NUMERICAL ANALYSIS OF CLIMATE CHANGE IMPACT ON REGION OF FRESHWATER INFLUENCE IN THE ARIAKE SEA,JAPAN

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NUMERICAL ANALYSIS OF CLIMATE CHANGE IMPACT ON REGION OF FRESHWATER INFLUENCE IN THE ARIAKE SEA, JAPAN

By

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Prof. Shinichiro YANO, Dr. Eng.

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To the
DEPARTMENT OF MARITIME ENGINEERING
GARDUATE SCHOOL OF ENGINEERING
KYUSHU UNIVERSITY
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August, 2017

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CERTIFICATE

The undersigned hereby certify that they have read and recommended to the Graduate School of Engineering for acceptance of this thesis entitled, ***"Numerical Analysis of Climate Change Impact on Region of Freshwater Influence in the Ariake Sea, Japan"*** by **Abdul Nasser Arifin** in partial fulfillment of the requirements for the degree of Doctor of Engineering.

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ABSTRACT

The climate research has been begun since in the early 19th century, according to Intergovernmental Panel on Climate Change (IPCC) report 2008. The anomaly phenomena caused by extreme events as primary climate change indicator in nature such: extreme temperatures, heat waves, precipitation extreme, droughts, change in tropical cyclone activity, and sea level rise in extreme are some of the impacts of climate change.

In the global environments, aquatic ecosystems are the critical component to determine the quality of the environment. In addition to being vital contributors to biodiversity and productivity, they also provide a variety of services for the human. Aquatic ecosystems have a limited ability to adapt with climate change effect. However, aquatic systems have been increasingly threatened directly and indirectly by climate change. Alteration of water temperatures will alter water ecosystem significantly. At the marine ecosystem, increased water temperature, precipitation intensity, and longer periods of low flows are projected to exacerbate many forms of water pollution including sediments, nutrients, dissolved organic carbon, pathogens, pesticides, salt and thermal pollution.

The aquatic ecosystem consists of seawater ecosystem and freshwater one. The region of freshwater influences (ROFI) that was proposed for the first time by Simpson is an interfacial area of water between seawater and freshwater. ROFI plays an important role in determining the condition of the marine environment and ecosystem in coastal regions. Related to climate change phenomena, this region becomes a vulnerable area to degradation of water quality due to alteration effects from both sides of seawater and freshwater. In natural of water activity, the physical parameters of water such density and temperature are two components that can play a significant role to determine water quality level in an aquatic environment. Therefore alteration of water density and water temperature are used as the primary parameter in this study.

In the environmental fluid dynamics, the baroclinic is the motion of fluid in ocean or atmosphere that is measured how misaligned the density/temperature gradient from its gradient of pressure. In the sea, baroclinic plays various roles related to the alteration of water quality condition such as developing of water nutrition components, water stratification, and adjustment on it causes distribution pattern of chemical and physical components will change vertically and horizontally due to the sensitivity of them caused by fluctuation of water density and water temperature. Therefore, to see the climate change impact on ROFI, the alteration of baroclinic assessment was used to obtain climate change impact by using several numerical experiment cases relate to climate change indicators.

In the present study, to see the climate change impact on the Ariake Sea ROFI, our study was divided in some chapter in this thesis, and described as follows:

Chapter 1 explains about research background, research problem, research objectives, the scope of the study, and also the overview of the thesis as an introduction.

Chapter 2 shows several previous research related to our study. How the impact of climate change on the aquatic system was showed from some research results that have been conducted by some experts, more than that, the study about ROFI as the primary object of this study was discussed to shows how its vulnerary and potential threat due to climate change impact.

Chapter 3 indicates the numerical analysis conducted to compare an effect of runoff pattern on the baroclinic flow for 20 days in July, 2012. We modify river discharge data by using multiplier factor α (0.8-2.0) to make several case conditions. A comparison among numerical experiments for several extreme floods is considered as a projection of climate change. The result from this study can show that the change of rainfall pattern can change the baroclinic structure in a coastal region of the Ariake Sea.

In **Chapter 4**, numerical experiments are conducted with the observation data of river discharge and river water temperature to investigate the baroclinic structure in ROFIs due to both of salinity stratification and thermal one in several cases that show the actual water temperature difference (ΔT) 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 different in the Ariake Sea ROFIs on the baroclinic structure. The results can be used for considering adaptation for aquatic environment and marine ecosystem in a coastal region to the global warming.

In **Chapter 5**, an assessment of the climate change effects on thermal stratification in coastal waters is carried out by using data from the Ariake Sea – a semi-enclosed bay in the island of Kyushu, Japan. The river water temperature data after August 2015 at the discharge observation stations of Class-A rivers that feed the bay is used. Numerical simulations are performed on the density stratification in the Ariake Sea to assess the effects of temporal changes in river water temperature on thermal stratification. It is shown that during a summer flood, river water temperature can 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 are indicated.

In **Chapter 6**, an assessment of potential threat of water temperature alteration effect on the aquatic ecosystem is done. In the following climate change issue, the region of freshwater influences (ROFI) is vulnerable area to degradation of water quality. In this chapter, differences of water temperature in ROFI associated with the global warming effect is conducted by some numerical experimental conditions on water temperature simulation that has an extreme different temperature (ΔT_{sr} = 10 °C to ‐ 8 °C) in the Ariake Sea. The results show how the global warming can be a problem in aquatic environments and how the distribution pattern of potential threats of water temperature change in seawater–freshwater mixing related to water temperature in aquatic ecosystems. This is important because changes in water temperature have implications for aquatic biota such as seaweed (Nori: *Porphyra yezoensis*), fish and other organisms, especially in the ROFI. The results can be utilized to determine some methods to mitigate the effects of global warming on aquatic environments and marine ecosystems in coastal regions.

Chapter 7 concludes all chapters in this thesis and also proposes some recommendation for future works.

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CHAPTER 1

INTRODUCTION

ABSTRACT

Climate change has been the global issue since in the early 19th century when the natural greenhouse effect first identified. In this introductory chapter, the climate change description of is given to establish the same perception about why the climate change is a fundamental issue in nowadays. The explanation about the climate change indicators related to aquatic environments is a great way to understand and shows how our climate has been changed and has a significant effect on our environment now. The region of freshwater influence (ROFI) role in an aquatic environment is simply explained and also the climate change impact on ROFI is described. Ariake Sea as the study area and its extreme rainfall history in 2012 (as one of climate change indicator) are the main backgrounds from this research presented in this chapter.

1.1 RESEARCH BACKGROUND

The world is getting warmer [IPCC, 2014]. The climate research has been begun since in the early 19th century when ice ages and other natural changes in paleoclimate were first suspected, and the natural greenhouse effect first identified. In the 1960s, the warming effect of carbon dioxide gas became increasingly convincing. Some scientists also pointed out that human activities that generated atmospheric aerosols (e.g., "*pollution*") could have cooling effects as well. Since the 1990s, scientific research on climate change has included multiple disciplines and has expanded. Research has expanded our understanding of causal relations, links with historic data and ability to model climate change numerically. Research during this period has been summarized in the Assessment Reports (AR) by the Intergovernmental Panel on Climate Change (IPCC).

Definition of climate change is a significant and lasting change in the statistical distribution of weather patterns over periods ranging from decades to millions of years. It may be a change in the mean and the variability of weather properties conditions, or in the distribution of weather around the average conditions (such as more or fewer extreme weather events). The latter effect is currently causing global warming, and "*climate change*" is often used to describe human-specific impacts [IPCC, 2008].

1.1.1 Climate Change Indicator

One important way to track and communicate the causes and effects of climate change is through the use of indicators. An indicator represents the state or trend of certain environmental or societal conditions over a given area and a specified period. For example, long-term measurements of temperature in globally is used as an indicator to track and better understand the effects of changes in the Earth's climate.

Temperature rise in the lower atmosphere

The lowest layer of the atmosphere, called the troposphere, from satellite measurements, shows that this lowest layer of the atmosphere is warming as greenhouse gases build up and trap heat that radiates from the Earth's surface [U.S. Environmental Protection Agency, 2014]. This phenomenon shows a trend of rising from 0.22° to 0.26°C per 10 years, consistent with the global warming trend derived from surface meteorological stations [Vinnikov, Grody, 2003]

The warming phenomena in this region were predicted happening since 1850, the Earth's surface has been successively warmer at the last three decades than any proceeding. "*The period from 1983 to 2012 was very likely the warmest 30-year period of the last 800 years in the Northern Hemisphere, where such assessment is possible (high confidence) and likely the warmest 30-year period of the last 1400 years (medium confidence)*" [IPCC, 2014].

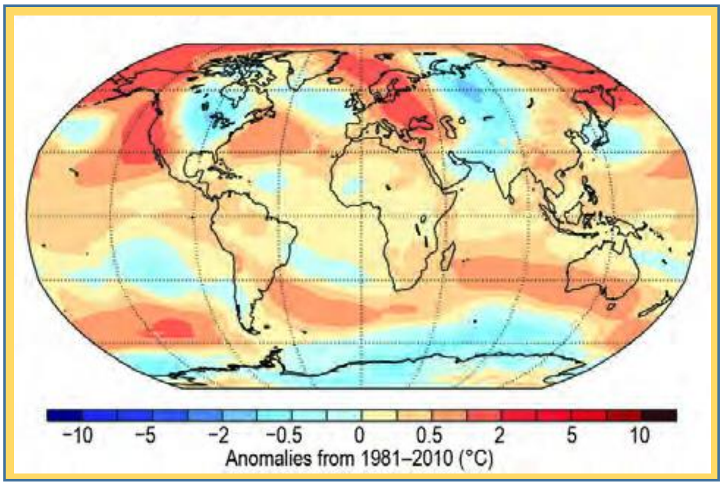


Figure 1.1 Annual anomalies temperature in lower tropospheric [Blunden, 2015]

Air temperatures rise in over land

Warming is greater over land than over the oceans, because water is slower to absorb and release heat (thermal inertia). From the weather stations on land average air temperatures are rising, and as a result, the frequency and severity of droughts and heat waves are increasing. Intense droughts can lead to destructive wildfires, failed crops, and low water supplies, in many parts of the world.

Air temperatures rise over ocean

Our planet is a watering place. "*There are 71 % our planet surface is water-covered, and the oceans hold about 96.5 percent of all Earth's water*" [U.S. Department of the Interior | U.S. Geological Survey, 2016]. Therefore the increasing trend of air temperature in over them could make a vast difference in the climate system.

Oceans evaporate more water as the air right near the surface gets warmer. This condition can be caused more floods, more hurricanes, and more extreme precipitation events.

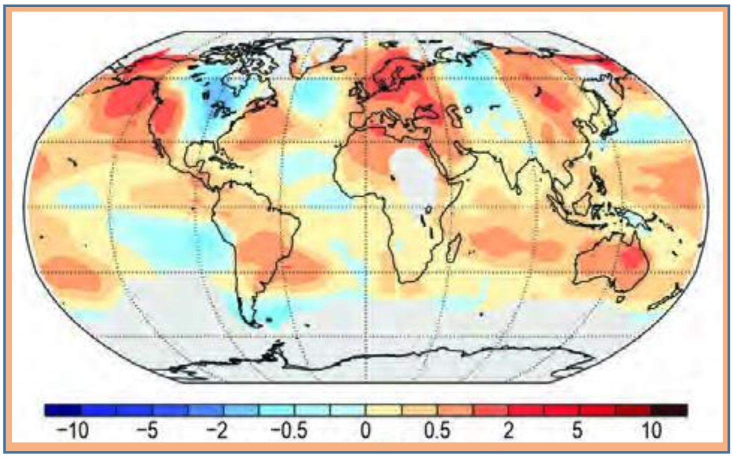


Figure 1.2 Annual anomalies temperature from 1981-2010 [Blunden, 2015]

Sea surface temperature rising

Increasing air temperature over the ocean is followed by the ocean warming, it is largest near the surface, and "*the upper 75 m warmed by 0.11 [0.09 to 0.13] °C per decade over the period 1971 to 2010. It is virtually certain that the upper ocean (0−700 m) warmed from 1971 to 2010, and it likely warmed between the 1870s and 1971. It is likely that* *the ocean warmed from 700 to 2000 m from 1957 to 2009 and from 3000 m to the bottom for the period 1992 to 2005*" (**Figure 1.3**) [IPCC, 2014].

