Assessing effects of temporal changes in River water temperature on stratification in the Ariake Sea

A N Arifin¹, S Yano², A T Lando³

¹Department of Mechanical Engineering, Faculty of Engineering, ATI Makassar Polytechnic, Indonesia
²Department of Urban and Environmental Engineering, Faculty of Engineering, Kyushu University, Japan
³Department of Environmental Engineering, Faculty of Engineering, Hasanuddin University, Makassar, Indonesia

E-mail: nasser.abdul76@yahoo.com

Abstract. The upward trend of river water temperature due to climate change has recently been confirmed. However, its effects on thermal stratification in coastal waters are not clear. Therefore, targeting the Ariake Sea – a semi-enclosed bay in the island of Kyushu, Japan – we continuously monitored river water temperature during and after August 2015 at the discharge observation stations of Class-A rivers that feed the sea, located in the non-tidal areas of the rivers and closest to the respective river mouths. Numerical simulations were performed on the density stratification in the Ariake Sea using the obtained hourly river water discharge and temperature data, to assess the effects of temporal changes in river water temperature on thermal stratification. It was shown that during a summer flood, river water temperature could influence the reproducibility of the development of thermal stratification depending on the river water temperature used, and the reproducibility of the base water temperature differed during the transition to the mixing period. Effects of river water temperature on the water temperature structure of the sea were indicated.

1. Introduction

According to the Working Group I Report of the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change [1], warming of the climate was unequivocal and further warming was unavoidable even if mitigation measures were implemented. Therefore, it is now necessary to promote research on adaptation measures with the basic assumption that global warming will continue. Discussions on adaptation measures for climate change have already started for the fields of a natural water disaster, water resource (drought and water quality), natural ecosystems, agriculture, heatstroke and infectious diseases [2]. In the field of civil engineering, the Committee on Adaptation to a Changing Climate of the American Society of Civil Engineers submitted a report [3] listing their policies on future mitigation measures for the fields of buildings and other structures, transportation, water resources, urban water systems, coastal management, energy supply and cold regions, but did not consider aquatic environments. In the field of water engineering, adaptation to water disasters associated with an increase in precipitation and typhoons, and adaptation to drought damage associated with an increase in annual precipitation range, among others, are now attracting
attention [4]. In the fields of water quality and aquatic environments (e.g., hydrosphere ecosystem), effects on individual rivers, lakes, coastal areas or oceans have been assessed. However, effects have not been assessed, and adaptation measures have not been developed for entire catchment areas. The reasons may be that there is significant uncertainty even surrounding the physical processes of water discharge and heat budget – two of the most basic components of an aquatic environment – in forecasting warming, and that it is difficult to forecast parameter changes in water quality forecasting models and to forecast the artificial discharge of water, heat and substances.

In recent years, many phenomena suspected of being abnormal environmental events caused by climate change have been observed. For example, the increased water temperature has been observed in many public glasses of water [5]. The IPCC’s AR5 [1] reported increased average temperature and increased water temperature in the surface layer of the sea (depth of 0–700 m). With the progression of global warming, there is growing concern of increases in river water and atmospheric temperatures. Increased river water temperature may affect the Region of Freshwater Influence [6], but few studies have been conducted on this topic.

The Ariake Sea, the subject of this study, is a semi-enclosed bay in Japan fed by many Class-A rivers (e.g., Chikugo River) and Class-B rivers, forming a gulf type of ROFI susceptible to the effect of river water. However, in this area the only continuous data of river water temperature previously available was hourly data collected at one point on the Chikugo River; and for performing numerical calculations of physical phenomena, such as water flow, for rivers other than the Chikugo River, hypothetical water temperature data (e.g., monthly measurements or data from the Chikugo River) have been given. Because stratification is associated with the development of anoxic water masses in the bottom layer, which has been worsening in the Ariake Sea, the strength of density stratification is the most important physical phenomenon in assessing the effect of warming on this aquatic environment.

Therefore, as the first step in assessing the effects of changes in river water temperature on the aquatic environment of the watershed, water temperature was continuously measured at observation stations situated near the mouths of Class-A rivers, and the effects of changes in river water temperature on stratification in the Ariake Sea were assessed using a hydrodynamic model based on the data collected.

2. Continuous observation of river water temperature

Small memory-type water-temperature loggers were installed at Class-A rivers from August 2015 onwards to continuously collect water temperature data at rivers that feed the Ariake Sea. The observations were made at the Chikugo River, where hourly data have been collected by the Ministry of Land, Infrastructure and Transport (MLIT) at the Kurume Ohashi Bridge Gauging Station, and six other Class-A rivers (the Honmyo River which currently feeds the retention pond constructed in the Isahaya Bay Reclamation Work was excluded).

