Numerical analysis of water temperature difference on baroclinic flow in the region of freshwater influence (ROFI)

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Abstract. IPCC had reported in the 5th assessment report (AR5) that global warming has been occurring from the past to the end of this century. This fact shows us that the temperature gradually increases in the average temperature of the atmosphere and oceans. Investigations of this issue have been conducted by experts to assess the effect of global warming on human life. In the coastal area, especially in the regions of freshwater influence (ROFIs), the effect can be seen in the river discharge trend, which increases due to the upward trend of precipitation. Delft3D model was used as the numerical model to conduct the three-dimensional hydrodynamic numerical simulation in the Ariake Sea’s region of freshwater influence (ROFIs), Japan. A numerical experiment was performed with the observation data of river discharge and river water temperature to investigate the baroclinic flow in the Ariake Sea’s ROFIs, due to both of stratification (salinity and thermal) in several cases occur at different water temperatures ($\Delta T$) between seawater temperature and riverine freshwater temperature from -0.29°C to 9.27°C. Results from this research assessed the effects of the water temperature difference in the Ariake Sea ROFIs on the baroclinic flow.

1. Introduction
Phenomena of global warming have been occurring since the past until the end of the 21st century. The global surface temperature change is likely to exceed 1.5°C relative to 1850 - 1900 for all RCP scenarios except for RCP 2.6, and this liable to exceed 2°C for RCP6.0 and RCP8.5. Warming will continue beyond 2100 under all RCP scenarios except for RCP 2.6 and the rate of warming averaged over the last 50 years (0.13°C ± 0.03°C per decade) is nearly twice that for the last 100 years [1]. This trend is followed by the rising seawater surface temperature (SST) [1], where the SST predicted by using several models such as HadSST2, NCDC, and COBE-SST. The SST in the period above 1961 to 1990 on average had been warmer 0.44°C, 0.38°C and 0.37°C for HadSST2, NCDC, and COBE-SST, respectively. The five warmest years in all analyses have occurred after 1995 [1].

The fluctuation of temperature on the seawater surface will directly affect the participation pattern, including frequency and intensity. Under the RCP8.5 scenario, the annual mean precipitation trend shows in many mid-latitude wet regions, including some areas in Japan [2] yearly mean precipitation will likely increase [1]. Change in surface temperature and precipitation trend as the impact of global warming are two variables that have contributed directly to the evolution of seawater temperature of both seawater surface and subsurface one, and freshwater temperature. Water temperature is one of the physical quantities that can play an important role in determining the environmental quality of the
aquatic ecosystem. For example, it can be seen on the pH level of water that is associated with water temperature; increasing water temperature will be followed by a decreasing trend of water pH [3]. When the pH drops below 6, the number of species in several groups of organisms (phytoplankton and zooplankton, bottom fauna and several other groups of invertebrates) may decrease considerably, thus affecting the variety of foods for fish and other animals [3]. A decrease in primary production causes a decrease in some individuals at higher trophic levels, including fish that depend on phytoplankton as food [4]. Therefore, in many cases, it is reasonable to believe that the warming of seawater will decrease fish stocks [4]. The regions of freshwater influence (ROFIs), which was proposed by Simpson, has an important role in determining the condition of the marine environment and ecosystem in coastal areas [5]. The climate change effect, especially in ROFIs, can be seen in river discharge into this region was increased, because the precipitation trend was increasing too. Some rivers reached the highest discharge above the past largest recorded one. Even though this event has not had evidence of this phenomenon can be associated with the global warming effect but as anomaly events have interested some expert in conducting some researches by using data from this moment to protect water environment and its ecosystem in the future. Our previous research discussed how the precipitation could change the baroclinic structure during heavy rainfall in the Ariake Sea [8], by numerical analysis by 3-dimensional hydrodynamic model DELFT3D on the meteorological conditions. From the comparison of some numerical experiment cases on the several extreme floods, it was found that a projection alteration of rainfall pattern in the future which caused by climate change was able to change the baroclinic structure in a coastal region of the Ariake Sea. Thus, alteration of rainfall patterns can be deduced as one factor that can change in the baroclinic structure in the bay.

