TREND ANALYSIS OF LONG-TERM CHANGE IN ANNUAL MEAN EQUILIBRIUM WATER TEMPERATURE IN JAPAN

BY MANN-KENDALL TEST

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This paper analyzed the trend in long-term change in annual mean equilibrium water temperatures and air temperatures all over Japan for 50 years (1963–2012), and investigated their regional characteristics. To analyze the time series data of the temperatures, Mann-Kendall test was used to statistically detect the trend and Sen’s slope was used to quantitatively evaluate its significance. The results showed that a tendency for temperature to rise in the equilibrium water temperature was common in the coastal part of the Pacific Ocean in the western part from the Kanto region. In these areas, a positive correlation was found in the rising tendency between the equilibrium water temperature and the air temperature. Furthermore, a trend towards lowering of temperature in the equilibrium water temperature was detected more often in the northern part of Tohoku and Kyushu regions as well as the coastal part of the Sea of Japan. In these areas, there was a negative correlation between the equilibrium water temperature and the air temperature.

\textbf{Key Words:} river environment, equilibrium water temperature, climate change, air temperature, trend analysis, and Mann-Kendall test

1. INTRODUCTION

Global climate change causes air temperature rise and precipitation change, resulting in great influences on river environments.\textsuperscript{1,2} River water temperature is one of the important indicators for proper aquatic environmental management, and such water temperature changes in rivers are largely affected by human activities. For example, the influx of sewerage drainage in the city increases the river water temperature and has an adverse effect on aquatic organisms, such as fish.\textsuperscript{2} Also, cold water discharge from dam reservoirs leads to poor growth of crops in irrigation usage. Therefore, in order to achieve sustainable human activities while preserving an appropriate balance in river ecosystems, it would be of great importance to understand the factors affecting change in river water temperature from a long-term/wide-area perspective and to adapt to the influence of global climate change as well.

Factors that affect river water temperature primarily include solar and terrestrial radiations. At the same time, there are many other important factors, e.g., the advection heat fluxes from upstream river water, groundwater and spring water, riverbed heat transfer, the surrounding riparian topography, and so forth. Therefore, it is necessary to devise measures to uniformly understand the river water temperature formation all over the rivers in Japan from a long-term / wide-area perspective. This paper chose the equilibrium water temperature\textsuperscript{3,4} as an alternative index of the river water temperature, and tried to analyze its long-term trend throughout Japan. Equilibrium water temperature is defined as that state when the atmosphere and river water are in a thermal equilibrium through the water surface thermal exchanges. There have been many studies on equilibrium water temperature,\textsuperscript{5,6} stating that, in general, the annual mean river water temperature could approach the annual mean equilibrium water temperature in the downstream section of rivers.\textsuperscript{6} However, few studies have examined long-term temporal changes in equilibrium water temperature and its regional distribution characteristics in Japan. In the preliminary study,\textsuperscript{7} the authors had attempted to analyze the trend in equilibrium water temperature using regression analysis;
however, the statistical significance of the result was relatively smaller than expected.

This paper examined the trend in long-term change in annual mean equilibrium water temperatures all over Japan for the past 50 years from 1963 to 2012. As for the trend analysis of time series data, the Mann-Kendall test, which is one of the nonparametric methods, was adopted instead of the regression analysis used in the previous study. Also, the trend in air temperature time series was examined in the same manner, discussing the correlation between the equilibrium water temperature and air temperature, and their regional distribution characteristics in Japan.

2. METEOROLOGICAL DATA TO BE ANALYZED

The 156 meteorological stations in Japan have the meteorological data necessary for calculating equilibrium water temperature. Excluding several stations in small islands, the calculation used the data at the 132 points indicated in Fig. 1. This paper depicted all the maps of Japan without the small islands. The period analyzed was 50 years from January 1, 1963 to December 31, 2012. In this paper, the meteorological data necessary for calculating equilibrium water temperature were the latitude, altitude, air temperature, ground-level air pressure, relative humidity, wind speed, and sunshine duration from the website of the Japan Meteorological Agency. A missing part found in the data was replaced by the mean values of the preceding and the following ones if the missing element was small enough for the calculation.