Sea level rising

There was high confidence if the global average sea level had been increased since between the mid-19th and the mid-20th centuries. "*The average rate was 1.7 ± 0.5 mm/yr. for the 20th century, 1.8 ± 0.5 mm/yr. for 1961–2003, and 3.1 ± 0.7 mm/yr. for 1993–2003*" [Bates, 2008]. It is not known whether the higher rate in 1993–2003 is due to decadal variability or an increase in the longer-term trend. Spatially, "*the change is highly non-uniform, over the period 1993 to 2003, rates in some regions were up to several times the global mean rise while, in other regions, sea levels fell*" [Bates, 2008]

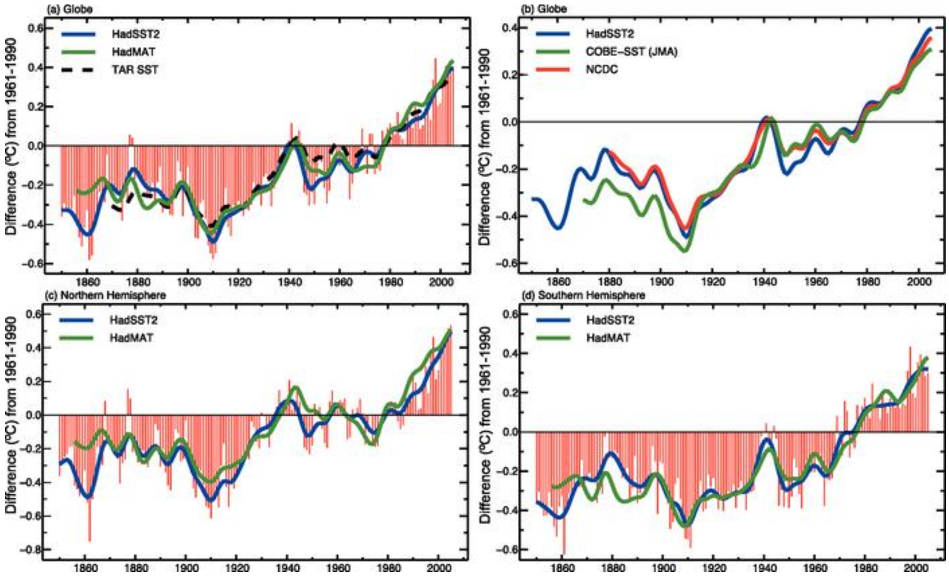


Figure 1.3 Annually anomalies of sea surface temperature difference (^{o}C) from 1961-1990 (HadSST2; red bars and blue solid curve), 1850 to 2005, and global NMAT (HadMAT, green curve), 1856 to 2005, relative to the 1961 to 1990 mean (°C) from the UK Meteorological Office [Rayner, 2006] and [IPCC, 2014]

Extreme events are increasing in frequency and intensity

Impacts from recent climate-related extremes, such as heat waves, droughts, floods, cyclones, and wildfires, reveal significant vulnerability and exposure of some ecosystems and many human systems to current climate variability (very high confidence). Impacts of such climate-related extremes include alteration of ecosystems, disruption of food production and water supply, damage to infrastructure and settlements, human morbidity and mortality and consequences for mental health and human well-being. For countries at all levels of development, these impacts are consistent with a significant lack of preparedness for current climate variability in some sectors [IPCC, 2014].

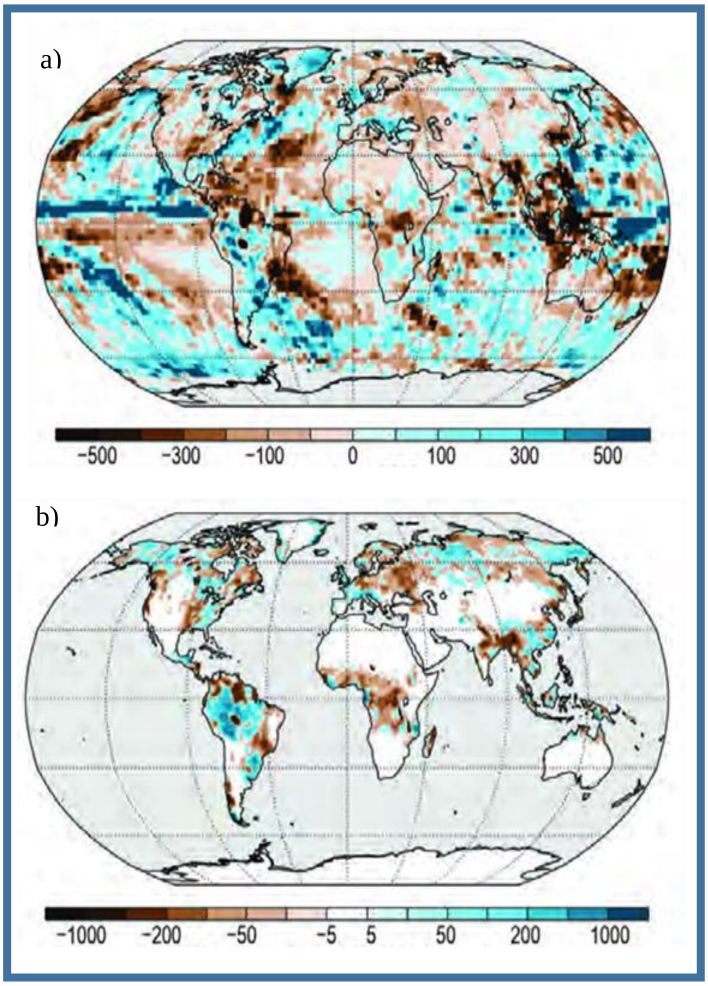


Figure 1.4 Annual anomalies precipitation from 1988-2010 (a) and annual anomalies runoff from 1979-2013 (b) (mm yr^{-1}) [Blunden, 2015]

1.1.2 Climate Change Impact to the Aquatic Environment

In the global environment, aquatic ecosystems are critical components. In addition to being essential contributors to biodiversity and ecological productivity, they also provide a variety of services for human populations. However, aquatic systems have been increasingly threatened, directly and indirectly, by global climate change (**Figure 1.5**).

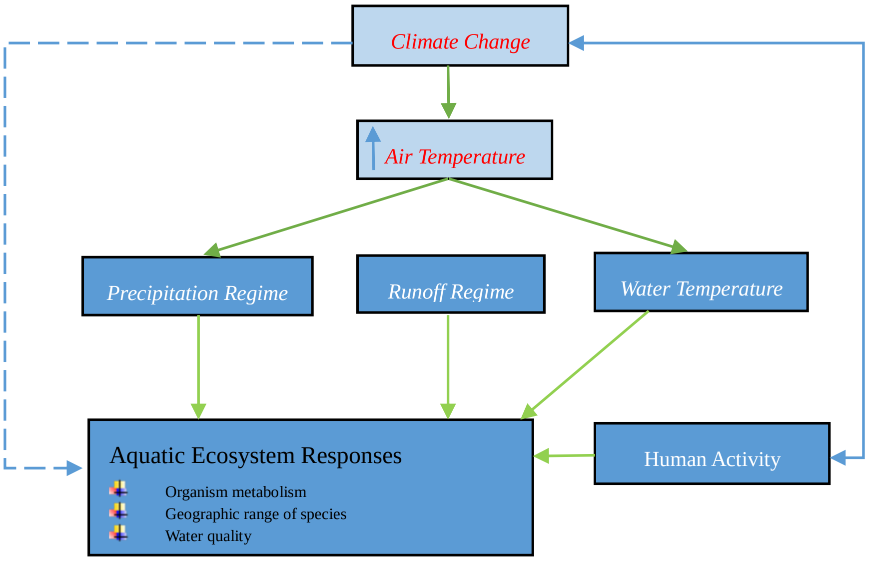


Figure 1.5 Linkages between climate change and environmental drivers of temperature and precipitation that regulate many ecological processes and patterns in inland freshwater and coastal wetland ecosystems [Poff, Brinson, 2002]

Changes in temperature

According to some indicators of climate change that mentioned above, the aquatic ecosystems is the vulnerable area to the adverse effects of climate change both directly and indirectly. An increase in air temperature due to global warming will translate directly into warmer water temperatures for most streams and rivers, thereby altering fundamental ecological processes and species distributions. Streams and rivers are relatively shallow, turbulent, and well-mixed systems, meaning they exchange heat and oxygen readily with the atmosphere. Therefore, they will become warmer under projected climate change [Eaton et al., 1996].

The life processes of many aquatic organisms are temperature- dependent. Warmer water can increase growth rates and stimulate ecosystem production. For example, marine invertebrates at the base of the food web (e.g., aquatic insects) may mature more rapidly, albeit to a smaller size, and reproduce more frequently [Arnell, 1998]. Assuming no change in food resources, invertebrate production of streams and rivers may increase, potentially yielding more food for fish. However, higher water temperatures will also increase the rate of microbial activity and thus the rate of decomposition of organic material, which may result in less food being available for invertebrates and ultimately fish [Mayer et al., 1990].

Annual anomalies temperature as impact climate change are predicted to increase especially at the higher latitude, and some areas of the continent will become wetter and some drier, and the variability in the timing and quantity of precipitation will also change, altering patterns of runoff to aquatic ecosystems.

Changes in precipitation and runoff regimes

Many studies argue if the phenomena of climate change have strong influence on the seasonal of precipitation pattern. For example the increasing temperatures over the oceans as one of the indicators of climate change has implications on increasing rate of evaporation that occurs on the sea surface, this condition gives impact on the rate of precipitation, and it will affect to each step of the hydrologic cycle in **Figure 1.6**.

The seasonal pattern of precipitation falling on a watershed is translated into the surface runoff that feeds into streams and rivers. In ecological terms, the extremes of flow are critical events that influence species composition and the productivity of aquatic and wetland communities. In the eastern United States, precipitation is high enough to sustain year-round flow in streams. Thus, knowledge of the particular regional changes in stream flow regimes brought about by climate change is critical to anticipating ecological impacts. Some projections are reasonably well supported, and others need to be considered as possible scenarios to evaluate the range of ecological concerns related to a changing climate.

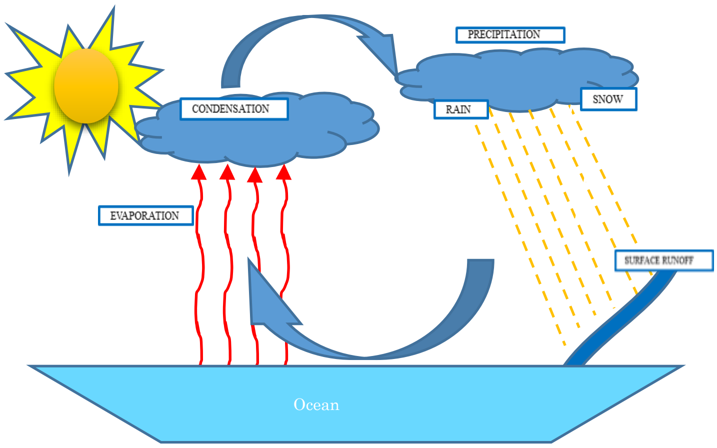


Figure 1.6 Hydrological cycle

Sea level

Global mean sea level has been rising, and there is high confidence that the rate of rising has increased between the mid-19th and the mid-20th centuries. The average rate was 1.7 ± 0.5 mm/yr. For the 20th century, 1.8 ± 0.5 mm/yr. For 1961–2003, and 3.1 ± 0.7 mm/yr. for 1993–2003. It is not known whether the higher rate in 1993–2003 is due to decadal variability or an increase in the longer-term trend. Spatially, the change is highly non-uniform; e.g., over the period 1993 to 2003, rates in some regions were up to several times the global mean rise while, in other areas, sea levels fell [IPCC, 2014].

Runoff and river discharge

Trends in runoff are always consistent with changes in precipitation. This may be due to data limitations (in particular the coverage of precipitation data), the effect of human interventions such as reservoir impoundment (as is the case with the major Eurasian rivers), or the competing effects of changes in precipitation and temperature There is, however, far more robust and widespread evidence that the timing of river flows in many regions where winter precipitation falls as snow has been significantly altered. Higher temperatures mean that a greater proportion of the winter precipitation falls as rain rather than snow, and the snowmelt season begins earlier.

1.1.3 Future Risk

The risk of climate-related impacts results from the interaction of climate-related hazards (including hazardous events and trends) with the vulnerability and exposure of human and natural systems, including their ability to adapt. Rising rates and magnitudes of warming and other changes in the climate system, accompanied by ocean acidification, increase the risk of severe, pervasive and in some cases irreversible detrimental impacts. Some risks are especially relevant for individual regions, while others are global. The overall risks of future climate change impacts can be reduced by limiting the rate and magnitude of climate change, including ocean acidification. The precise levels of climate change sufficient to trigger abrupt and irreversible change remain uncertain, but the risk associated with crossing such thresholds increases with rising temperature (medium confidence). For risk assessment, it is important to evaluate the widest possible range of impacts, including low-probability outcomes with large consequences.

Precipitation extremes

Climate projections using multi-model ensembles show increases in globally averaged mean water vapor, evaporation, and precipitation over the 21st century. It is very likely that heavy precipitation events will become more frequent. The intensity of precipitation events is projected to increase, particularly in tropical and high-latitude areas that experience increases in mean precipitation. There is a tendency for drying in midcontinental areas during summer, indicating a greater risk of droughts in these regions. In most tropical and mid- and high-latitude areas, extreme precipitation increases more than mean precipitation.