One of the factors that can cause changes in water temperature in the ROFIs is the temperature difference between seawater and freshwater, and this condition almost occurs throughout a year. In general, the freshwater temperature tends to be lower than seawater in Kyushu. Similar to our previous paper, in this study, we still focus on how baroclinic flow and its structure changed by the interaction between two types of water (seawater and freshwater) to see the impact on the baroclinic structure and thermal stratification during the mixing process. In this numerical simulation, some cases with the difference of water temperature are established to conduct the assessment of an impact on them on the baroclinic structure using anomaly discharge (as a representative of climate change impact) from several rivers surrounding in the Ariake Sea.

2. Methodology

2.1. Water temperature and salinity data

Water temperature is the primary physical quantity in this research. Water temperature data on average from seawater and freshwater are used in this numerical simulation, and they are taken from two different locations to obtain ideal temperature data. The seawater temperature data was taken in Shimabara observation station (figure 1), because we didn’t see a significant influence on seawater temperature at this area by freshwater input according to our previous calculation result (figure 2) by using an extreme temperature difference between two kinds of water ($\Delta T_{sr} = 10.0 \, ^{\circ}C$), in which discharge data and simulation period are same. Therefore, it could be assumed that seawater temperature tends to be stable for all time in this location. Furthermore, this location also is quite close to the mouth of the bay that links with the open sea. Thus, the seawater temperature of the Ariake Sea, which is quite pure than other locations in the bay, can be obtained from this station. Meanwhile, as the biggest river which has a significant influence in the Ariake Sea, freshwater temperature data from the Chikugo River is used here. Therefore, it could be assumed that seawater temperature tends to be stable for all time in this location. Furthermore, this location also is quite close to the mouth of the bay that links to the open sea. Thus, the seawater temperature of the Ariake Sea, which is quite “pure” than other locations in the bay, can be obtained from this station.
Meanwhile, as the biggest river which has a significant influence in the Ariake Sea, freshwater temperature data from the Chikugo River is used here. The normal salinity (29.26 ppt) is used in this study for all numerical experiment cases to see the impact of the difference in water temperature between seawater and freshwater [9].
2.2. Numerical model

The linear orthogonal coordinate system of 10" interval resolution (Δx= approx. 250m) horizontally and the ten layers σ-coordinate system vertically are applied in this research [10]. The harmonic constants (amplitude and lag) only for the four major tidal components (M2, S2, K1, and O1 tide) are adjusted to the measurement result of the tide at several tide gauges. Further, the moving wall boundary model for a flat tidal area [10] is adapted. The accuracy of calculation on the model is not discussed in detail in the present paper because it has been confirmed fully in our previous paper that discussed salinity stratification, the tide, and tidal currents gauges. The salinity and temperature of the water are used as a physical quantity in the calculation processes. Furthermore, for an initial condition of the temperature of the seawater and freshwater are used in different temperature in each case (see: table 1) and that of is uniform (i.e., 0 ppt for freshwater and 29.26 ppt for seawater as a boundary condition of the outer sea). In general, the freshwater temperature is lower than seawater, such in our numerical experiment here, but especially case-5 shows opposite to other cases, where the temperature of seawater is lower than freshwater temperature. This phenomenon can be caused by the thermal properties effect of the mud during spring tide [11]. "No flux mode" is selected for the physical process of heat transfer [10].

![Figure 3. Calculated tide at Sta. C and total runoff from A-class rivers [12].](image)

2.3. Numerical experiment condition

In this chapter, numerical simulation was carried out using observed river discharge data. Further, the numerical analysis is conducted to compare the effect of temperature difference pattern on the baroclinic flow for 20 days. Figure 4.3 shows the temporal variation of the calculated tide at Sta. C (center part of the bay) and total river discharge of A-class Rivers in the Ariake Sea. From the previous study, the momentum of mixing water between seawater and freshwater will be more effective in low tide [16]. Therefore, observation in the baroclinic structure by using the peak river discharge about 14,000 m3/s is conducted twice. The first observation was carried out in one hour after the peak river discharge occurred. For the second, it was conducted when tide showed low tide after one day from the peak, then the freshwater spread and gave significant effects on the sea area. In the present study, the difference temperature ΔTs = 0 °C (case-1) was considered as an essential condition of temperature to assess its effect on the baroclinic structure during the flood event and one day after the flood event. The temperature which was used in the calculation was 18.70 °C. In a comparison of horizontal water temperature distribution, the computational result at the first layer (surface layer) was used to assess all cases, which could show freshwater distribution most clearly.
Table 1. Numerical experiment cases.