In the present chapter, accurate discharge data were necessary because the main focus was the assessment of the effects of river water temperature on coastal areas. Therefore, observation points were chosen from the gauging stations managed by the MLIT that were closest to the respective river mouths provided they were not situated in a tidal compartment. For the Chikugo River, water temperature data of the MLIT’s Database for Hydrology and Water Quality collected hourly at the Kurume Ohashi Bridge Gauging Station were used. The water temperature gauges were installed at Funagoya for the Yabe River, at Ikemori for the Kase River, at Myoken-Bashi for the Rokkaku River (Ushitsu River), at Yotsugi-Bashi for the Shira River, at Jonan for the Midori River and Tamana for the Kikuchi River (figure 1). However, it became apparent during an observation in 2015 that the Tamana observation point was in a tidal compartment and so the observation point was moved to the upstream Komoda observation point when the gauge was exchanged in December 2015. Therefore, the 2015 data does not include data for the Kikuchi River. Water temperature was measured hourly using small memory-type water temperature logger Water Temp Oro v2.
Time-series observation data for river water temperature for 2015 during and after August are shown in figure 2, and corresponding data for 2016 in figure 3. It should be noted that as a result of slope failures caused by the Kumamoto Earthquakes in April 2016, and other reasons, a large amount of sediment accumulated in the Shira River during a large-scale flood in late June, which made impossible the collection of the water temperature logger installed there; therefore, Figure 3 does not include data for the Shira River. As for other rivers, the data loggers were collected and exchanged without major issue, providing continuous water temperature data for over one year, including data for the flood season.

Figure 1. Water temperature observation points for the rivers studied and the comparison points for simulation.

3. Correlations between river water and atmospheric temperatures
Correlations between river water temperature measured and atmospheric temperature in nearby areas at the same hours were examined. For atmospheric temperature, data from the Japan Metrological Agency’s AMeDAS observation station nearest to each water temperature observation station were used. As an example, figure 4 shows the correlation between all 2015 water temperature data with the atmospheric temperature at the Shira River (Yotsugi-Bashi). A good first-order correlation was shown ($R^2 = 0.78$). Water temperature in natural waters such as rivers is expected to fluctuate due to such factors as solar radiation.
Figure 2. Water temperatures for the rivers studied.

Figure 3. Water temperatures for the rivers studied.

Figure 4. Correlation between water temperatures measured at the Shira River (Yotsugi-Bashi) and atmospheric temperature.

Figure 5. Correlation between water temperatures measured at the Shira River and atmospheric temperature.

a) During 01:00–04:00 h

b) During 17:00–20:00 h
Therefore, we divided each day into six 4-h blocks and examined correlations for each block. For example, figure 5 shows the data from the Shira River for the blocks 01:00–04:00 h and 17:00–20:00 h. Higher correlations were confirmed for both blocks ($R^2 = 0.90$ and 0.89, respectively) compared with when each day was not divided into time blocks. Likewise, high correlations ($R^2 \geq 0.80$) were confirmed for all time blocks for other rivers.

**Figure 6.** Correlation between water temperatures measured at the Ushitsu River (Myoken-Bashi) and atmospheric temperature (all 2016 data for the block 0900–1200 h).

These results suggest that at observation points near the river mouths, the river–atmosphere heat exchange reached equilibrium as water flowed downstream (i.e., equilibrium water temperature). Therefore, it was assumed that in assessing the effects of warming, the temperature of river water flowing down to the estuarine area did not significantly differ even if based solely on temperature. Likewise, a high correlation ($R^2 > 0.84$) was confirmed for the one-year data for 2016 (an example is shown in figure 6).

4. Numerical Simulations

4.1. Numerical model

In the present chapter, numerical simulations were performed using the Ariake Sea–Yatsushiro Sea coupled model, which is based on Delft3D [7], a general-purpose coastal hydrodynamic numerical model. The linear orthogonal coordinate system of 10”-interval resolution ($\Delta x \approx 250$ m) horizontally and the 10-layer $\sigma$-coordinate system vertically were applied. As the open boundary condition, 40 tide components were given on the open boundary that connects the Kabashima Channel in Nagasaki Prefecture with the north-south and east-west lines. For a flat tidal area, the moving wall boundary model (dry-wet model) was used to describe submergence and drying-up. The Sub-Grid Scale (SGS) Model was used for the horizontal turbulent viscosity and diffusion coefficients and the $k$-$\varepsilon$ turbulence model that included the buoyancy term was used for the vertical turbulent and diffusion coefficients.