Changes in precipitation will not be uniform as shown in **Figure 1.7**. The high latitudes and the equatorial Pacific are likely to experience an increase in annual mean precipitation under the RCP8.5 scenario. In many mid-latitude and dry subtropical regions, mean precipitation will likely decrease, while in many mid-latitude wet regions, mean precipitation will likely increase under the RCP8.5 scenario. Extreme precipitation events over most of the mid-latitude land masses and humid tropical regions will be very likely become more intense and more frequent.

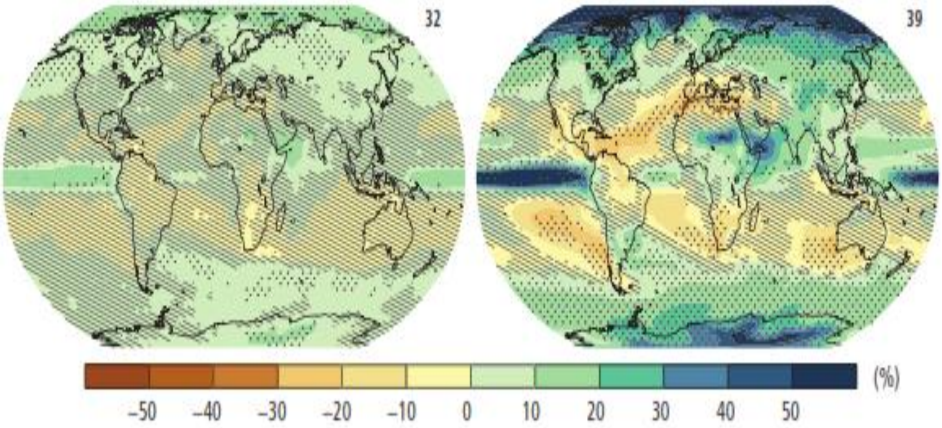


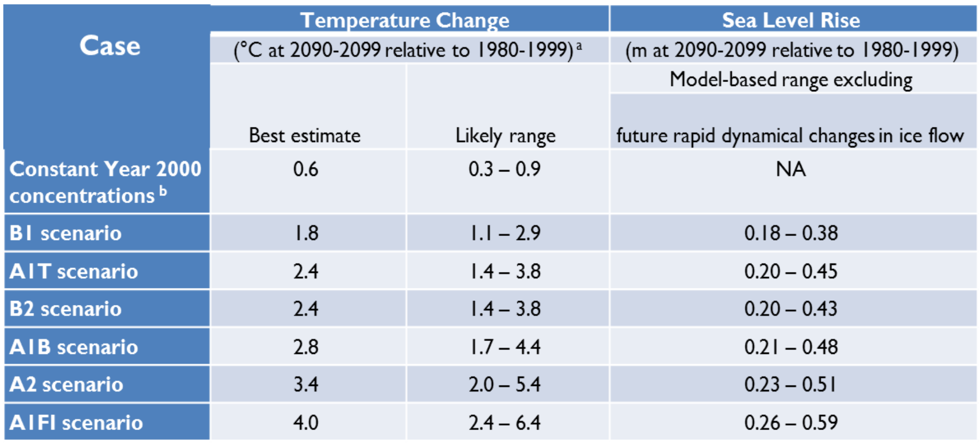
Figure 1.7 Change in average precipitation (1986 – 2005 to 2080 – 2100) under the RCP2.6 (left) and RCP8.5 (right) scenarios [IPCC, 2014]

Also associated with the risk of drying is a projected increase in the risk of intense precipitation and flooding. Though somewhat counter-intuitive, this is because precipitation is projected to be concentrated in more intense events, with longer periods of lower precipitation in between. Therefore, intense and heavy episodic rainfall events with high runoff amounts are interspersed with longer relatively dry periods with increased evapotranspiration, particularly in the sub-tropics. However, depending on the threshold used to define such events, an increase in the frequency of dry days does not necessarily mean a decrease in the frequency of extreme high-rainfall events. Another aspect of these changes has been related to changes in mean precipitation, with wet extremes becoming more severe in many areas where mean precipitation increases and dry extremes becoming more severe where mean precipitation decreases.

Sea level

The average rate of sea-level rise during the 21st century is very likely to exceed the 1961–2003 average rate (1.8 ± 0.5 mm/yr.) [Glick, Clough, Nunley, 2010]. Thermal expansion is the largest component, contributing 70–75% of the central estimate in these projections for all scenarios (**Table 1.1**) [IPCC, 2007].

Table 1.1 Projected global average surface warming and sea level rise at the end of the 21st century [IPCC, 2007].



Case	Temperature Change (°C at 2090-2099 relative to 1980-1999)[a]		Sea Level Rise (m at 2090-2099 relative to 1980-1999)
	Best estimate	Likely range	Model-based range excluding future rapid dynamical changes in ice flow
Constant Year 2000 concentrations[b]	0.6	0.3 – 0.9	NA
B1 scenario	1.8	1.1 – 2.9	0.18 – 0.38
A1T scenario	2.4	1.4 – 3.8	0.20 – 0.45
B2 scenario	2.4	1.4 – 3.8	0.20 – 0.43
A1B scenario	2.8	1.7 – 4.4	0.21 – 0.48
A2 scenario	3.4	2.0 – 5.4	0.23 – 0.51
A1FI scenario	4.0	2.4 – 6.4	0.26 – 0.59

Glaciers, ice caps, and the Greenland ice sheet are also projected to contribute positively to sea level. GCMs indicate that, overall, the Antarctic ice sheet will receive increased snowfall without experiencing substantial surface melting, thus gaining mass and contributing negatively to sea level. Sea-level rise during the 21st century is projected to have significant geographical variability. Partial loss of the Greenland and Antarctic ice sheets could imply several meters of sea-level rise, major changes in coastlines and inundation of low-lying areas, with the greatest effects in river deltas and low-lying islands. Current modeling suggests that such changes are possible for Greenland over millennial time-scales, but because dynamic ice flow processes in both ice sheets are currently poorly understood, more rapid sea-level rise on century timescales cannot be excluded.

Runoff and river discharge

Changes in river flows, as well as lake and wetland levels, due to climate change depend primarily on changes in the volume and timing of precipitation and, crucially, whether precipitation falls as snow or rain. Changes in evaporation also affect river flows. The larger of river runoff changes reach 20% or more of the simulated 1980–1999 values, which range from 1 to 5 mm/day in wetter regions to below 0.2 mm/day in deserts (**Figure 1.8**) [Bates, 2008].

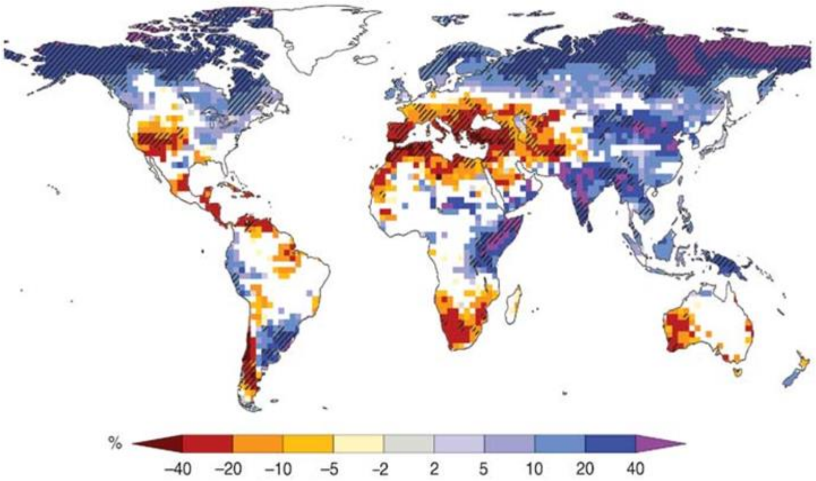


Figure 1.8 Large-scale relative changes in annual runoff for the period 2090–2099, relative to 1980–1999 [Bates, 2008]

This global map of annual runoff illustrates large-scale changes and is not intended to be interpreted at small temporal (e.g., seasonal) and spatial scales. In areas where rainfall and runoff are very low (e.g., desert areas), small changes in runoff can lead to large percentage changes. In some regions, the sign of projected changes in runoff differs from recently observed trends. In some areas with projected increases in runoff, different seasonal effects are expected, such as increased wet-season runoff and decreased dry-season runoff.

1.2 STUDY AREA

Ariake Sea is used as study area here, The Ariake Sea located in the west part of Kyushu Island, Japan, is a semi-closed shallow sea with macro-tidal and several well-mixed estuaries (see **Figure 1.9**). The total area of the sea is about 1,700 km^2 with l00 km gulf axial length, 16 km in average width, and 20 m of average water depth. The basin is very large area extending to 5 prefectures of Saga, Fukuoka, Kumamoto, Nagasaki, and Oita, or 8,400 km^2.

Figure 1.9 Kyushu Island and the Ariake Sea location
(Data source: Google map)

The intensity of mixing water between salt water and fresh water is higher in here, as the largest bay in Kyushu Island, Ariake Sea has over 100 rivers, both small and large and flows into it, such as the Chikugo River which runs down from Mount Kujyu. Water tides here can reach up to six meters, and the tidal flats that this creates provide a unique ecosystem forms of life. In the Ariake

Sea environment here allows a broad range of marine products to be harvested, and these are then delivered across the country. In particular, the vast taste of the Nori across Japan farmed here, and it is known as Ariake Nori.

1.3 THE HEAVY RAINFALL IN 2012 ON KYUSHU ISLAND

Precipitation extreme as one climate change indicator is used in this study as a research subject to simulate several numerical experiment cases. Therefore, precipitation data from the study area (Kyushu Island) will be assessed for several years to find when is the heavy rainfall occur in Kyushu region.

Table 1.2 July monthly precipitation (in mm) at 21 stations (from north to south) in the area of Kyushu. Precipitation totals of July 2012 exceeding the mean of 1961-1990 are red marked [Japan Meteorological Agency, 2017].

	July precipitation (mm)	
station	**2012**	**1961-1990**
Shimonoseki	**376**	264
Iizuka	**456**	308
Fukuoka	**464**	258
Hirado	317	330
Hita	**1015**	323
Saga	**649**	341
Oita	**517**	240
Sasebo	**374**	327
Asosan	**1130**	670
Kumamoto	**489**	393
Unzendake	**588**	530
Nagasaki	223	334
Nobeoka	249	261
Hitoyoshi	**581**	425
Ushibuka	**325**	288
Akune	325	338
Miyazaki	**395**	288
Miyakonojo	**636**	343
Aburatsu	**340**	277
Kagoshima	**418**	304
Makurazaki	**299**	239

In the period from 11th to 14th July 2012, in the Northern Kyushu, heavy rain fell on the northern part of Kyushu, Japan. The record-breaking heavy rain (see **Table 1.2**) caused floods and landslides, especially in Kumamoto, Oita, Fukuoka, and Saga Prefectures and some rivers reached the highest discharge above the past largest recorded one [Haeseler, 2012]. Although these events have not had evidence associated with global warming effect however as anomaly events, this has interested some expert in conducting some researchers by using data from this phenomenon to protect water environment and its ecosystem in future.

1.4 THE PROBLEMS OF RECENT STUDY

1 Climate change is the main problems in this study. IPCC has reported in the 5th assessment report (AR5) [IPCC, 2013] that there is no doubt about global warming during the past and until the end of this century. Related to the aquatic environment and its ecosystems global warming has the significant impact on each alteration of the aquatic environment.

2 Aquatic ecosystems are critical components of the global environment. In addition to being essential contributors to biodiversity and ecological productivity. However, aquatic systems have been increasingly threatened, directly and indirectly.

3 There are some environmental problems in the aquatic system caused by climate change effects such as changes in seasonal patterns of precipitation and runoff will alter hydrologic characteristics of aquatic systems, affecting species composition and ecosystem productivity.

4 Climate change impact implies all component in an aquatic system due to populations of marine organisms are sensitive to shifts in the frequency, duration, and timing of extreme precipitation events, such as floods or droughts.

5 Increases in water temperatures as a result of climate change will alter fundamental ecological processes and the geographic distribution of aquatic species. Such impacts may be ameliorated if species attempt to adapt by migrating to suitable habitat.

6 Climate change is likely to alter interaction pattern between seawater and freshwater system due to alteration of precipitation pattern and increasing trend of sea surface level (SST). This condition implies the distribution

of the total river runoff that flowing in the coastal area.

7 The region of freshwater influence (ROFI) was promoted by Simpson (1997) is water interfaces area between seawater and freshwater, this region is vulnerable area to some environmental problems related to alteration of the aquatic system due to climate change phenomena.

8 ROFI is an important area in the aquatic environmental system due to it has a pivotal role in determining water quality in the coastal zone and shelf seas.