| Case | Water Temperature (°C) | Water Condition in Sea (T_s) | River (T_r) | ΔT_{sr} | Mean temperature |
|------|------------------------|-----------------------------|------------|--------|-----------------|
| 1    | 18.70                  | 18.70                       | 0.00       | Mean temperature |
| 2    | 27.60                  | 24.91                       | 2.69       | Summer          |
| 3    | 18.70                  | 9.43                        | 9.27       | Winter          |
| 4    | 21.80                  | 15.22                       | 6.25       | Autumn          |
| 5    | 19.50                  | 19.79                       | -0.29      | Spring          |
| 6    | 15.50                  | 12.25                       | 3.25       | Spring          |

Figure 4. The monthly average temperature comparison between seawater and river water in the Ariake Sea [12,13].

To obtain a computation result of thermal stratification from this simulation four observation stations in different location, such as in front of mouth of the Chikugo River (Sta. A), head of bay (Sta. B), center part of the bay (Sta. C), and area around mouth of Isahaya Bay (Sta. D). Meanwhile, the isopleth graph and the temporal change of vertical thermal gradient ΔT/Δh of water in all cases from all observation stations were used to assess how different water temperatures can change the baroclinic structure in the ROFI.

3. Result and discussion

All computation results of horizontal temperature distribution in each case show a pattern of the spread of freshwater temperature that occurred during the flood in the Ariake Sea, where the ROFIs developed. The differences in watercolor can show an effect of freshwater that flows from the head of the bay where the biggest river (Chikugo River) is located. Some rivers on the eastern side of the sea (such as Kikuchi River and Shira River) can have an effect in almost all regions of the bay. Figure 5 and figure 6 show the horizontal sea surface temperature distribution pattern from three cases. These figures show dissimilarity in distribution patterns caused by the temperature difference between seawater and freshwater. This occurs when seawater obtains high pressure from freshwater (peak discharge of river) till one hour after the flood. This trend can continue for one day after the flood when the freshwater assumed has become widespread in this region. This phenomenon occurs in all cases. The variation of difference in the distribution pattern of temperature shows alteration of the baroclinic structure at each case caused by the difference of water temperature between seawater and freshwater. Therefore, it can be assumed that the difference in water temperature is one factor that caused a change of baroclinic structure horizontally in the Ariake ROFIs. Figure 7 shows the temporal change of vertical thermal gradient ΔT/Δh in all numerical experiment cases at observation Station in
Sta. C (upper) and Sta. D (lower) that located around the inner part of the bay and Isahaya Bay, respectively (figure 1).

Figure 5. Comparison of the computation result of horizontal temperature distribution in the surface layer of the Ariake Sea among case-3, case-4 and case-6.

It can be seen that the trend of thermal stratification before the flood events is rather stable for all cases. It means that the water temperature on the surface layer and the bottom layer doesn't have a significant difference, or the water temperature at this moment is rather uniform. This condition is different during flood events, where thermal stratification starts to develop at two hours before the observation time. Its trend continues maximum value and starts to reduce at one hour after the 2nd observation time. This phenomenon occurs almost in all numerical experiment cases except for case-1 and case-5. In case-1 trend of thermal stratification is almost flat because of the same temperature between both of waters. Meanwhile, in case-5, its thermal stratification is the opposite that is water temperature on the surface is lower than in the bottom layer.

Figure 6. Comparison of the computation result of horizontal temperature distribution in the surface layer of the Ariake Sea among case-3, case-4 and case-6.
4. Conclusion

From this comparison result from numerical experiments in several cases of water temperature difference, between seawater and freshwater temperature, we can deduce that dissimilarity of water temperature can give an effect on the baroclinic flow and its structure in the regions of freshwater influence (ROFIs). The large or small deformation of baroclinic flow and its structure in the region can be affected by two factors. The first one is the difference ratio of water temperature between seawater temperature and freshwater one. Second is the freshwater discharge from rivers around ROFIs. Flood events considered as an effect of climate change can be boosters to change baroclinic flows and the structure in the Ariake Sea ROFI.

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