3. METHODS

1) Equilibrium water temperature

The equilibrium water temperature $T_{eq}$ was calculated from the following heat balance equation on the river water surface:

$$H_s - H_{sr} + H_a - H_{ar} - H_{br}(T_{eq}) - H_{se}(T_{eq}) - H_{la}(T_{eq}) = 0,$$

(1)

where, $H_s$: short wave radiation, $H_{sr}$: short wave reflection, $H_a$: long wave radiation, $H_{ar}$: long wave reflection, $H_{br}$: long wave upward radiation from water, $H_{se}$: sensible heat flux, and $H_{la}$: latent heat flux. This paper, at first, calculated daily mean equilibrium water temperatures by using Eq.(1) with the meteorological data all over Japan. Then, it obtained the annual mean equilibrium water temperature by averaging them. It should be noted that the daily average equilibrium water temperature might be calculated as a negative value in calculation. In this case, the temperature was corrected to 0°C since water temperature did not fall below the freezing point. The model equations in each term in Eq.(1) are explained in the following subsections.

a) Short wave radiation $H_s$ and short wave reflection $H_{sr}$

The daily mean short wave radiation $H_s$ and its reflection $H_{sr}$ were calculated by the following empirical equation with the sunshine hour $N$:

$$H_s = \left[ a + b \frac{N + \Delta N}{N_0} \right] I_{0d}, \quad \left( 0 < \frac{N}{N_0} \leq 1 \right)$$

$$= c, \quad \left( \frac{N}{N_0} = 0 \right),$$

(2)

$$H_{sr} = \gamma_{sr} H_s,$$

(3)

where, $I_{0d}$: daily mean solar radiation on the horizontal surface at the top of the atmosphere, $N_0$: possible duration of daylight, $(a, b, c, \Delta N)$: model constants (0.244, 0.511, 0.118, 0), and $\gamma_{sr}$: albedo for the short wave radiation.

b) Long wave radiation $H_a$, long wave reflection $H_{ar}$, and long wave upward radiation $H_{br}$

The long wave radiation $H_a$, its reflection $H_{ar}$, and the long wave upward radiation from water $H_{br}$ were calculated by the following equations:

$$H_a = \sigma \Theta_a (c_a - d_a \sqrt{e_a}),$$

(4)

$$e_a(T) = \exp \left[ a_e \left( \frac{b_e T}{T + c_e} + d_e \right) \right],$$

(5)

$$H_{ar} = \gamma_{ar} H_a,$$

(6)

$$H_{br} = S_{br} \sigma \Theta_w^4,$$

(7)

where, $\sigma$: Stefan-Boltzmann constant, $\Theta_a$: absolute air temperature, $(c_a, d_a)$: model constants (0.44, 0.081), $e_a$: atmospheric water vapor pressure, $T$: temperature in Celsius, $(a_e, b_e, c_e, d_e)$: model constants (2.303, 7.5, 237.3, 0.7858), $\gamma_{ar}$: albedo for
the short wave radiation, $H_{br}$: emission ratio, and $\Theta_w$: absolute temperature of water.

c) Sensible heat flux $H_{se}$ and latent heat flux $H_{la}$

The sensible heat flux $H_{se}$ and latent heat flux $H_{la}$ were calculated by the following bulk equations:\(^{(10)}\)

$$
H_{se} = \rho_a c_p C_c (T_w - T_a) W, \\
H_{la} = \rho_a L_{va} C_l \frac{0.622}{\rho} (e_w - e_a) W,
$$

where, $\rho_a$: air density, $c_p$: specific heat at the constant air pressure, $C_c$: sensible heat transport coefficient, $W$: wind speed, $L_{va}$: vaporization heat, $C_l$: water vapor transport coefficient, $\rho$: atmospheric pressure, and $(e_w, e_a)$: water vapor pressures at the water surface and in the air.

(2) Mann-Kendall test

Hydrological and meteorological data could be random due to the influence of the weather. Their occurrence probability does not always follow a normal distribution. Therefore, this paper used the Mann-Kendall test\(^{(8)}\) for the time series analysis of equilibrium water temperature, which is one of the nonparametric methods.

Mann-Kendall test examines whether a null hypothesis $H_0$ holds or not, where the null hypothesis in $H_0$ states that “data ($x_1, x_2, \ldots, x_n$) in a time series are statistically independent and in the same probability distribution.” If the null hypothesis $H_0$ is rejected, then the time series has a trend in a statistical manner. In the Mann-Kendall test, the statistic $S$ is defined in Eqs. (10) and (11).

$$
S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \text{sgn}(x_j - x_k),
$$

$$
\text{sgn}(x) = \begin{cases} 
1, & (x > 0) \\
0, & (x = 0), \\
-1, & (x < 0)
\end{cases}
$$

The mean $E[S]$ and variance $\text{Var}[S]$ of the statistic $S$ are given in Eqs. (12) and (13).

$$
E[S] = 0,
$$

$$
\text{Var}[S] = \frac{1}{18} \left[ n(n - 1)(2n + 5) - \sum_{j=1}^{k} t_j (t_j - 1)(2t_j + 5) \right],
$$

where, $t_j$ denotes the $j$-th total count of consecutive same-values in the time-series data sorted in ascending order, and $k$ indicates the maximum number of the $j$. The statistic $S$ is then normalized as follows:

$$
Z = \begin{cases} 
\frac{S - \text{sgn}[S]}{\sqrt{\text{Var}[S]}}, & (S > 0) \\
0, & (S = 0), \\
\frac{S + \text{sgn}[S]}{\sqrt{\text{Var}[S]}}, & (S < 0)
\end{cases}
$$