9 The sustainability of all organisms in an aquatic ecosystem is most depend on stirring process between seawater and freshwater in ROFI. The freshwater that contains abundant nutrient from river runoff for all marine organisms will be affected if the interaction patterns between seawater and freshwater in this area is disturbed.

10 Related to the climate change impact on the aquatic ecosystem, alteration of precipitation trend and increasing trend of water temperature are two climate change indicators implicate to the ROFI condition.

11 Water stratification and change of baroclinic flow and its structure are some aquatic environment problems caused by the difference of water density, and its temperature is vulnerable in ROFI area.

12 Aquatic ecosystems have a limited ability to adapt to climate change, to reduce the likelihood of significant impacts to these systems.

13 Climate change impact on the aquatic environment and its ecosystem, this is not simply because this global project involved many nations in worldwide and it is needed political will from all governments to work

together to look for solutions and solve this problem. These include maintaining riparian forests, reducing anthropogenic activity cause global warming and greenhouse effect.

1.5 RESEARCH OBJECTIVES

According to some aquatic environmental issues related to climate change phenomena that mentioned above. The action to solve some problems have been done by many researchers and environment expert since climate change issue begin and become the global problem. However, considering the enormity of environmental challenges caused by climate change impact, the effort that has been done to date is still considered not enough. Therefore, by this research, we try to make some contribution by making some research assessment to solve some aquatic environmental problems especially in Region of Freshwater Influences (ROFI) related to climate change effect due to pivotal role ROFI to determine water quality in an aquatic environment.
By this research, we want to some assess to the ROFI physical condition after heavy rainfall occurs by using numerical simulations method such as:

1. To see how is heavy rainfall effect to alteration of physical condition of water in ROFI.

2. To see how extreme precipitation effect on the change of baroclinic flow and baroclinic structure in ROFI area.

3. To see how change of precipitation intensity effect to baroclinic flow and its structure in ROFI.

4. To see how different of water temperature between seawater and freshwater effect on baroclinic flow and Its structure related to precipitation extreme in ROFI

5. To see how is the potential threat of water temperature alteration due to climate change impact in ROFI.

1.6 DISSERTATION ORGANIZATION

This dissertation comprises of six chapter. The structure of the dissertation can be schematized as in **Figure 1.10.**

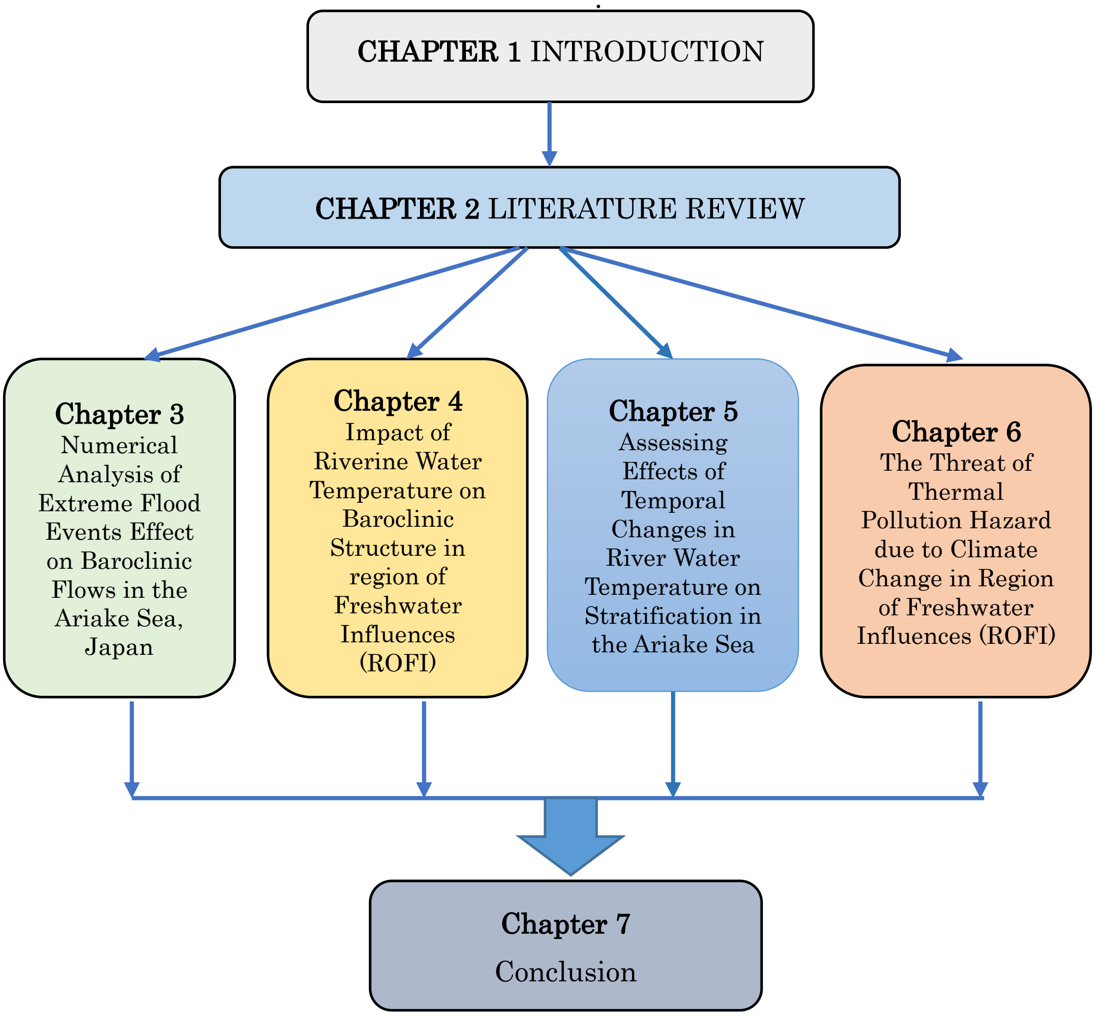


Figure 1.10 Dissertation organization

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CHAPTER 2
LITERATURE REVIEW

ABSTRACT

This chapter shows several previous researches related to our study. How the impact of climate change to the aquatic environmental system is shown from some research results that have been conducted by some experts, more than that, the study about ROFI as the primary object of this study is discussed to show how its vulnerary and potential threat due to climate change impact. The resulting study about the heavy rainfall that caused flood and landslide in the Northern Kyushu at the middle of 2012 is shown in this chapter, too. And to obtain the description in detail, all research topic is discussed separately each other.

2.1 INTRODUCTION

The world is getting warmer [IPCC, 2014]. Currently, after climate change become a hot issue in some environmental experts meetings, the environmental study has been an interesting issue and inviting many researchers and the scientist group that involves and organized by the government organization, non-governmental organization (NGO) and many universities in the worldwide. In the global environment, aquatic ecosystems are critical components. In addition to being essential contributors to biodiversity and ecological productivity, they also provide a variety of services for human populations. However, aquatic systems have been increasingly threatened, directly and indirectly by global climate change (shown on **Figure 2.1**) [Poff, Brinston, 2002].

In a marine aquatic environment, the region of freshwater influences (ROFI) which proposed by Simpson has an important role to determine the condition of the marine environment and ecosystem [Simpson, 1997]. All ROFI systems in the distinctive feature are the input of the significant amount of buoyancy from river runoff [Simpson, 1997]. However, the climate change impact on ROFIs has not been discussed, yet.

2.2 CLIMATE CHANGES IMPACT ON MARINE SYSTEM STUDIES

The study that discusses climate change impact on the marine system is the most popular theme that conducted by many aquatic environmental experts. The marine environmental research related to climate change impact has done by many researchers in many themes and topics in order to assess an aquatic environmental quality by using some climate change indicators such as rising trend of temperature at the surface over the sea and land, sea level rise, extreme event, and so on [U.S. Environmental Protection Agency, 2014].

Many studies argue if the phenomena of climate change have the strong influence on the seasonal of precipitation pattern [Miranda *et al.,* 2011]. For example, the increasing temperature over an ocean as one of the indicators of climate change has implications for increasing rate of evaporation that occurs on the sea surface, this condition gives an impact on the precipitation [Trenberth, 2011], and it will affect to each step of the hydrologic cycle.

Precipitation in meteorology term is a result of the condensation of atmospheric water vapor that falls under gravity influence. The drizzle, rain, sleet, snow, and hail are main forms of precipitation. Precipitation occurs when a portion of the atmosphere becomes saturated with water vapor so that the water condenses and precipitates. Most precipitation falls as rain [Trenberth, 2011]. Precipitation is a crucial component of how water moves through Earth's water cycle, connecting the ocean, land, and atmosphere [NASA, 2017]. Precipitation is responsible for depositing most of the freshwater on the planet. Approximately 505,000 km^3 of water falls as precipitation each year, 398,000 km^3 of it over the oceans. Given the Earth's surface area, that means the globally averaged annual precipitation is 990 mm [Wikipedia, 2017].

Trends in precipitation are always consistent with changes in runoff [Trenberth, 2011]. The seasonal pattern of precipitation falling on a watershed is translated into the surface water that feeds into streams. In ecological terms, the extremes of runoff are critical events that influence species composition and the productivity of aquatic and wetland communities [Poff, Brinston, 2002]. .

Precipitation is high enough to sustain year-round flow in streams. Thus, the knowledge of the particular regional changes in stream flow regimes brought about by climate change is critical to anticipating ecological impacts. Some projections are reasonably well supported, and others need to be considered as possible scenarios to evaluate the range of ecological concerns related to a changing climate (see **Figure 2.1**) [Poff, Brinston, 2002].

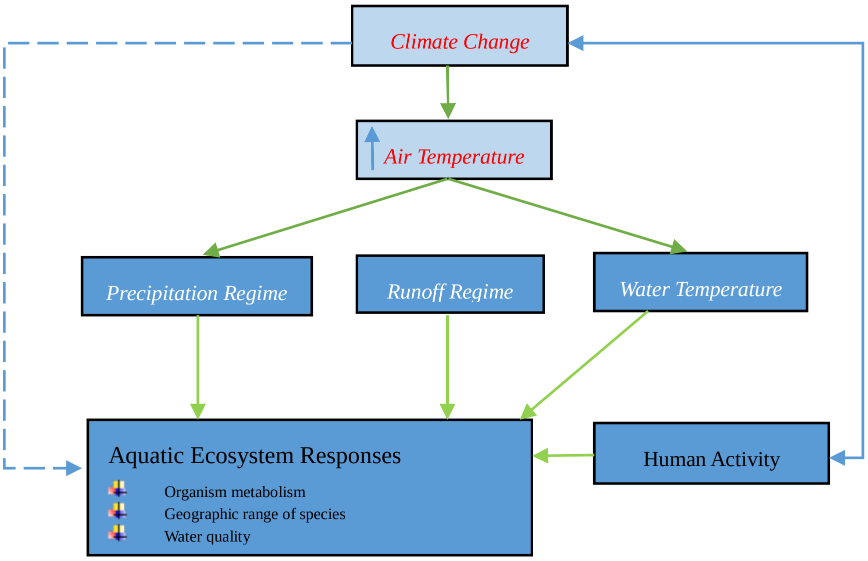

Figure 2.1 Linkages between climate change and environmental drivers of temperature and precipitation that regulate many ecological processes and patterns in inland freshwater and coastal wetland ecosystems.
[Poff, Brinston, 2002]

Estuaries are naturally productive, supporting abundant fisheries also different habitats, including shellfish reefs, ocean grass meadows, what's more, limitless expanses for fringing marshes [Levinton, Doall, Ralston, 2011]. Like the climate, estuaries are infrequently in a steady state, even under existing weather patterns. In general, water reflects the physical condition of an area, including the underlying geology and subsequent geomorphology, and the long-term driving forces such as a climate. Alteration in the atmosphere beyond the natural, historical patterns (as may happen due to climate change) will be subsequently reflected in the estuary [Glamore, Rayner, Rahman, 2016].

Estuarine conditions are inherently connected to and influenced by, climate factors operating over a range of temporal scales. Precipitation patterns and river runoff, temperature, evaporation, radiation, and the wind, along with numerous additional forcing factors, have implicate to the geophysical and biological nature of estuarine landforms, environments and natural communities [Glamore, Rayner, Rahman, 2016]. Imbalances between annual rainfall and heat (temperature and evaporation) can result in climatic extremes, particularly in areas with intense rainfall seasonality. This can dramatically alter the hydrology and salinity throughout an estuary as freshwater inflows influence the tidal processes.

In estuaries, climate change impact will alter nutrition cycle and behavior through modifications to temperature, wind patterns, the hydrological cycle, and sea level rise [Statham, 2011]. They cause the alteration in some impacts such as inundation of freshwater framework, change in stratification, flushing times and phytoplankton productivity, increased coastal storm activity, changes in species and ecosystem function [Statham, 2011].

