air temperature had changed heat fluxes through the lake surface. The default values of solar radiation, air temperature, and surface water temperature were the values from January to June in 2000. Because solar radiation and air temperature were both expected values on the regression line (solar radiation or air temperature vs. year) in 2000, we chose the year as the default year. For the sensitivity analysis, we determined the magnitude of the increase in solar radiation and air temperature based on the slope of the regression line between the solar radiation/air temperature and years during the observation period. We set the magnitude of the increase in solar radiation from about -3% (-5.1 W m^{-2}) and $+8\%$ ($+13.5 \text{ W m}^{-2}$) based on the values in 2000. The magnitude of the increase in air temperature was set to about -2.0% ($-0.21 \text{ }^\circ\text{C}$) and $+4.0\%$ ($+0.43 \text{ }^\circ\text{C}$) from the values in 2000. The sensitivities of air temperature and solar radiation were calculated with the following equation:

$$\text{Sensitivity (\%)} = \left| \frac{\beta - \alpha}{\alpha} \right| \times 100 \quad (13)$$

where β is the calculated value of each heat flux, and α is the default value of each heat flux.

2.5. Statistical analysis

We used the Pearson product-moment correlation to determine the significance of long-term increases or decreases. A type I error rate (α) of less than 0.05 was regarded as significant. We used the software Microcal Origin ver. 8.5.1.J for the calculations.

3. RESULTS AND DISCUSSION

3.1. Long-term changes of surface water temperature and meteorology

We first analyzed monthly meteorological data from 1992 to 2019 (Figure 2 and Table 1). Surface water temperature increased markedly during the study period, especially in May. The rate of increase in May was $0.74 \text{ }^\circ\text{C decade}^{-1}$ (Table 1). In June, increases of both atmospheric and surface water temperature were observed (air temperature: $0.40 \text{ }^\circ\text{C decade}^{-1}$; surface water temperature: $0.56 \text{ }^\circ\text{C decade}^{-1}$). The rate of increase of the surface water temperature was much greater than that of air temperature. The higher rate of increase of surface water temperature than air temperature was consistent with results of previous studies (Li *et al.* 2019), and the increase of surface water temperature in spring was also consistent with previous studies in shallow lakes in China (Li *et al.* 2019). An increase of air temperature was also observed in August, but surface water temperature did not increase significantly during that time. Many studies have analyzed the water temperature increase in summer, but our study showed the clear increases during the springtime.

Solar radiation increased in May and June by $\sim 25\%$ between 1992 and 2019 (Figure 2(c)). The reason for the increase in solar radiation could be the decrease in SPM in the atmosphere (Tanaka *et al.* 2016). The SPM concentrations decreased from

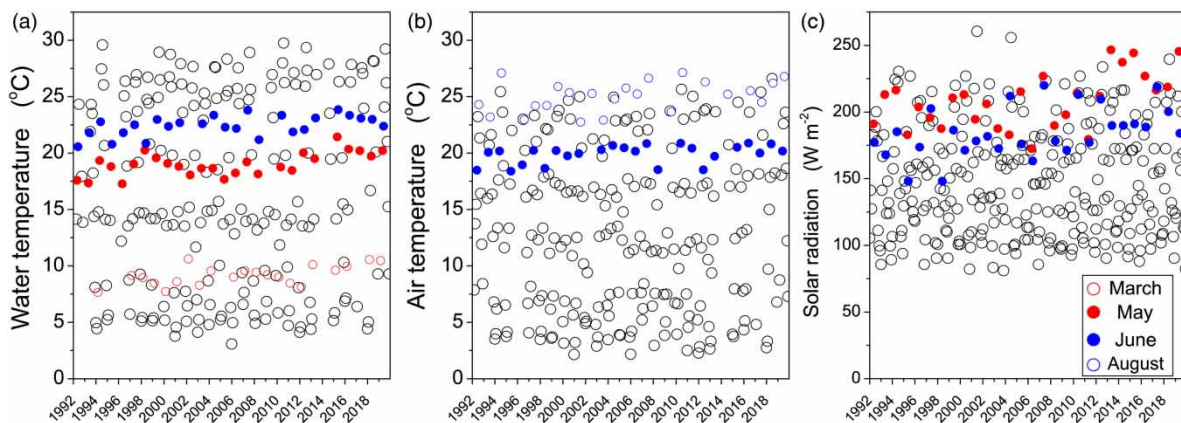


Figure 2 | Monthly water temperature (a), air temperature (b), and monthly average solar radiation (c) from 1992 to 2019. Months when there was a significant increase are indicated by colored symbols. Please refer to the online version of this paper to see this figure in colour: <http://dx.doi.10.2166/nh.2021.148>.