This paper assumed that the normalized statistic $Z$ followed a normal distribution since the number $n$ of the time series data was 50, and was statistically large enough ($n > 10$) for the Mann-Kendall test. If the $|Z| > Z_{\alpha/2}$ was satisfied with a significance level $\alpha$, then the null hypothesis $H_0$ was rejected. The result showed that the time series could statistically have a trend. This paper set the significance level $\alpha$ of 5%.

When the time series statistically had a trend, its slope was estimated by the Sen’s slope $\beta$\(^{(12)}\) in Eq. (15).

$$
\beta = \text{Median} \left( \frac{x_i - x_j}{i - j} \right), \quad \forall j < i.
$$

The time series has a rising trend when $\beta > 0$, while a falling trend when $\beta < 0$. In this paper, the Sen’s slope indicated the amount of change per year as the annual mean values were analyzed both in equilibrium water temperature and air temperature. In the next chapter, the Sen’s slope was converted to the value per 100 years.

(3) Sen’s slope ratio

Rivers are always in contact with the atmosphere on the water surface, through which energy exchange between rivers and the atmosphere significantly affects the formation of river water temperature. Consequently, the time series trend in river water temperature could have a correlation with that in air temperature. Therefore, this paper analyzed not only equilibrium water temperature but also air temperature as well. The former was an alternative index of river water temperature, while the latter was one of the meteorological data for calculating the equilibrium water temperature. This paper defined Sen’s slope ratio in Eq. (16) as an index for discussing their relationship and regional characteristics in Japan.

$$
R_s = \frac{\beta_{eq}}{\beta_{air}}.
$$

where, $\beta_{eq}$ denotes the Sen’s slope of the equilibrium water temperature, and $\beta_{air}$ does that of the air temperature. The Sen’s slope ratio was calculated only in the locations where statistical trends were detected both in the equilibrium water temperature and air temperature.
4. RESULTS AND DISCUSSION

(1) Long-term trend in the equilibrium water temperature and air temperature at several locations

Table 1 indicates the results of the Mann-Kendall test for the equilibrium water temperature and air temperature at the four locations with different latitudes (i.e., Tokyo, Osaka, Sapporo, and Kagoshima). Here, the values of Sen’s slope appear in the cases where the Mann-Kendall test detected trends with a significance level of 5%. Figs. 2 and 3 show the time series of the annual means in equilibrium water temperature and air temperature, respectively, which were used in the Mann-Kendall test of Table 1. Besides, the figures include the regression lines for the time series data.

|         | Tokyo      | Osaka      | Sapporo    | Kagoshima |
|---------|------------|------------|------------|------------|
| $T_{eq}$ | 2.10*      | 2.75*      | No trend   | No trend   |
| $T_{air}$| 3.41*      | 3.21*      | 3.39*      | 4.30*      |

Table 1: Sen’s slopes of equilibrium water temperature and air temperature at four locations.

$T_{eq}$: equilibrium water temperature, $T_{air}$: air temperature

*statistical significance level of 5% (1.960)

Fig. 2 Time series of equilibrium water temperatures at the locations in Table 1.

Fig. 3 Time series of air temperatures at the locations in Table 1.

(2) Long-term trend in the equilibrium water temperature and air temperature all over Japan

The trends in the time series of equilibrium water temperature and air temperature all over Japan were analyzed by the Mann-Kendall test. Figs. 4 and 5 show the Sen’s slope distributions obtained at the locations where the trend was statistically detected. The colors in Figs. 4 and 5 denote the ranges of Sen’s slope that were classified by cluster analysis.

As for the equilibrium water temperature shown in Fig. 4, the trend detection rate of the Mann-Kendall test was 38% of the total 132 locations. Twenty-nine percent of them had rising trends (plots in warm colors or black), while the remaining 7% had falling trends (plots in cool colors).

Fig. 4 reveals that many locations having the rising trends existed in the Kanto region and the Pacific coastal region west of the Kanto region. In particular, more significant rising trends appeared in the metropolitan areas of the Chubu and Kinki regions (i.e., the cities of Yokkaichi and Kobe). These results indicated that the heat island phenomenon would influence the rising trends in addition to the effect of the global warming since there were many urban cities along with the Pacific coast (in particular, the Tokaido region). Furthermore, the rising trends also appeared in the inland area of Kanto and Chubu regions, e.g., the city of Karuizawa, which was indicated in the red plot in the central part of the Japanese main island. This result supported the fact that the locations in higher altitudes could also have rising trends in the
vealing the physical mechanism of the falling trends remains a future work because meteorological factors other than the air temperature should be investigated in detail.