Climate change influence the vulnerability of estuaries to eutrophication in several ways, including changes in mixing characteristics caused by alterations in freshwater runoff, and changes in temperature, sea level, and exchange with the coastal ocean [Najjar *et al*., 2000]. A direct effect of changes in temperature and salinity may be seen through changes in suspension feeders such as mussels, clams, and oysters. The abundance and distribution of these consumers may change in response to new temperature or salinity regimes, and they can significantly alter both phytoplankton abundance and water clarity [National Research Council (NRC), 2000].

The increasing trend of water temperature is the main of climate change indicator that has the significant effect on aquatic organisms. Temperature and moisture regimes are the key variables that determine the distribution, growth and productivity, and reproduction of plants and animals. Changes in hydrology can influence species in a variety of ways, but the most completely understood processes are those that link moisture availability with intrinsic thresholds that govern metabolic and reproductive processes [Burkett *et al*., 2005].

There are several climate change impacts on abiotic change such as biological performance, chemistry changes, changes in temperature for the performance and survival of many organisms, ocean circulation, distributional shifts and finally, synergistic effects between climate [Harley *et al.*, 2006]. The alteration of abiotic has consequences on climate that related to water quality variables such as CO and pH level.

In order to anticipate the climate change impact on the coastal marine system is needed to establish the marine protected areas to understand and determine the all ecologists process must such as: when, where, and how the role of any given climatic driver is dependent upon other forcing variables [Harley *et al.*, 2006].

2.3 THE ROFI RESEARCH

The ROFI term was introduced in the first time by Simpson (1993) is the part of the coastal area where the freshwater from river runoff contributes a significant input of buoyancy to those parts of the shelf seas adjacent to estuaries [Simpson, 1997]. The buoyancy input is responsible for producing a physical regime which is radically different from the other parts of the shelf seas. In the ROFI, interaction process from two kinds of water from estuarine and Shelf Sea creates a complex water regime

In the marine system, ROFI has a significant role to determine the quality of aquatic environmental condition due to the existence of ROFI role in managing nutrient runoff under the river flow [Simpson, Sharples, 2012]. The river runoff contaminants that come from estuary will affect to this region, furthermore impact on the shelf sea environment. It is also in ROFIs that river-borne particulate matter is initially deposited and frequently re-suspended. Land-derived inputs frequently maintain high nutrient concentrations in ROFIs with attendant dangers of nuisance blooms which may be toxic and eutrophication which may result in hypoxia. The proper management of these problems, and of the pollution threats posed by heavy metals and xenobiotic, will depend on our understanding and modeling of the ROFI.

This baroclinic flow acts to induce stratification of the water column of the ROFI in competition with the stirring processes. It is the interaction of this buoyancy forcing with the stirring mechanisms provided by tides, wind, and waves, and worked out in a variety of different topographic settings, which provides the necessary subtlety and variety of ROFI.

According to schematic of the characteristic regimes of the shelf, estuary, and ROFI by Simpson, ROFI characteristic in water column located between estuary (freshwater) and water mixed nature (see **Figure 2.2**). In estuary characteristic is dominated by freshwater, therefore, stratification of water is not found in here caused by differences in water density. This condition almost related same with the characteristics of water in the mixed zone, where the water density in here as the result of a stirring process creates water density tend to uniform in another term the stratification of water in here is "zero".

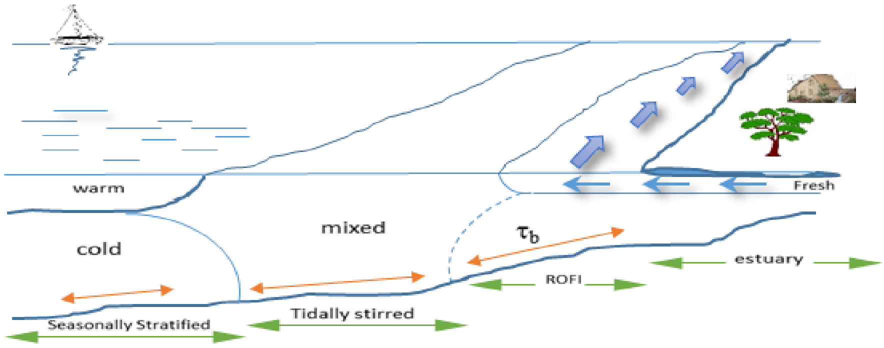

Figure 2.2 Schematic of the characteristic regimes of shelf, estuary and ROFI [Simpson, 1997]

Before being mixed into the deep ocean circulation, all freshwater from river runoff must first pass through the shelf regime, where it is progressively diluted as it mixes with the ambient seawater. It is not surprising, therefore, to obtain that the impact of river runoff is most evident in estuary and in adjacent regions. In some cases this input may act as the dominate buoyancy source for all parts of annual cycle.

In estuarine environments, the competition between buoyancy input and stirring occur. Freshwater input from rivers enters through the lateral boundaries and is distributed by buoyancy-driven flows in a manner which is familiar to estuary and ROFI. This re-distribution of buoyancy makes the problem much harder than its heating-stirring counterpart.

In the development of the ROFI research, it has been done by some researchers due to ROFI role, and this becomes the more interesting research object when they discuss on the climate change impact in all implication and alteration on ROFI area. In the book “National Security and Human Health Implications of Climate Change”, the chapter 25: Implication climate change for marginal and inland seas shows the assessment of the ROFI area conducting by evaluation of the change of pH level due to alteration of Sea Surface Temperature (SST) related to climate change impact in several measurements regions on the marginal and inland seas by using the rising trend of ocean water temperature data as climate change indicator to make assessment. In this research, the evaluation of climate change impact on the ROFI area was done to see the correlation rising water temperature trend with pH level. The assessments of pH level were done by examining the SST directly following increasing water temperature in the ocean,

The ROFI study by using numerical modeling conducted by Gensen (2016) explored the effect of the Sand Engine on the Rhine ROFI in several type model of the tide. In a very pragmatic approach, this problem has been simplified and analyzed using Delft3D-FLOW. The analysis of climate change impact on this study did not discuss, the specific case of the Sand Engine, a sandbar-shaped peninsula in front of the Holland coast, was studied. The objective was to identify changes in the Rhine ROFI caused by the Sand Engine and their possible causes

The most important result from this study was the fresh water feature distribution was affected by the tide level condition in the front of at the location of the Sand Engine.

2.4 MIXING PROCESS IN OCEAN RESEARCH

In general studies, the alteration of physical water characteristic where the river water meets the sea water area affected by temporal variations in tidal amplitude, river flow, seasons, winds, and waves. Furthermore, fluctuations in ocean temperature produced by surface heating and cooling, and in salinity due to evaporation, precipitation, river runoff and freezing, are stirred into the sea by permanent current systems and large scale eddies, and finally dissipated by molecular action on small scale irregularities produced by a variety of processes. A thorough understanding and correct parameterization of these sub-grid scale stirring and mixing mechanisms are likely to be important in any ocean general circulation model used in studies of climate.

The climate impact on the mixing in an estuary is the product of a variety of effects and factors - including *wind stirring, tidal excursion, barometric pressure fluctuations, buoyancy input from freshwater inflow, bathymetry variations, and gravitational circulation* [Fischer, 1979], [Simpson, 1997] , [Hamilton, Chan, Robb, 2001]. These factors combine, interact and superimpose to create circulation patterns unique to each estuary. In addition to this, it is rare for any estuary to be in a steady state for a long period, due to the natural fluctuations of these influencing factors and the differing timescales of each [Fischer, 1979].

Figure 2.3 shows the velocity profile that develops in the water column as the shear-flow system is established, including a depiction of the “no-slip” condition, where frictional forces at the bottom boundary reduce the velocity of the water to zero. With no further inputs of potential or kinetic energy (such as tides or wind action), the estuary will tend toward complete stratification and fresh water will flow towards the sea in an undisturbed layer at the surface, and the salt flux of the system would be dominated by adjective transport [Fischer, 1979]. **Figure 2.4** illustrates how as this basic estuarine circulation is extended into three dimensions, transverse circulation occurs but the longitudinal flow continues to exhibit the same correlations between flow direction and depth – surface waters flow towards the ocean, and deeper waters flow landward.

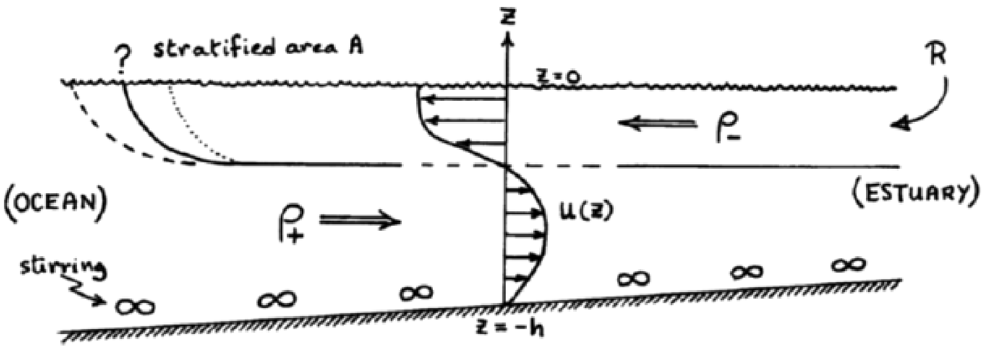

Figure 2.3 The development of stratification through the freshwater input, including the effects of the no-slip condition at the lower boundary of the water column [Simpson, 1990].

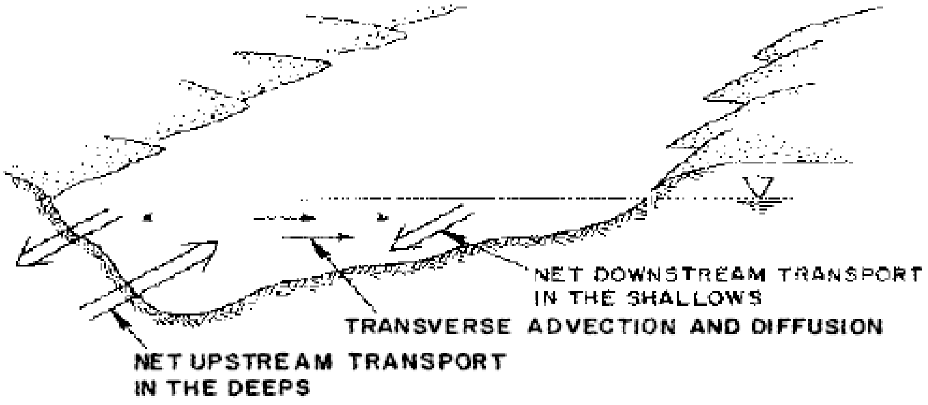

Figure 2.4 Simplified estuarine circulation incorporating 3-dimensional variation and flow [Fischer, 1979]

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2.4.1 Tidal Mixing

In tidal mixing processes the oscillation of water levels causes the boundary layer between the fresh and salt water to travel up- and down-stream, and it is this motion which contributes kinetic energy to the system [Fischer, 1979]. *The extent of this mixing is determined by the amplitude and period of the tidal oscillation*. As a result, an estuary with minimal tidal influence and a steady freshwater inflow will tend to be dominated by the buoyancy input of the river and form a vertically stratified water column. Conversely, the high levels of kinetic energy contributed to an estuary experiencing large tidal oscillations will tend to override the freshwater inflow, causing turbulence and forming a well-mixed water column [Fischer, 1979], [Simpson *et al*., 1990].

2.4.2 Tidal Straining

Tidal straining is another potentially major stratification and mixing process in aquatic systems. During the ebb of a tidal cycle, a shear develops as the less dense fresh water flows faster towards the ocean, overtaking the denser seawater. The development of shear instability from this process, and drives the system towards a vertically stratified state [Simpson *et al*., 1990]. As with all mixing controls, the level of dominance that this mixing process exerts varies widely between estuaries, and often changing seasonally within each estuary.

2.5 ARIAKE SEA AND HEAVY RAINFALL EVENTS IN 2012 RESEARCH

Ariake Sea is used as study area here, The Ariake Sea located in the west part of Kyushu Island, Japan (see **Figure 2.6**), is a semi-closed shallow sea with macro- tidal and several well-mixed estuaries. The total area of the sea is about 1,700 km^2 with l00 km gulf axial length, 16 km in average width, and 20 m of average water depth. The basin is a very large area extending to 5 prefectures of Saga, Fukuoka, Kumamoto, Nagasaki, and Oita, or 8,400 km^2. Vast quantities of nutrients flow into the sea, and due to its shape, the retention period is long. Hence, the Ariake Sea is a homeostatic eutrophic area. Typically, eutrophic areas tend to suffer from the formation of red tides or the appearance of anoxic water mass leading to a decrease of fish production.