Table 1 | Slopes of the regression lines (Slope) and correlation coefficients (r values) between measured values and year (1992–2019) for water temperature (WT), air temperature (AT), solar radiation, humidity, and average wind speed (Wind speed)

Unit	WT		AT		Solar radiation		Humidity		Wind speed	
	$^{\circ}\text{C decade}^{-1}$		$^{\circ}\text{C decade}^{-1}$		$\text{W m}^{-2} \text{decade}^{-1}$		$\% \text{decade}^{-1}$		$\text{m s}^{-1} \text{decade}^{-1}$	
	Slope	r -value	Slope	r -value	Slope	r -value	Slope	r -value	Slope	r -value
January	-0.04	-0.03	-0.27	-0.21	3.88	0.30	-2.9	-0.49*	0.090	0.21
February	0.36	0.29	0.040	0.03	-6.12	-0.37	0.14	0.020	0.020	0.045
March	0.72	0.59**	0.45	0.32	5.54	0.32	0.39	0.055	0.040	0.10
April	0.23	0.17	-0.25	-0.18	4.39	0.18	-0.58	-0.093	0.16	0.31
May	0.74	0.59**	0.45	0.40	13.1	0.52**	-2.0	-0.56**	-0.010	-0.025
June	0.56	0.53**	0.40	0.41*	11.0	0.48**	-0.68	-0.22	0.070	0.16
July	0.72	0.37	0.71	0.38	6.10	0.15	-0.18	-0.048	0.070	0.13
August	0.64	0.37	0.68	0.42*	0.66	0.021	-0.18	-0.047	0.090	0.15
September	0.42	0.25	0.35	0.22	3.00	0.16	-1.2	-0.34	-0.050	-0.093
October	0.42	0.41	0.39	0.36	-1.10	-0.070	-0.74	-0.21	0.31	0.55*
November	0.39	0.31	0.09	0.083	-0.12	-0.009	-1.5	-0.31	0.018	0.35
December	0.44	0.30	-0.02	-0.014	-0.91	-0.089	-1.2	-0.20	0.006	0.16

The symbols '***' indicate a significance (p -value) less than 0.01, and '**' indicates a significance (p -value) less than 0.05. The bold means the significant relationships between measured values and year.

1995 to 2019 (Figure 3(a)). There was a negative correlation between solar radiation and SPM concentrations in the atmosphere during spring (Figure 3; in May and June: $r = -0.56$, $p < 0.01$). This correlation is consistent with previous studies that have shown that a decrease of aerosol concentrations can increase the flux of solar radiation to Earth's surface around the world (Tanaka *et al.* 2016).

Changes in wind velocity were observed only in October (Table 1); wind velocity can be changed by global warming and urbanization (Shen *et al.* 2019). In the Kanto Plain of Japan, where Lake Kasumigaura is located, land-sea breezes, which are dominant from spring to autumn (Yoshikado 2013), affect water quality in the area (Shinohara & Isobe 2010, 2012). The other factors that affect the heat flux through the water surface changed only a little from 1992 to 2019. The precipitation and humidity during each month exhibited no significant increase during that time.