As for the air temperature shown in Fig. 5, the trend detection rate of the Mann-Kendall test was almost 100% of the 132 locations, excluding the city of Miyako in the Iwate Prefecture and the city of Takamatsu in the Kagawa Prefecture. All of the detected locations had rising trends, unlike the trends in equilibrium water temperature. It showed that the rising trend identified by the Mann-Kendall test was nationwide. This result strongly supported the fact that the effect of global warming existed as a fundamental cause of the rising trend in addition to the local effects, such as the heat island phenomenon and of geographical factors in mountainous and plain areas.

The average of all the Sen’s slopes for air temperature detected by the Mann-Kendall test was 2.66 (°C / 100 years). On the other hand, the trend in air temperature in Japan estimated by the Japan Meteorological Agency\(^{14}\) was 2.41 (°C / 100 years) for the period analyzed in this paper between 1963 and 2012. Here, the Agency’s calculation included just 15 meteorological stations that were less influenced by urbanization. Thus, the difference would be due mainly to the air temperature rise by urbanization besides the difference in the analytic methods. The average of Sen’s slopes became 2.37 (°C / 100 years) when the calculation confined the 13 locations that matched those in the Japan Meteorological Agency’s estimate. This average was almost the same as that by the Japan Meteorological Agency, confirming the validity of the analysis of this paper. Furthermore, these averages were much larger than the rising trend of 1.19 (°C / 100 years) in Japan for the past 119 years between 1898 and 2016 calculated by the Japan Meteorological Agency.\(^{14}\) This result would support the acceleration of the rising trend in the second-half of the 20th century due to global warming.

(3) Trend comparison between equilibrium water temperature and air temperature

Fig. 6 shows the relationship between the trend in equilibrium water temperature and that in air temperature. Fig. 7 shows the distribution of the Sen’s slope ratio \(R_s\). The plots shown in both figures were categorized and colored by three absolute values of Sen’s slope ratio \(R_s\), i.e., 0.5, 1.0, and 2.0 for discussion.

When the Sen’s slope ratio was \(R_s > 0\), there was a positive correlation between the trend in equilibrium water temperature and that in air temperature. It corresponded to the plots in warm colors shown in Figs. 6 and 7. In this case, the range \(0.5 < R_s < 1\) was predominant in number, i.e., about half of the plots were included in this range. It can be inferred
On the other hand, when the Sen’s slope ratio was $R_s < 0$, there was a negative correlation between the trend in equilibrium water temperature and that in air temperature. It corresponded to the plots in cool colors shown in Figs. 6 and 7. These plots were consistent with the locations having the falling trends in Fig. 4. Therefore, a negative correlation would result from a thermal imbalance on the water surface in which the cooling effect due to the latent and sensible heat transfers surpassed the warming effect due to the air temperature rise. In other words, the trends in equilibrium water temperature at these locations would be less susceptible to the air temperature rise due to global warming. It will be up to a future research work to reveal which meteorological factors other than the air temperature suppress the rising trend in equilibrium water temperature by examining their long-term trends in detail.

5. CONCLUSIONS

This paper analyzed the trend in long-term change in annual mean equilibrium water temperatures and air temperatures by using the Mann-Kendall test.

A rising trend in the equilibrium water temperatures was detected in the Kanto region and westward along the Pacific Coast. More significant trends, in particular, arose in the metropolitan areas of the Chubu and Kinki regions. Among many locations characterized by a rising trend where the Sen’s slope in equilibrium water temperature was slightly smaller than that in air temperature, there was a strong positive correlation between air temperature and equilibrium water temperature. Therefore, the air temperature in these locations would have a strong influence on the rising trend of equilibrium water temperature.

On the other hand, a falling trend in equilibrium water temperature was detected in the Tohoku and northern Kyushu regions, and the Sea of Japan coast. These locations showed a negative correlation in the long-term trend between the equilibrium water temperature and air temperature. It would result from a thermal imbalance on the water surface where the cooling effect due to the latent and sensible heat transfers surpassed the warming effect due to the air temperature rise.

Several future works remain in this research. One of them will be to reveal which meteorological factors, e.g., wind and humidity that could be predominant in coastal areas, will suppress the rising trend in equilibrium water temperature. It is also important to have a seasonal analysis of long-term change in equilibrium water temperature in order to examine the effect of climate change in more detail. Moreover, using equilibrium water temperature as an alternative to river water temperature will be checked in terms
of its effectiveness for the long-term trend analysis of the thermal environment in a river stream.

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