STATISTICAL ANALYSIS OF DECADAL WARMING AND COOLING TRENDS IN EQUILIBRIUM WATER TEMPERATURE IN JAPAN

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ABSTRACT

In this paper, the seasonal trend of decadal change in equilibrium water temperature was examined in Japan for the recent 50 years from 1963 to 2012. For the time-series data in equilibrium water temperature, the statistical analysis used the Mann-Kendall test to detect a warming or cooling trend, and the Sen's slope to evaluate its quantitative values. The results showed that there were both warming and cooling trends in the decadal changes in the equilibrium water temperature. As for their regional distribution characteristics, the warming trend was evident in the coastal part of the Pacific Ocean in Japan. Both the global warming and urban heat island phenomenon could have had effects on this coastal part. On the other hand, the cooling trend was detected in the northern part, i.e., the Tohoku region and the southern part, north Kyushu region, as well as the coastal part of the Sea of Japan. These parts indicated a strong tendency on either a decrease in short wave radiation or an increase in latent heat transfers in the spring and summer seasons.

Keywords: Water Temperature, Trend Analysis, Global Warming, Seasonality, and Mann-Kendall Test

1. INTRODUCTION

Global climate change has been causing air temperature rise and precipitation change, resulting in great influences on river environments (Caissie, 2006; Cooper et al., 2013). Water temperature is one of the important indices for aquatic environmental management, and its changes in rivers and lakes are largely affected from human activities. For example, the influx of sewerage drainage into cities increases the river temperature (e.g., Xin and Kinouchi, 2013), and has an adverse effect on aquatic organisms such as invertebrates and fish. Also, cold water discharge from dam reservoirs leads to poor growth of crops in irrigation usage. Therefore, in order to achieve sustainable development in human activities while preserving an appropriate balance of river ecosystems, it would be of great importance to grasp predominant factors of change in river temperature from a long-term/wide-area perspective, and to adapt to the influence of global climate change as well.

While factors that form river water temperature primarily include solar and terrestrial radiations, there are many other important factors, i.e., the advection heat fluxes from upstream river water, groundwater and spring water, riverbed heat transfer, the surrounding riparian topography, forest trees, and so forth. Therefore, it is necessary to devise measures to uniformly understand the river water temperature formation all over Japan from a long-term/wide-area perspective. This study chose the equilibrium water temperature (Edinger et al., 1968) as an alternative index of the river water temperature, and tried to analyze its long-term trend throughout Japan. Here, the equilibrium water temperature is defined by the temperature when the atmosphere and river water are in a thermal equilibrium state through the water surface thermal exchanges. Generally, the annual mean river water temperature could approach the annual mean equilibrium water temperature in the downstream section of rivers without abrupt thermal input. However, few studies have examined long-term temporal changes of the seasonal equilibrium water temperature and its regional distribution characteristics in Japan.

This paper examined the decadal trends of long-term change and its main factors in the annual and seasonal equilibrium water temperatures all over Japan for recent 50 years from 1963 to 2012. As for the statistical assessment of time series data in the equilibrium water temperatures, Mann-Kendall test (Hirsch et al., 1982) was used to detect a warming or cooling trend and Sen's slope (Sen, 1968) was used to evaluate its quantitative values.

2. METHODS

2.1 Equilibrium water temperature

The equilibrium water temperature T_{eq} was calculated from the heat balance equation (1) on the water surface.

$$H_s - H_{sr} + H_a - H_{ar} - H_{br}(T_{eq}) \pm H_{se}(T_{eq}) \pm H_{la}(T_{eq}) = 0, \tag{1}$$

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 back radiation from water, H_{se}: sensible heat transfer, and H_{la}: latent heat transfer. In this paper, the annual and seasonal mean equilibrium water temperatures were obtained by averaging the daily mean equilibrium water temperatures calculated from Eq. (1) with daily data in meteorological observatories all over Japan (Japan Meteorological Agency). It should be noted that the daily average equilibrium water temperature might be calculated in a negative value in calculation. In this case the temperature was corrected to 0 °C since it does not fall below the freezing point. The model equations used to calculate each term in Eq. (1) are described below.

The daily mean short wave radiation H_s and its reflection H_{sr} were given by the following empirical equations (Kondo et al., 1991) with the sunshine hours N.

$$H_s = \left[a + b\frac{N + \Delta N}{N_0}\right] I_{0d}, \left(0 < \frac{N}{N_0} \leq 1\right), \tag{2a}$$

$$= c, \left(\frac{N}{N_0} = 0\right), \tag{2b}$$

$$H_{sr} = \gamma_{sr} H_s, \tag{3}$$

where, I_{0d}: daily mean solar radiation on the horizontal surface at the upper end of the atmosphere, N_0: possible duration of daylight, $(a, b, c, \Delta N)$: model constants (= 0.244, 0.511, 0.118, 0) (Kondo et al., 1991), and γ_{sr}: albedo for short wave radiation.