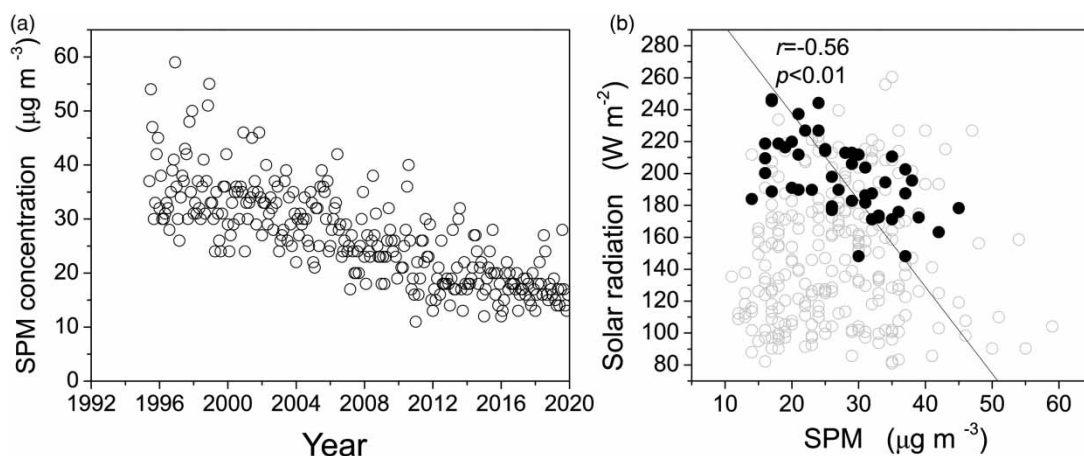


Figure 3 | Timeseries fluctuations of monthly average SPM concentrations in the atmosphere from 1992 to 2020 (a). The relationship between monthly average SPM concentration in the atmosphere and solar radiation observed at Tsukuba from 1995 to 2019 (b). Filled circles in panel (b) are the data observed in May and June. The open circles indicate data collected during months other than May and June. The data were collected at the Air Quality Research Station of the National Institute for Environmental Studies in Tsukuba (Figure 1).

3.2. Heat fluxes and sensitivity analyses

The surface energy flux was calculated (Figure 4); the calculated values were comparable to those in the previous Lake Kasumigaura report (Masunaga & Komuro 2019). We also verified the downward longwave radiation flux with that observed at Tsukuba (Figure 5). The high correlation coefficient ($r = 0.91$, $p < 0.001$) and the slope of the regression line (slope = 1.0) suggested that the simulated values were realistic.

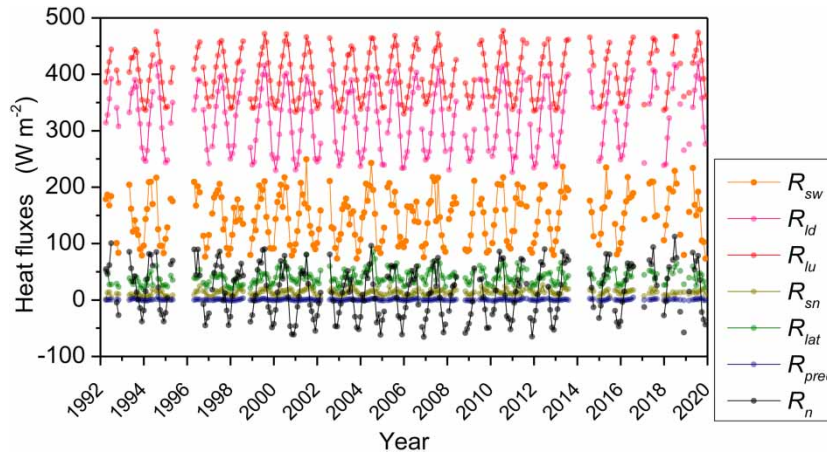


Figure 4 | Observed heat fluxes at the water surface. The fluxes include shortwave radiation (R_{sw}), downward longwave radiation (R_{ld}), upward longwave radiation (R_{lu}), sensible heat flux (R_{sn}), latent heat flux (R_{lat}), heat flux by rainfall (R_{prec}), and net heat flux (R_n).