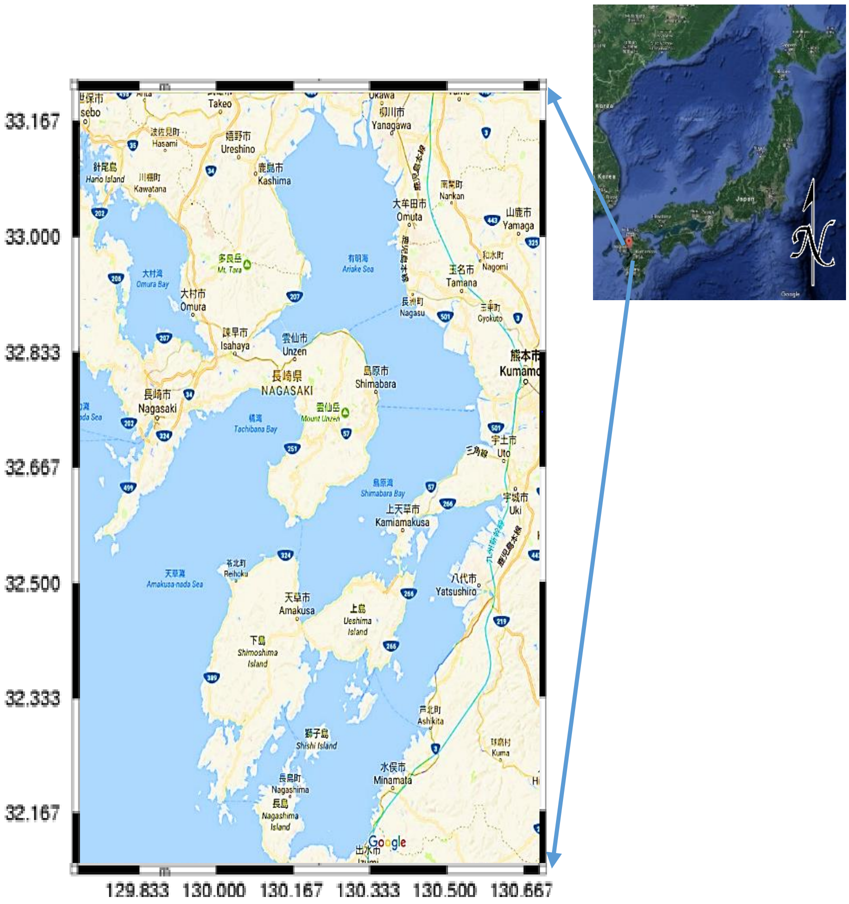

Figure 2.5 Japan map and Ariake Sea location (Data source: Google map)

The intensity of mixing water between salt water and fresh water is higher in here, as the largest bay in Kyushu Island, Ariake Sea has over 100 rivers, both small and large and flows into it, such as the Chikugo River which runs down from Mount Kujyu. Water tides here can reach up to six meters, and the tidal flats that this creates provide a unique ecosystem forms of life. In the Ariake Sea the environment here allows a broad range of marine products to be harvested, and these are then delivered across the country. In particular, the vast taste of the nori across Japan farmed here, and it is known as Ariake Nori.

However, owing to its unique character, the Ariake Sea has not suffered from any of these issues. In fact, seaweed (Nori) aquafarming has been increasing in the Ariake Sea, currently accounting for 40% of the Nori production in Japan. Moreover, because there are large areas of tidal flats (>200 km^2), many bivalves inhabit this area; in turn, the Ariake Sea has been renowned for bivalve production. Thus, the Ariake Sea was known for its high biological productivity. Previously, the Ariake Sea has not suffered from environmental issues, despite the eutrophic nature of the area. However, its environmental deterioration is becoming a serious social problem with the recent occurrence of large red tides. Since 1985, the number of red tide outbreaks has exceeded 20 times/year. During the period 1998-2002, red tides occurred > 30 times/year.

The heavy rains fell on the Japanese main island of Kyushu, in 11th to 14th July 2012, record-breaking heavy rain [Japan Meteorological Agency, 2012], namely the Northern Kyushu Heavy Rain fell on the northern part of Kyushu, causing floods and landslides, especially in northern regions such as Kumamoto, Oita, Fukuoka, and Saga Prefectures [Haeseler, 2012]. Some rivers reached the highest discharge above the past largest recorded one. Thus, we attempt to investigate the effect of global warming on freshwater dynamics in a coastal region in the Ariake Sea by three-dimensional numerical experiments in several cases with river runoff in the Northern Kyushu Heavy Rain Event in 2012 and some modified runoff as a projection of climate change. Although these events have not had evidence associated with global warming effect however as anomaly events, this has interested some expert in conducting some researchers by using data from this phenomenon to protect water environment and its ecosystem in future.

2.6 NUMERICAL SIMULATION AND CLIMATE MODEL

Numerical simulation scientific advances as an ever-increasing reach of geophysical phenomena will include tremendously should our understanding of unpredictable forms within our climate system. The results for humankind about continuous climate change will be broad. Numerical climate models of Earth were needed to make prediction fluctuation and alteration on atmosphere regimes about previous and future millennia.

Related to climate change issues, the utilizing numerical simulation on climate model has been done to make climate change simulation mode by using some climate change indicator to see the implication of climate change impact to the environmental system and furthermore to determine the proper method as anticipation action to protection on our environmental existence.

The development of numerical simulation research to make weather and climate prediction has occurred since early 19th century till now. From the Intergovernmental Panel on Climate Change (IPCC) report as the assessments result of climate change report can be see that the climate prediction reflection on The Representative Concentration Pathways (RCPs), which is used for making projections based on some factors, such as: pathways of greenhouse gas (GHG) emissions, air pollutant emissions, precipitation, air temperature, seawater temperature, and land use. The different RCPs report shows some condition of climate scenarios and certain functions, they can be seen at the stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0) and very high scenario one (RCP8.5) [IPCC, 2014].

The implementation of numerical simulation model in climate prediction on the RCP can be seen on the prediction of the global mean surface temperature change for the period 2016–2035 relative to 1986–2005 (see **Figure 2.7**) is similar for the four RCPs and will likely be in the range 0.3°C to 0.7°C [IPCC, 2014], in addition to the global mean surface temperature, prediction extreme precipitation events is the important thing relate climate change issue. Change in average precipitation based on multi-model mean projections for 2081–2100 relative to 1986–2005 under the RCP2.6 and RCP8.5 scenarios (see **Figure 2.7**). The number of models used to calculate the multi-model mean is indicated where the projected change is large compared to natural internal variability and where at least 90% of models agree on the sign of change [IPCC, 2014].

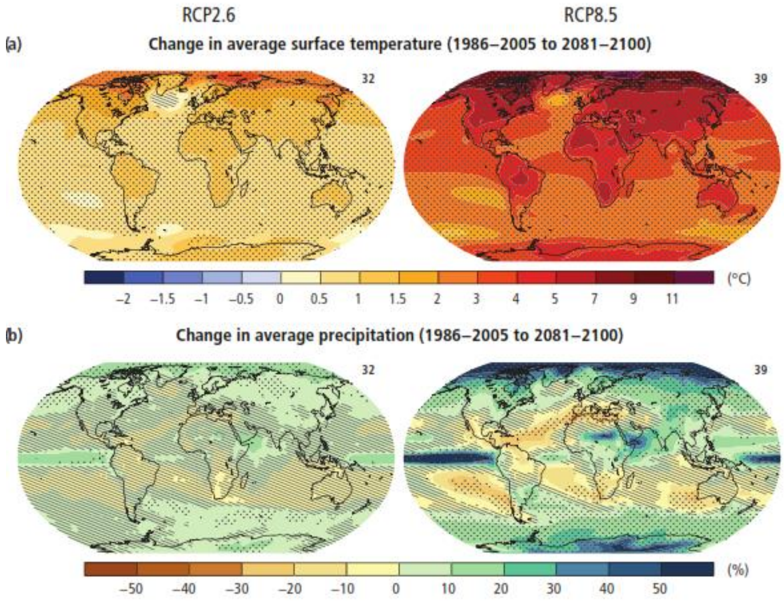

Figure 2.6 the prediction of the global mean surface temperature (a) and precipitation (b) based on multi-model mean projections for 1986-2005 to 2081-2100 [IPCC, 2014]

In this study, the Delft3D model is used to make calculation and simulation. Delft3D is the integrated flow and transport modeling system of Deltares for the aquatic environment. The flow module of this system, viz. Delft3D-FLOW provides the hydrodynamic basis for other modules such as water quality, ecology, waves, and morphology. For steady and non-steady modeling of the far-field water quality and ecology [Deltares, 2011].

The hydrodynamic module Delft3D-FLOW simulates two-dimensional (2DH, depth-averaged) or three-dimensional (3D) unsteady flow and transport phenomena resulting from tidal and meteorological forcing, including the effect of density differences due to a non-uniform temperature and salinity distribution (density-driven flow). The flow model can be used to predict the flow in shallow seas, coastal areas, estuaries, lagoons, rivers, and lakes. It aims to model flow phenomena of which the horizontal length and time scales are significantly larger than the vertical scales [Deltares, 2011].

Three-dimensional modeling is of particular interest in transport problems where the horizontal flow field shows significant variation in the vertical direction. This variation may be generated by wind forcing, bed stress, Coriolis force, bed topography, or density differences. Examples are the dispersion of waste or cooling water in coastal areas, upwelling and downwelling of nutrients, salt intrusion in estuaries, freshwater discharges in bays and thermal stratification in lakes and seas [Deltares, 2011].

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CHAPTER 3
NUMERICAL ANALYSIS OF EFFECTS OF EXTREME FLOOD EVENTS ON BAROCLINIC FLOWS IN THE ARIAKE SEA, JAPAN

ABSTRACT

IPCC had reported in the 5th assessment report (AR5) that there is no doubt about global warming during the past and until the end of this century. Many investigations as an evaluation of the impact of global warming on a coastal region have been conducted, for example, on sea level rise, sea water temperature increase, sea water acidification, and so on. However, the baroclinic structure in a coastal region due to change of rainfall pattern has not been discussed, yet, except for effect on the marine ecosystem. In this chapter, the Delft3D model in a coastal area was used as the numerical model to makes a three-dimensional hydrodynamic model analysis. In the other hand, the numerical experiment condition, the river discharge data was used and observed start from January 1, 2012. Firstly, the preliminary numerical simulation was carried out for approximately six months (till 5th July). Next, we conducted the numerical analysis to compare an effect of runoff pattern on the baroclinic flow for 20 days from 6th July to 26th July 2012. Finally, we modification river discharge data by using multiplier factor α *(0.8 - 2.0) to make several case condition and makes a comparison for each case. From the comparison among numerical experiments for several extreme floods considering as a projection of climate change, change of rainfall pattern can change the baroclinic structure in a coastal region of the Ariake Sea. This result suggests that regime change of marine environment and ecosystem can change due to climate change.*

3.1 BACKGROUND AND RESEARCH OBJECTIVES

IPCC has reported in the 5th assessment report (AR5) [IPCC, 2013] that there is no doubt about global warming during the past and until the end of this century. Thus, we have to take account of global warming as a fundamental condition to consider the countermeasures as an adaptation to the future situation. In the report, we can see the upward trend of yearly precipitation in the mid-latitude region including Japan in high confidence after 1951. Many investigations as an assessment of the impact of global warming on a coastal area have been conducted, for example, on sea level rise, sea water temperature increase, sea water acidification, and so on. However, an effect on regions of freshwater influence (ROFIs) [Simpson J. H., 1997] on the baroclinic structure in a coastal area due to change of rainfall pattern has not been discussed, yet, except for effect on the marine ecosystem. The ROFIs which proposed by Simpson has an important role in determining the condition of the marine environment and ecosystem in coastal areas [Simpson Sharples, 2012].

In 11th to 14th July 2012, record-breaking torrential rains [Japan Meteorological Agency, 2012], namely the Northern Kyushu Heavy Rain fell on the northern part of Kyushu, causing floods and landslides, especially in Kumamoto, Oita, Fukuoka, and Saga Prefectures [Haeseler, 2012]. Some rivers reached the highest discharge above the past largest recorded one. Thus, we attempt to investigate the effect of global warming on freshwater dynamics in a coastal region in the Ariake Sea by three-dimensional numerical experiments in several cases with river runoff in the Northern Kyushu Heavy Rain Event in 2012 and some modified runoff as a projection of climate change.

3.2 METHODOLOGY

3.2.1 Numerical Model

In this study, we use the numerical model that Yano *et al.* (2010) have developed by applying the Delft3D [Deltares, 2011] which is a generalized three-dimensional hydrodynamic model in a coastal area. As shown in **Figure 3.1** computational domain is the range combining the Ariake Sea and the Yatsushiro Sea, which is also one of the largest semi-enclosed bays in Japan. We apply the linear orthogonal coordinate system of 10" interval resolution (Δx=250 m) horizontally and the ten layers σ-coordinate system vertically.