First, the accuracy of calculation was assessed for the reproducibility of thermal stratification. Concerning freshwater inflow, Class-A rivers (figure 1), nine relatively large Class-B rivers and the north and south drain gates of the Isahaya Bay flood control dykes were considered. As for river water temperature, the hourly data obtained in the study were used. For the Class-B Rivers, the same water temperatures and the same specific discharges with those of neighbouring Class-A rivers were assumed. For heat flux $Q_{\text{tot}}$ on the sea surface the following Murakami Model [8] was used:
\[ Q_{\text{tot}} = Q_{\text{sn}} - Q_{\text{eb}} - Q_{\text{ev}} - Q_{\text{co}} \]

Where:
- \( Q_{\text{sn}} \) = net solar radiation (shortwave radiation),
- \( Q_{\text{eb}} \) = effective radiation (long-wave radiation),
- \( Q_{\text{ev}} \) = latent heat transportation and
- \( Q_{\text{co}} \) = sensible heat transportation.

Each term was assessed as follows:

\[ Q_{\text{eb}} = \varepsilon \sigma \bar{T}_a^4 (0.39 - 0.058\sqrt{e_a})(1.0 - 0.65F_c^2) + 4\varepsilon \sigma \bar{T}_a^3 (\bar{T}_s - \bar{T}_a) \]  
\[ (2) \]

\[ Q_{\text{ev}} = L_v E \]  
\[ (3) \]

\[ L_v = 2.5 \times 10^6 - 2.3 \times 10^3 T_s \]  
\[ (4) \]

\[ E = f(U_{10})(e_s - e_a) \]  
\[ (5) \]

\[ f(U_{10}) = cU_{10} \]  
\[ (6) \]

\[ e_s = 23.38 \exp(18.1 - 533.33/T_s) \]  
\[ (7) \]

\[ e_a = \gamma_{\text{hum}} 23.38 \exp(18.1 - 533.33/T_a) \]  
\[ (8) \]

\[ Q_{\text{co}} = R_b Q_{\text{ev}} \]  
\[ (9) \]

\[ R_b = \gamma(T_s - T_a)/(e_s - e_a) \]  
\[ (10) \]

Where:
- \( \varepsilon \) = emissivity (0.97),
- \( \sigma \) = the Stefan-Boltzmann constant (5.670 \times 10^{-8} \text{W/m}^2\text{K}^4),
- \( T_a \) = atmospheric temperature [K],
- \( F_c \) = cloud cover,
- \( T_s \) = surface water temperature [K],
- \( c \) = bulk coefficient (1.2 \times 10^{-9}),
- \( \gamma_{\text{hum}} \) = relative humidity,
- \( \gamma \) = the Bowen constant (0.66) and
- \( U_{10} \) = wind velocity.

For temperature in °C, the symbol does not carry a bar. For \( Q_{\text{sn}} \), measured values are used. As meteorological data necessary for assessment, for the amount of global solar radiation, the AMeDAS Fukuoka data were used; for wind velocity, the data collected at Observation Tower B6 (figure 1) in the Isahaya Bay managed by the Ministry of Agriculture, Forestry and Fisheries of Japan (MAFF) were used; and for atmospheric temperature, the AMeDAS Saga data were used. As the water temperature in the open boundary, the weekly sea surface temperature data published by the Japan Coast Guard were used as vertically constant data. Separately, the effects on seawater temperature of the Ariake Sea under an open boundary condition were investigated; the seawater temperature was not sensitive in the highly closed Ariake Sea, and a basic field was formed through heat exchange with the atmosphere.

Calculations were performed for the year 2015 for which both the measured water temperature data and river discharge data were available. As a spin-up, calculations were performed for the five months of March–July of the same year, for which river water temperature during the period was estimated.
from the hourly temperature using the correlation model obtained in Section 3. Comparison with the continuous water temperature distribution data (figure 7), collected by the MAFF at the Isahaya Bay Point B6 in late August 2015, showed that the model calculations (figure 8) were quite consistent with actual sea water temperature and the development and annihilation processes of the thermal stratification. It was thus considered that this model had sufficient accuracy in assessing the effects of river water temperature changes on thermal stratification in the coastal sea area.

4.2. Assessment of the Effects of Changes in River Water Temperature on Thermal Stratification

Next, by comparing two cases – measured data were applied for each river (Case 1) and water temperature data measured monthly at each river were applied for one month (Case 2) – we assessed the effects of the temporal fluctuation of river water temperature on thermal stratification.

![Figure 7. Water temperature measured at the Isahaya Bay Point B6.](image1)

![Figure 8. Water temperature calculated for the Isahaya Bay Point B6.](image2)

The comparison was made for Sta. A (figure 1) in the northern Ariake Sea, which was the area in the sea most susceptible to the effects of freshwater. The comparison period was August 2015 for which both water temperature data and river discharge data were available, and development of thermal stratification was expected. August was chosen because although salinity stratification, which is attributed to the inflow of river water, is dominant in density stratification in the Ariake Sea, thermal stratification tends to develop in the hot month of August.
a) Total discharge and water temperature of a Class-A river (Chikugo River) that feeds the Ariake Sea

b) Global solar radiation (Fukuoka Prefecture in orange) and atmospheric temperature (Saga Prefecture in grey)

**Figure 9.** River discharge and metrological conditions used for calculation (late August 2015).

The changes in meteorological conditions, river discharge and river water temperature for August when comparisons were made are shown in figure 9 (results for late August are shown). As a meteorological event during the period, a flood occurred during 25–27 August as a result of the rain caused by Typhoon 1515. The isopleths for salinity for Sta. A (northern Ariake Sea) and Point B6
(Isahaya Bay) show that in this area into which several rivers including the Chikugo River feed water, salinity is low especially in the surface layer (figure 10).