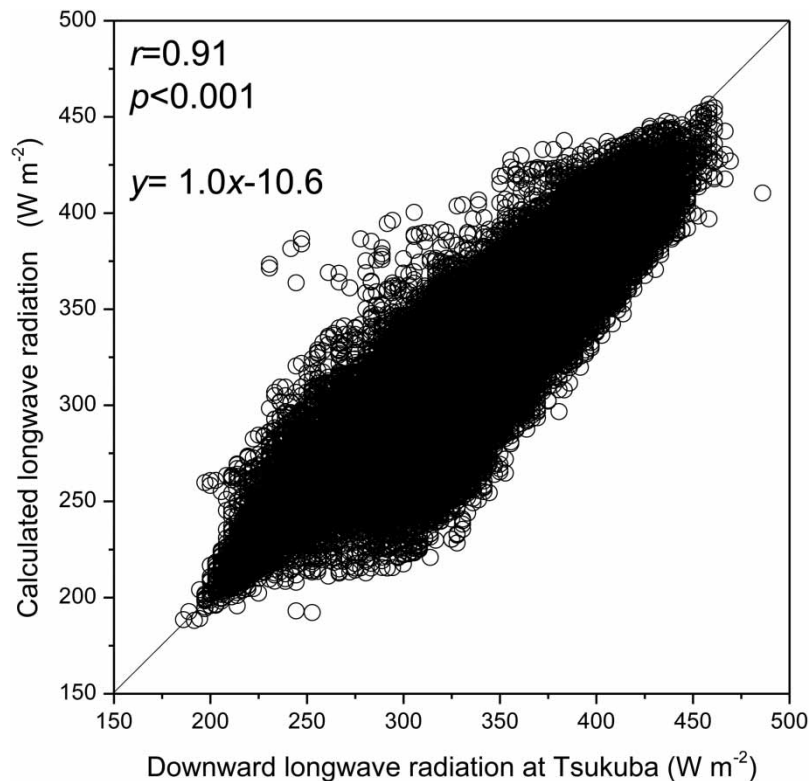


Figure 5 | Observed and calculated downward fluxes of longwave radiation. The observed longwave radiation flux was collected hourly in Tsukuba. The data were downloaded from the website of the JMA. The solid line indicates 1:1 line between the measured and calculated values.

To determine whether surface water temperature was more sensitive to changes in solar radiation or air temperature, we calculated the effects of solar radiation and air temperature on R_n values at the lake surface (Tables 2 and 3). The initial air temperatures and solar radiation fluxes are shown in Figure 6(a) and 6(b).

Because the mean values of air temperature and solar radiation during January and June were the expected values on the regression line (Supplementary Material, Figure S1), the values of 2000 were set to the default value for the analyses of their sensitivities on net heat flux (R_n). The magnitudes of the increase in solar radiation and air temperature were determined by the slope of the regression lines: air temperature was set to a value between 10.4 °C (−2.0% from the default value in 2000) and 11.1 °C (+4.0% from the default value in 2000). Similarly, the flux of solar radiation was set to a value between 164 W m^{−2} (−3.0%) and 183 W m^{−2} (+8.0%).

Increases of air temperature were associated with increases of downward longwave radiation (~1.0%), sensible heat flux (~28.6%), latent heat flux (~3.1%), precipitation (~92.0%), and R_n values (31.1%). Increases of solar radiation affected the net heat flux (R_n), which increased from the default value by 88.4%. Surface water temperature at the lake surface was therefore more sensitive to increases of solar radiation. The greater sensitivity of surface water temperature to the increase of solar radiation was consistent with the conclusion of a previous study of temperate lakes (Li *et al.* 2019). The increase of solar radiation has been observed globally (Wild 2009) and has been associated with an increase in the volume of hypoxic water in coastal areas (Tanaka *et al.* 2014).

3.3. Heat fluxes other than fluxes through the lake surface: uncertainties and limitations

There are heat fluxes other than those through the water surface, such as heat fluxes associated with river/groundwater inflow and the heat flux through the bottom (Chikita *et al.* 2019; Masunaga & Komuro 2019; Sugita *et al.* 2020). The values of these heat fluxes were unknown at the time of this study. The heat flux through the bottom sediment can be calculated with the following equation (Hipsey *et al.* 2019):

$$R_G = K_{\text{sed}} \frac{T_w - T_{\text{sed}}}{\delta z} \quad (14)$$

Table 2 | Parameters used in the sensitivity analysis

	Default	Minimum	Maximum	Slope (decade ^{−1})
Air temperature (°C)	10.6	10.4 (−2.0%)	11.1 (+4.0%)	0.21
Solar radiation (W m ^{−2})	169	164 (−3.0%)	183 (+8.0%)	5.3

The default value was the value in 2000. The rates of increase or decrease are shown in parentheses. The slope (decade^{−1}) means the slope of the regression line of mean air temperature/solar radiation during January and June vs. year (Supplementary Material, Figure S1).