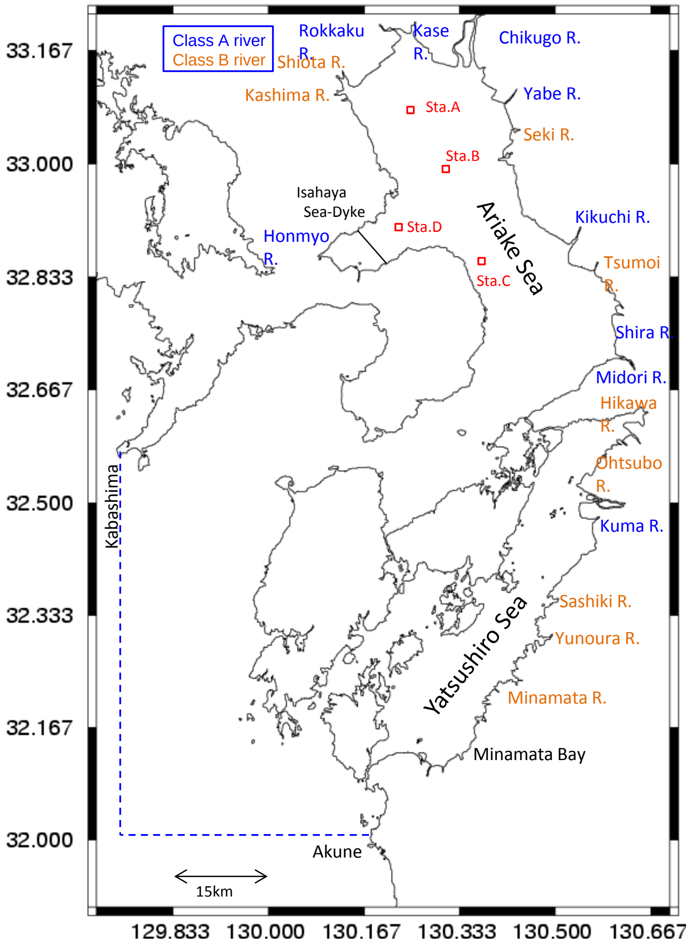

Figure 3.1 Computational Domain

The open boundary was set as a line connecting Akune to Kabashima. 40 tide components are given as an open boundary condition, based on the known harmonic constant of both edges. The harmonic constants (amplitude and lag) only for the four major tidal components (M_2, S_2, K_1, and O_1 tide) were adjusted to the measurement result of the tide at several tide gauges [Yano *et al,* 2009]. Further, the moving wall boundary model for a flat tidal area [Deltares, 2011] is adapted. We omitted description in detail for the calculation accuracy of the present model here, because it was fully confirmed by our previous studies on stratification, the tide and tidal currents [Yano *et al,* 2009].

We consider hourly river discharge from eight A-class rivers (the Chikugo R., the Yabe R., the Kase R., the Rokkaku R., the Kikuchi R., the Shira R., the Midori R., and the Kuma R.) and nine B-class rivers (the Shiota R., the Kajima R., the Seki R., the Tsuboi R., the Hikawa R., the Ohtsubo R., the Sashiki R., the Yunoura R., and the Minamata R.) for simulation of the baroclinic flows due to freshwater inflow (see **Figure 3.1**).

3.2.2 Numerical Experiment Condition

In the present chapter numerical simulation was carried out using observed river discharge data from January 1, 2012. Firstly, the preliminary numerical simulation was carried out for approximately six months (till 5th July). Next, we conducted the numerical analysis to compare an effect of runoff pattern on the baroclinic flow for 20 days from 6th July to 26th July 2012.

Figure 3.2 shows temporal variation of the tide at Oura (near the mouth of Isahaya Bay) and river discharge of A-class Rivers in the Ariake Sea from 6th July 2012 to 26th July 2012. We can see two massive floods on 12th July and 13th-14th July. The first flood has a total peak discharge of about 9,000 m^3/s, and the second one has about 15,000 m^3/s [Japan

Ministry of Land Infrastructure Transport and Tourism, 2012].

Table 3.1 Case for numerical experiments.

Case (i)	Factor α_i
1	1.0
2	1.2
3	1.5
4	2.0
5	0.8

In the present study, this flood (Case-1) is considered as a basic condition of flood event after global warming. Factor α is used as a multiplier factor as shown in the equation (3.1).

$$Q_{(i(t))} = \alpha_i \cdot Q_{1(t)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (3.1)$$

where: i = case number, t = time,

Q_1 = the real river discharge (m^3s^{-1}), and

$Q_{(i(t))}$ = The manipulation of river discharge (m^3s^{-1}).

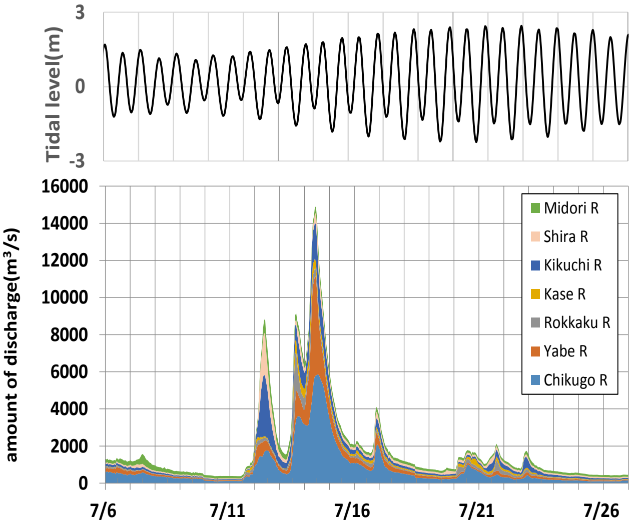

Figure 3.2 Tide and runoff from A-class rivers from 6th-26th July 2012 [Japan Ministry of Land Infrastructure Transport and Tourism, 2012].

Numerical experiments in five cases with a various value of α_i as shown

In **Table 3.1** were conducted to investigate effects of flood discharge on the baroclinic flows in the Ariake Sea due to changing the all river discharge. Especially, case-4 is the most extreme case with the twice discharge of the Northern Kyushu Heavy Rain event. On the other hand, case-5 is the smallest flood situations in this series.

3.2.3 Baroclinic Flow Assessment

Baroclinic in dynamic fluid term is the motion of fluid in ocean or atmosphere that is measured how misaligned the density gradient from the gradient of pressure [wikipedia, 2017]. In the environmental fluid dynamic, the baroclinic flow occurs when levels of constant pressure tend to surfaces of constant density. In this case, density varies with depth and horizontal position [Techet, 2006].

In the ocean, baroclinic play various roles related to alteration water quality condition such as developing of water nutrition components, water stratification, and adjustment of baroclinic flow and its structure cause distribution pattern of chemical and physical components will change vertically and horizontally due to the sensitivity of them on fluctuation of water density and water temperature.

The assessment of baroclinic flow change caused by extreme flood events in Ariake Sea was conducted by comparing the all calculation simulation result from each case that showed the image horizontally in each layer at the particular time.

3.3 RESULT AND DISCUSSION

3.3.1 Horizontal Salinity Distribution Pattern

Figure 3.3 shows the computation result of horizontal salinity distribution in the surface layer (top layer) of the Ariake Sea in case-1 at 00:00 14th July, when passed one day after the largest flood on 13th July. This timing is low tide when freshwater from rivers can spread in the widest area. We can see that riverine freshwater has distributed only in the northern region (head of the bay) where the Chikugo River and the Yabe River are located, and freshwater doesn’t reach to the southern region.

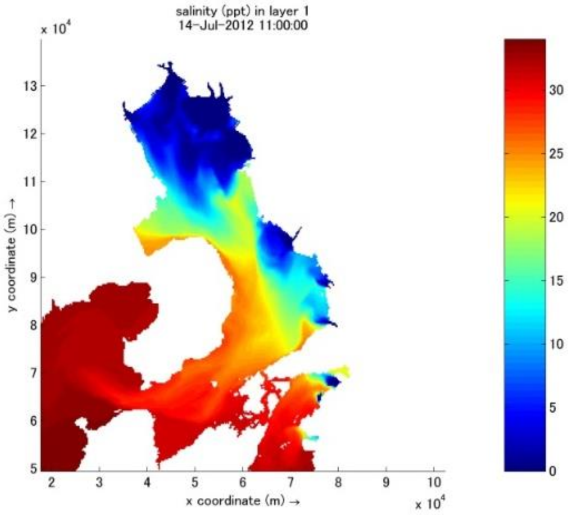

Figure 3.3 Computation result of horizontal salinity distribution in the surface layer in case-1 at 11:00 14th July 2012.

These difference mean possible difference of transport of terrestrial sediment and nutrient can be generated after global warming. It may affect the blooming of phytoplankton (red tide) and generation of bottom anoxic water due to change of stratification.

Figure 3.4 shows the same distribution in case-4, and **Figure 3.5** and **Figure 3.6** show ones in both cases at 12:00 15th July (at low tide after two tidal cycles). From the result in case-4 (**Figure 3.4**), we can see riverine freshwater can reach to Isahaya Bay. From **Figure 3.5**, freshwater in case-1 has reached to Isahaya Bay. From a comparison between **Figure 3.4** and **Figure 3.6**, a significant difference of freshwater spreading in the southern region of the bay can be seen.

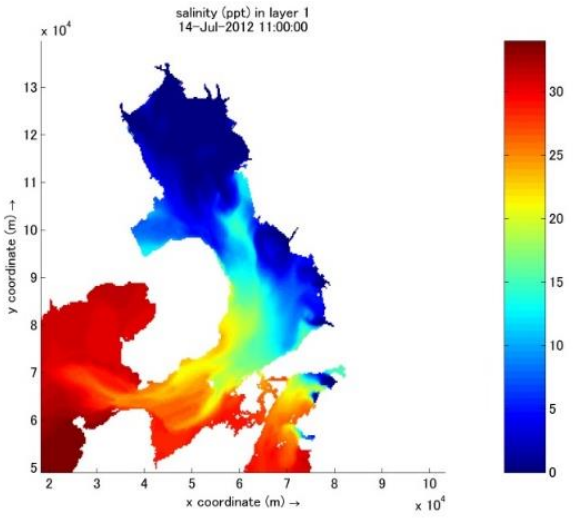

Figure 3.4 Computation result of horizontal salinity distribution in the surface layer in case-4 at 11:00 14th July 2012.

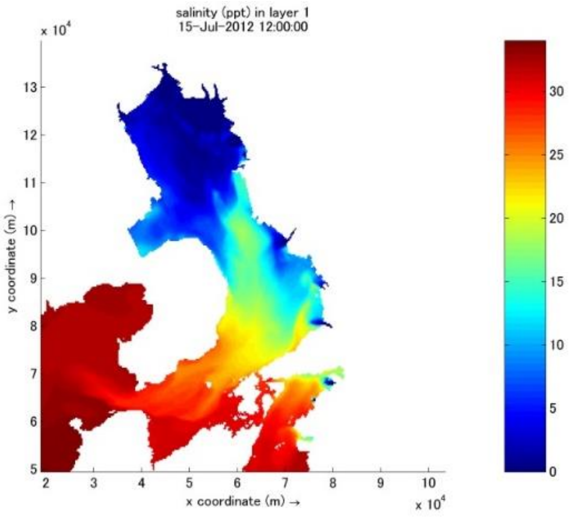

Figure 3.5 Computation result of horizontal salinity distribution in the surface layer in case-1 at 12:00 15th July 2012.

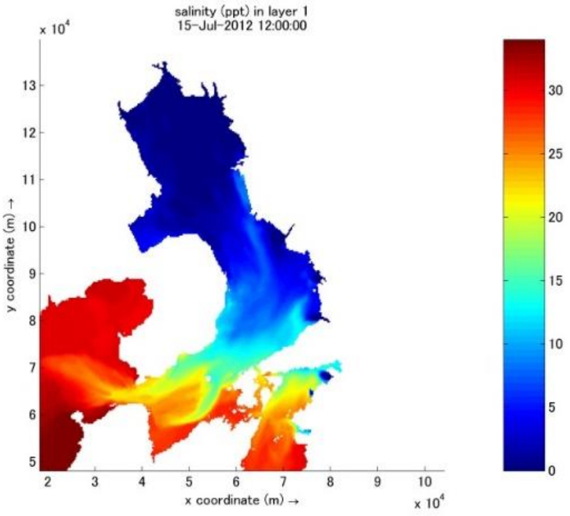

Figure 3.6 Computation result of horizontal salinity distribution in the surface layer in case-4 at 12:00 15th July 2012.

3.3.2 Vertical Structure of Salinity Stratification

Figures 3.7 and **3.8** show computation results of salinity isopleth in case-1 and 4 at Sta. A located in the head of the bay and at Sta. D in Isahaya Bay, respectively. In case-1 the salinity stratification developed during neap tide, and it was weakened in the spring tide. While, in case-4 stratification is weakened due to a large amount of freshwater input during neap tide strong stratification kept during spring tide.