The long wave radiation H_a, its reflection H_{ar}, and the long wave back radiation from water H_{br} were given by the following equations (Kondo, 1994).

$$H_a = \sigma \Theta_a{}^4 (c_a - d_a\sqrt{e_a}), \tag{4}$$

$$e_a(T) = exp\left[a_e\left(\frac{b_e T}{T + c_e} + d_e\right)\right], \tag{5}$$

$$H_{ar} = \gamma_{ar} H_a, \tag{6}$$

$$H_{br} = S_{br}\sigma\Theta_w{}^4, \tag{7}$$

where, σ: Stefan-Boltzmann constant, Θ_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), γ_{ar}: albedo for short wave radiation, S_{br}: emission ratio, and Θ_w: absolute water temperature.

The sensible heat transfer H_{se} and latent heat transfer H_{la} were calculated by using the following empirical bulk equations (Kondo, 1994).

$$H_{se} = \rho_a c_p C_c (T_w - T_a) W, \tag{8}$$

$$H_{la} = \rho_a L_{la} C_E \frac{0.622}{p} (e_w - e_a) W, \tag{9}$$

where, ρ_a: air density, c_p: specific heat at constant air pressure, C_c: sensible heat transfer coefficient, W: wind speed, L_{la}: vaporization heat, C_E: water vapor transfer coefficient, p: atmospheric pressure, and (e_w, e_a): water vapor pressures at water surface and in the air, respectively.

2.2 Mann-Kendall test

In this study, Mann-Kendall test (Hirsch et al., 1982) was used as a non-parametric test, to detect a warming or cooling trend in the time series of the equilibrium water temperatures since the occurrence probability of hydrologic data such as river water temperature does not always follow the normal distribution. The null hypothesis for the test is that there is no monotonic trend in the time series. When the null hypothesis is rejected by the significance level α, a trend does exist. This paper used the significance level $\alpha = 5\%$. Then, Sen's slope (Sen, 1968) in Eq. (10) was used to calculate the quantitative values of the trend.

$$\beta = Median\left(\frac{x_i - x_j}{i - j}\right), \quad \forall j < i, \tag{10}$$

where, x_i represents a hydrologic value in i-th order of the time series.

3. DATA TO BE ANALYZED

Figure 1 indicates the 132 locations in Japan where were analyzed by the Mann-Kendall test (Hirsch et al., 1982). The test period was 50 years from January 1, 1963 to December 31, 2012. The meteorological data necessary to calculate the equilibrium water temperature were the latitude, air temperature, ground pressure, relative humidity, wind speed, and daylight time. These meteorological data were downloaded from Japan Meteorological Agency.
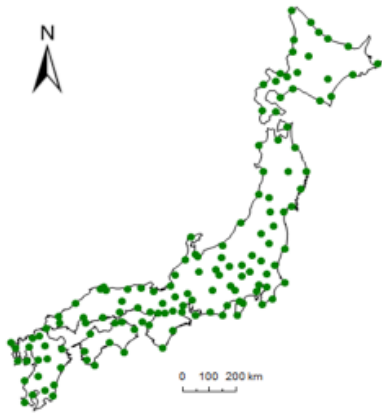

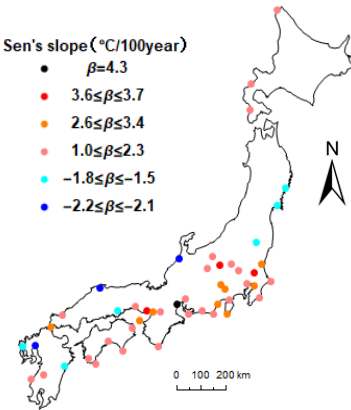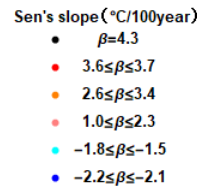Figure 1. The locations to be analyzed in Japan (132 points).

Figure 2. Sen's slope distribution of the annual mean equilibrium water temperature in Japan.

4. RESULTS AND DISCUSSION

4.1 Annual mean equilibrium water temperature

Figure 2 showed the spatial distribution of Sen's slopes obtained at the locations where the trend was statistically detected for annual mean equilibrium water temperature. The trend detection rate of the Mann-Kendall test was 38% of the total 132 locations. The 29% of them had warming trends (plots in warm colors or black), while the remaining 7% had cooling trends (plots in cool colors).

Figure 2 indicated that many locations having the warming trends existed in the Kanto region and the Pacific coastal region west of the Kanto region. These results inferred that the heat island phenomenon would influence the warming trends in addition to the effect of the global warming since there were many urban cities along with the Pacific coast. Furthermore, the warming trends also appeared in the inland area of Kanto and Chubu regions, which were indicated in the red plot in the central part of the Japanese main island. This result insisted that the locations in higher altitudes could also have warming trends in the time series of annual mean equilibrium water temperature.