Water temperatures for Cases 1 and 2 are shown in figure 11 and the isopleths showing the differences (i.e., Case 1 subtracted from Case 2) in figure 12. Water temperature was generally low in Case 1; and differences in water temperature stratification during 26–27 August when floodwater reached the area and differences in water temperature after 29 August when vertical mixing was strong due to a strong tide were confirmed. These results confirmed the effectiveness of continuous hourly data collected at rivers in reproducing water temperature. It was also confirmed that reverse stratification was strengthened when river water of relatively low temperature was discharged in a large amount due to a flood.

Comparisons of Cases 1 and 2 were also made for September when thermal stratification came to an end, and the transition to the mixing period started (data not shown). At this time, heating weakened in both cases, and stratification weakened due to a decrease in river water inflow, and there was a base water temperature difference of a few °C between the two cases.

It is predicted that precipitation patterns will change in the future due to the progression of warming, and thus these results suggest that stratification will strengthen with an increase in flood frequency. Strengthening of density stratification in summer may facilitate the development of anoxic water masses in the bottom layer, thereby seriously affecting the aquatic environment in coastal areas. A study conducted by Tadokoro assessed the distribution of dissolved oxygen in the Ariake Sea using a vertical 1D model and showed that a subtle increase in stratification strength suppressed vertical mixing, thereby decreasing oxygen in the bottom layer. Therefore, its influence should be accurately assessed. If assessment confirms that the marine ecosystem, especially benthic organisms such as bivalves, is seriously affected, then appropriate adaptation measures would be required.

In general, about adaptation measures against warming, there is increasing interest in the field of water disasters. In the future, impact assessment and the development of adaptation measures concerning the aquatic environment will be increasingly necessary. As the aquatic environment is expected to be affected widely and slightly, there will not be many suitable adaptation measures for which resources will be invested intensively.
Figure 10. Salinity calculated for Case 1 (late August 2015).

Figure 11. Water temperature calculated for Sta. A (northern Ariake Sea in late August 2015).

Figure 12. The difference in water temperature (Case 2 minus Case 1) calculated for Sta. A (northern Ariake Sea) results.

For existing dams built on rivers, it is expected that such options as adjustments to operation methods, reallocation of volumes by purpose, and an increase in volume by redevelopment such as raising of dam walls and adjustment to discharge-water temperature by installing siphon-type selective intake regulators can be provided. Assessment of the effects of these adaptation measures post-warming is a future issue that requires continued investigation.
5. Conclusion
The effects of river water temperature on stratification in seawater were assessed by comparing the
calculation results for water temperature stratification in the Ariake Sea with changing input
temperature data for river water. Because flood types will change with the progression of climate
change, changes in river water temperature may affect stratification in the sea, and so the aquatic
environment may deteriorate as a result of increased oxygen deficiency.

References
[1] IPCC 2013 Climate Change 2013: The Physical Science Basis (Cambridge: Cambridge
University Press) p. 1535
[2] Sivaperuman C, Velmurugan A, Singh A K, Jaisankar I 2018 Biodiversity and Climate Change
Adaptation in Tropical Islands (India: Academic Press)
[3] Douglas E, Jacobs J, Hayhoe K, Silka L, Daniel J, Collins M, Mallick R 2017 Progress and
challenges in incorporating climate change information into transportation research and
design. Journal of Infrastructure Systems 23(4) 0401-7018
[4] Panel on Infrastructure Development Japan 2015 Report on climate change adaptation
measures for water disasters (Japan: Panel on Infrastructure Development Japan) p. 49
[5] Ministry of the Environment, Japan. Report on the effects of climate change on water quality
etc. s.l.: Ministry of the Environment, 2013. p. 68.
[6] Simpson J H, Sharples J 2012 Introduction to the physical and biological oceanography of shelf
seas (Cambridge: Cambridge University Press)
[7] Deltares 2011 User Manual Delft3D-FLOW (Rotterdamseweg: Deltares Rotterdamseweg)
[8] Murakami M, Oonishi Y, Kunishi H 1985 A numerical simulation of the distribution of water
temperature and salinity in the Seto Inland Sea Journal of the oceanographical society of
Japan 41(4) 213-224