Table 3 | Results of sensitivity analyses

	R_{sw} (W m ^{−2})	R_{ld} (W m ^{−2})	R_{lu} (W m ^{−2})	R_{sn} (W m ^{−2})	R_{lat} (W m ^{−2})	R_{prec} (W m ^{−2})	R_n (W m ^{−2})
Default	161	288	−378	−10.3	−45.0	−0.11	14.5
AT − 2%	161	286	−378	−11.8	−44.3	−0.16	12.3
AT + 4%	161	291	−378	−7.4	−46.3	−0.01	19.0
SR − 3%	156	288	−378	−10.3	−45.0	−0.11	9.7
SR + 8%	173	288	−378	−10.3	−45.0	−0.11	27.4
Sensitivity (%)							
AT − 2%	0.0	0.5	0.0	14.4	1.5	46.0	15.6
AT + 4%	0.0	1.0	0.0	28.6	3.1	92.0	31.1
SR − 3%	3.0	0.0	0.0	0.0	0.0	0.0	33.1
SR + 8%	8.0	0.0	0.0	0.0	0.0	0.0	88.4

Rates of heat flux (W m^{−2}) are shown for shortwave radiation (R_s), downward longwave radiation (R_{ld}), upward longwave radiation (R_{lu}), latent heat flux (R_{lat}), sensible heat flux (R_{sn}), and net heat fluxes (R_n). The rate of change (%) of heat fluxes (R_n) is also shown.

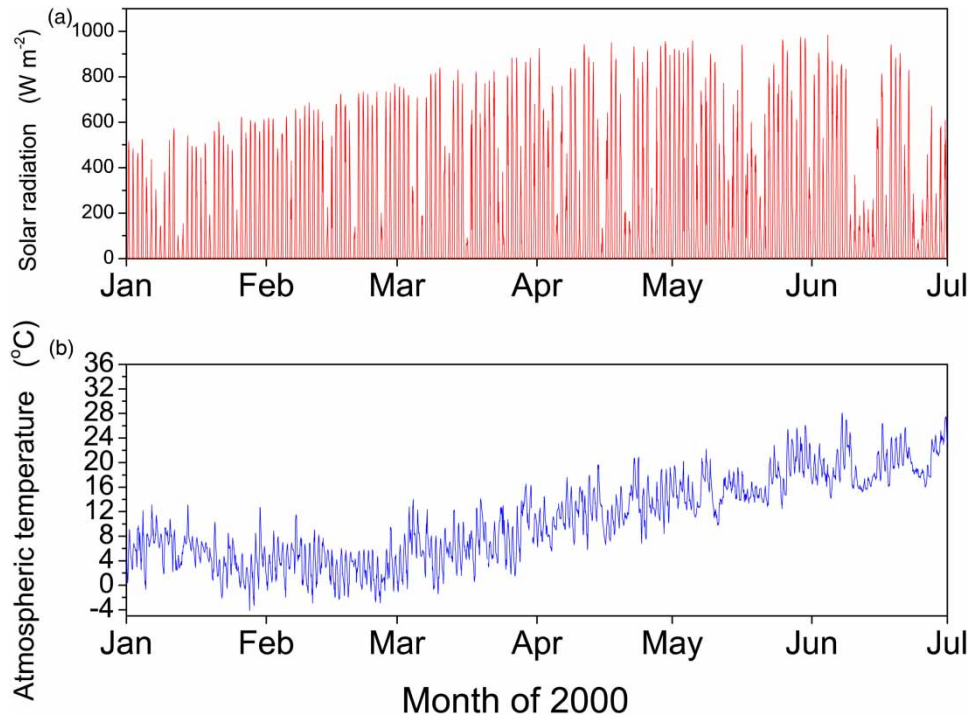


Figure 6 | The conditions used for the sensitivity analysis. Solar radiation (a) and air temperature (b) in 2000 were the default conditions.