The cooling trends, on the other hand, in annual mean equilibrium water temperature in Fig.2 appeared mainly on the Pacific coast of the Tohoku region, the northern Kyushu region, and the Sea of Japan coast. These regions had lower rates of trend detection in the Mann-Kendall test. These cooling trends would result from a thermal imbalance on the water surface that the cooling effect due to the latent and sensible heat transfers by evaporation, conduction, and convection surpassed the warming effect due to the long wave radiation by the air temperature rise.

4.2 Seasonal mean equilibrium water temperature

4.2.1 Trends of long-term change

Figure 3 showed the box plot of Sen's slopes obtained at the locations where the trend was statistically detected for the annual and seasonal mean equilibrium water temperatures. The trend detection rates of the Mann-Kendall test were also added in Fig.3. The result indicated that all the detection locations in autumn (SON) and winter (DJF) had warming trends. In particular, the trend detection rate in autumn was the largest in all seasons, 65%, and the 75% of them had
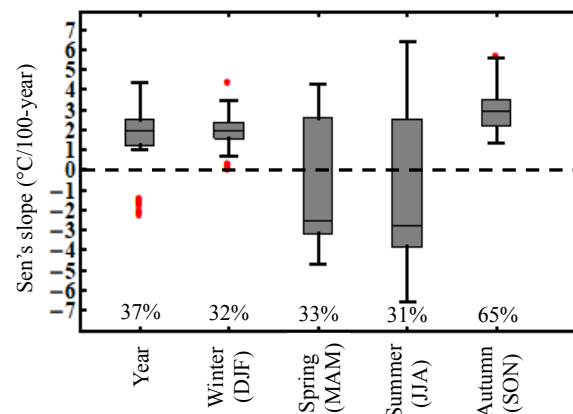

Figure 3. Box plot of Sen's slopes for the annual and seasonal mean equilibrium water temperatures.
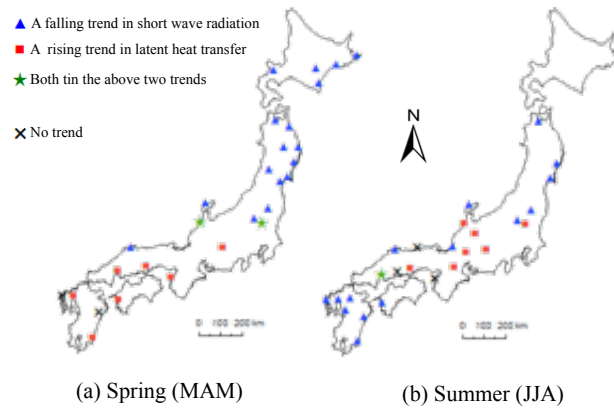
(a) Spring (MAM)　　　　　　　(b) Summer (JJA)

Figure 4. The distributions of the short wave radiation decreases and/or
the latent heat transfer increases in spring and summer in Japan.

stronger warming trends with over 2.0 °C/100year. On the other hand, spring (MAM) and summer (JJA) had both cooling trends and warming trends. Their trend detection rates were 32 and 31% of the total 132 locations, respectively, and the halves of them indicated the cooling trends.

4.2.2 Main factors of cooling trends in spring and summer

In order to examine predominant factors of the cooling trends in spring and summer, each term in the heat balance equation (1) was analyzed by the Mann-Kendall test. The result revealed that the locations with cooling trends had larger decreasing in short wave radiation and/or larger increasing in latent heat transfer. Figure 4 showed the distributions of the short wave radiation decreases and/or the latent heat transfer increases in spring and summer in Japan. The larger increasing in latent heat transfer was indicated in the western part of Japan in spring, while the larger decreasing in short wave radiation was found in all over Japan excluding its central part. It is a future research work to reveal which meteorological factors other than the air temperature affects the cooling trend in the seasonal equilibrium water temperature in detail.

5.　CONCLUDING REMARKS

This paper analyzed the annual and seasonal trends of equilibrium water temperature in Japan for the recent 50 years. The results showed that there were both warming and cooling trends in the decadal changes in the equilibrium water temperature. As for their regional distribution characteristics, the warming trend was obvious mainly in the coastal part of the Pacific Ocean in Japan. Both the global warming and urban heat island phenomenon could have had effects on this coastal part. On the other hand, the cooling trend was detected in the northern part, i.e., the Tohoku region and d the southern part, north Kyushu region, as well as the coastal part of the Sea of Japan. These parts indicated a strong trend in either a larger decrease in short wave radiation or a larger increase in latent heat transfer in spring and summer.

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