where R_G is the heat flux through the bottom sediment (W m^{-2}), K_{sed} is the thermal conductivity of sediment ($=0.25 \text{ W m}^{-1} \text{ K}^{-1}$), T_w is the surface water temperature (K), T_{sed} is the sediment temperature (K), and δz is the thickness of the sediment (m). Our observations involved monitoring water and sediment temperature monthly (Shinohara *et al.* 2017). Based on the temperatures of the water and sediment at 0.0 m and 1.5 cm, we estimated the heat flux between the water and bottom sediment to be in the range of -4.0 to 8.0 W m^{-2} .

The temperature of the groundwater was unknown during the current study. However, in the case of Lake Kasumigaura, groundwater seepage is only 10% of river inflow (Nakayama & Watanabe 2008). We have no information about the temperature of the inflowing river water, but the inflow of river water undergoes seasonal variations (Supplementary Material, Figure S2). The inflow from the closest river (the Ono River; see Figure 1) during May and October ($3.5 \times 10^7 \text{ m}^3$) was 1.3 times the inflow during November and April ($4.5 \times 10^7 \text{ m}^3$) in 2017. However, because the water retention time in Lake Kasumigaura is ~ 200 days and the level of the water surface of Lake Kasumigaura is controlled artificially, the heat flux associated with river inflow should be small. Sugita *et al.* (2020) have estimated that the net heat flux associated with river inflow/outflow is $\sim 3 \text{ W m}^{-2}$. Further detailed monitoring of heat fluxes associated with the heat stored in the sediment and inflows of groundwater and river water are needed to more accurately estimate the heat flux of Lake Kasumigaura.

The recent increase of cyanobacteria during the spring in Lake Kasumigaura could have resulted from the increase in solar radiation because photosynthetically active radiation controls the abundance of cyanobacteria in Lake Kasumigaura (Tomioka *et al.* 2011). Many studies have analyzed the effects of increases of surface water temperature on lake ecosystems (Czerniecki & Ptak 2018), but more attention should be paid to light effects during the springtime. For example, the increase of solar radiation could accelerate the photolysis of organic matter and thereby affect water chemistry (Zhang *et al.* 2019). Both increases and decreases of solar radiation have been observed globally and in Japan (Tanaka *et al.* 2016). Because aerosol concentrations are expected to decrease in the future (Goto *et al.* 2016), solar radiation reaching Earth's surface will increase to the extent.

4. CONCLUSIONS

We have monitored surface water temperature and meteorological conditions as part of a study of Lake Kasumigaura during the past 28 years. Surface water temperature increased, during the springtime, in May and June by $0.74 \text{ }^\circ\text{C}$ and $0.56 \text{ }^\circ\text{C decade}^{-1}$,

respectively. In May, the increase of surface water temperature was significant, but the change of air temperature was not. The rate of increase of water temperature in June ($0.40\text{ }^{\circ}\text{C decade}^{-1}$) exceeded that of air temperature. Solar radiation also clearly increased in May and June presumably because of the decrease in SPM as given the significant negative correlation between the concentrations of SPM and solar radiation. The result is consistent with Tanaka *et al.* (2016) that the brightening and dimming of solar radiation in Japan are caused by aerosols. A sensitivity analysis of changes in air temperature and solar radiation indicated that increases of solar radiation affected surface heat fluxes more than increases of air temperature. We observed increases in downward longwave radiation, precipitation, and sensible heat fluxes associated with the increase of air temperature. However, the impact of the increase of air temperature on the net heat flux (R_n) at the lake surface was smaller than the effect of the increase in solar radiation. If aerosols contribute to solar radiation, further investigation is needed to identify the future changes in the concentration of aerosols and the effects on heat flux on the lake surface including the seasonalities.

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AUTHORS' CONTRIBUTIONS

R.S. conducted a research and investigation process, wrote, reviewed and edited the manuscript. Y.T. and A.K. involved in data analysis and commentary. K.M. collected data and maintained meteorological devices and data analysis.

DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories (<http://www.cger.nies.go.jp/db/kasumi/index.html>).

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