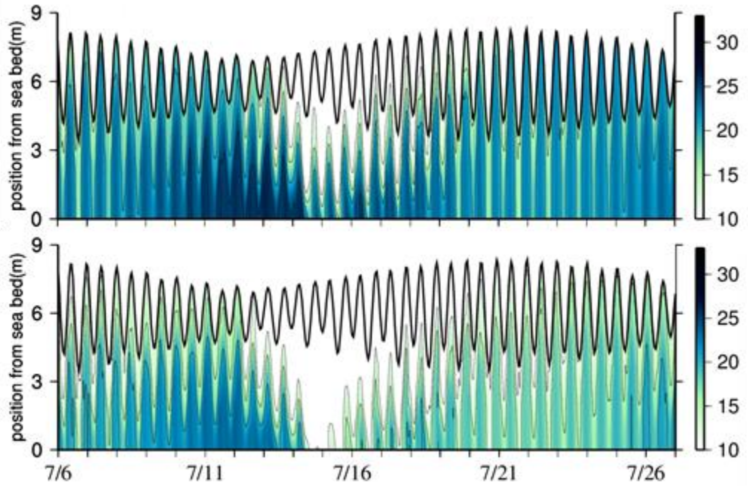

Figure 3.7 Computation results of salinity isopleth in case-1 (upper) and 4 (lower) at Sta. A.

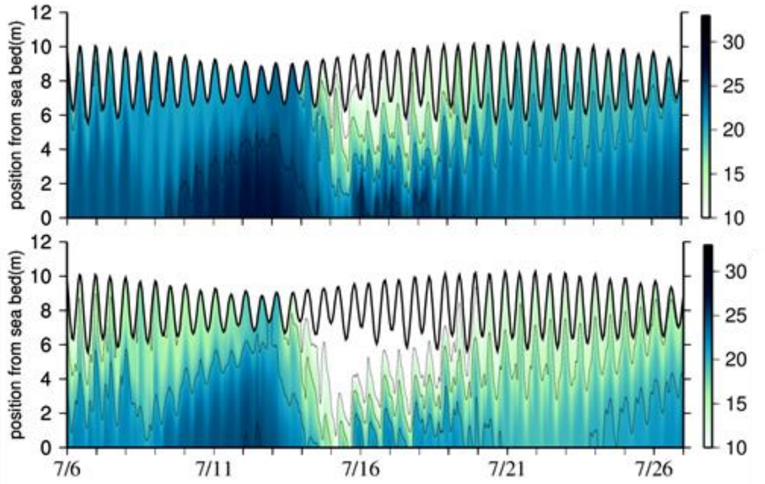

Figure 3.8 Computation results of salinity isopleth in case-1 (upper) and 4 (lower) at Sta. D.

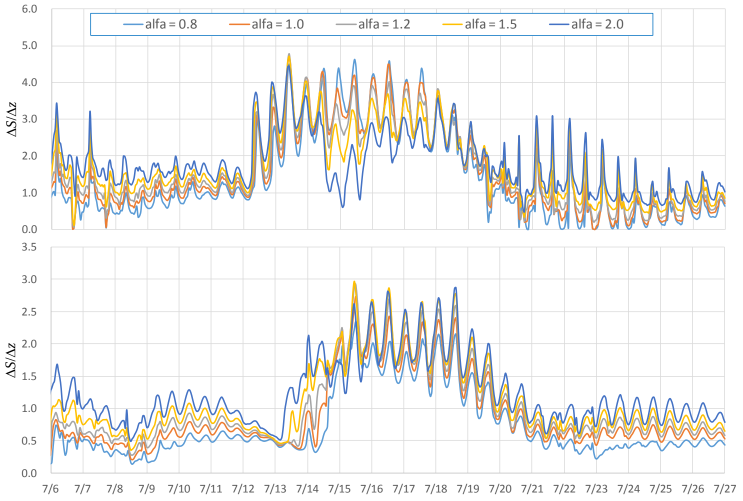

Figure 3.9 Computation results of the temporal change of $\Delta S/\Delta z$ at Sta. A (upper) and Sta. D (lower).

Finally, **Figure 3.9** shows the temporal change of vertical salinity gradient $\Delta S/\Delta z$ [1/m] in all cases at Sta. A and D. Here, ΔS is defined as a salinity difference between a surface layer and bottom one, and Δz is water depth h. $\Delta S/\Delta z$ can demonstrate the strength of stratification. Well mixed condition can be seen during the flood in case-3 and case-4, which are large discharge cases, at Sta. A in the head of the bay, but only strong stratification is shown at Sta. D in Isahaya Bay. This implies that an impact of large freshwater input can be characterized locally.

3.4 CONCLUSION

From the comparison among numerical experiments for several extreme floods considering as a projection of climate change, change of rainfall pattern can change the baroclinic structure in a coastal region of the Ariake Sea. This result suggests that regime change of marine environment and ecosystem can change due to climate change. Thus, further detailed assessment of the impact on water quality and ecosystems is necessary to evaluate the necessity of adaptation to the change.

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CHAPTER 4

IMPACT OF RIVERINE WATER TEMPERATURE ON BAROCLINIC STRUCTURE IN REGIONS OF FRESHWATER INFLUENCE (ROFIs)

Abstract

The global warming has been occurring since the past till 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 to assess an effect of the global warming in the 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.

In this chapter, the Delft3D model was used as the numerical model to conduct the three-dimensional hydrodynamic numerical simulation in the Ariake Sea, Japan. A numerical experiment was performed with the observation data of river discharge and river water temperature to investigate the baroclinic structure in ROFIs due to both of saline-freshwater stratification and thermal one in several cases that show the actual water temperature difference (ΔT*) 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 structure. The results can be used for considering adaptation to aquatic environment and marine ecosystem in a coastal region to the global warming.

4.1 INTRODUCTION

Phenomena of global warming have been occurring since the past till 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 RCP2.6, and this liable to exceed 2°C for RCP6.0 and RCP8.5. Warming will continue beyond 2100 under all RCP scenarios except for RCP2.6 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 [IPCC, 2014]. This trend is followed by rising of sea water surface temperature (SST) [IPCC, 2014], where the SST predicted by using several models such as HadSST2, NCDC, and COBE-SST. The SST in period above 1961 to 1990 in 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 [IPCC, 2014].

Every change of temperature on the sea water surface will directly affect the participation pattern including frequency and its intensity. Under the RCP8.5 scenario, the annual mean precipitation trend shows in many mid-latitude wet regions including some areas in Japan [Belda, Holtanová, Halenka, 2014] yearly mean precipitation will likely increase [IPCC, 2014]. 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 of water temperature will be followed by decreasing trend of water pH [Munn, 1976]. When the pH drops below 6, a 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 [Munn, 1976]. A decrease in primary production causes a decrease in some individuals at higher trophic levels, including fish that depend on phytoplankton as food [Harley, Hughes, Hultgren, Miner, 2006]. Therefore, in many cases, it is reasonable to believe that warming of seawater will decrease the fish stocks [Harley, Hughes, Hultgren, Miner, 2006].

The regions of freshwater influence (ROFIs) which was proposed by Simpson has the important role to determine the condition of the marine environment and ecosystem in coastal areas [Simpson, 1997]. 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. In the period from 11th to 14th July 2012, in the Northern Kyushu, torrential rains fell on the northern part of Kyushu, Japan [Japan Meteorological Agency, 2012]. The record-breaking heavy rain caused floods and landslides, especially in Kumamoto, Oita, Fukuoka, and Saga Prefectures [Haeseler, 2012]. Some rivers reached the highest discharge above the past largest recorded one. Even though this event has not had evidence if this phenomenon can be associated with global warming effect but as anomaly events have interested some expert to conduct 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 [Yano, Arifin, Nakamura, 2015], 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 pattern 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, 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 in the middle of July 2012. Moreover, a new topic research that discusses "Regions of Freshwater Temperature Influence" (ROFTIs) in a coastal area can be started to see a significant role of temperature determining the condition of the aquatic ecosystem in detail.

4.2 METHODOLOGY

4.2.1 Water Temperature and Salinity Data

Water temperature is the primary physical quantity in this research. Water temperature data in average from seawater and freshwater are used in this numerical simulation, and they are taken from two different location to obtain an ideal temperature data.

The seawater temperature data was taken in Shimabara observation station (Sta. E in **Figure 4.1**), because we didn't see a significant influence on seawater temperature at this area by freshwater input according to our previous calculation result (see **Figure 4.2**) by using an extreme temperature difference between two kinds of water (ΔT_{sr} = 10.0 °C), in which discharge data and simulation period are same.

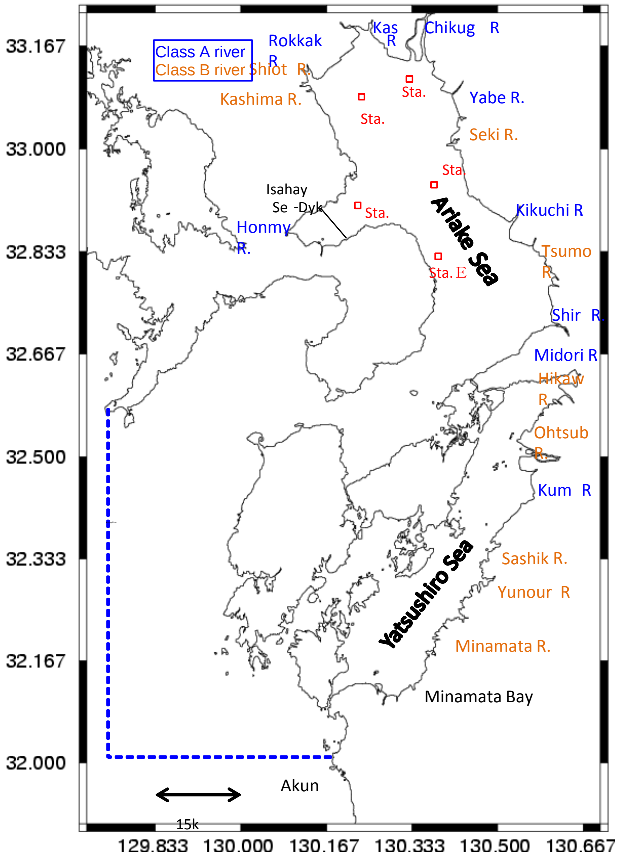


Figure 4.1 Computational Domain

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, 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 significant influence in the Ariake Sea, freshwater temperature data from the Chikugo River is used here.

The normal salinity (29.26 ppt) [Tabata, Hiramatsu, Harada, 2015] is used in this study for all numerical experiment cases to see the impact of the difference of water temperature between seawater and freshwater.

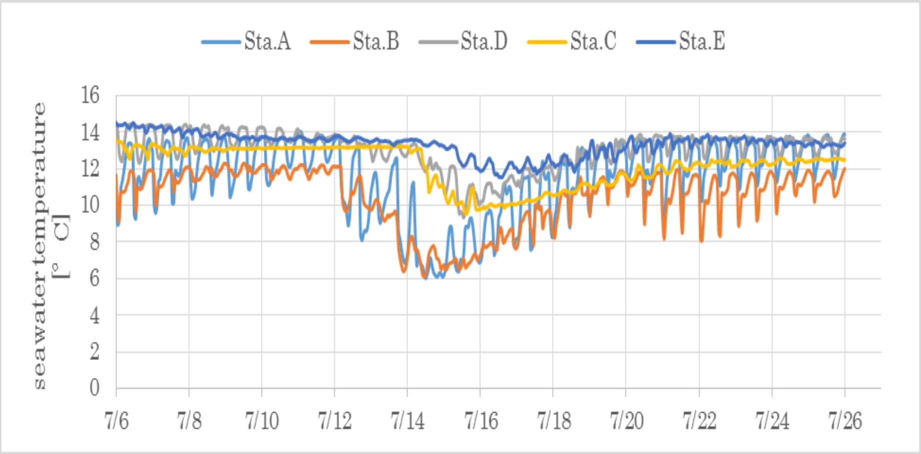


Figure 4.2 Comparison of seawater temperature from five observation stations in the different location during simulation period in the Ariake Sea.

4.2.2 Numerical Model

In this paper, the numerical model adapting Delft3D [Deltares, 2011] that has been developed by Yano *et al*. (2010) is used to conduct the simulation. Similar to our previous paper, the computational domain includes both of the Ariake Sea and the Yatsushiro Sea, which are known one of the largest semi-enclosed bay in Japan (see **Figure 4.1**). 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.

To carry out the calculation, the open boundary is set as a line connecting Akune to Kabashima. 40 tide components are given as an open boundary condition, based on the known harmonic constant of both edges. The harmonic constants (amplitude and lag) only for the four major tidal components (M_2, S_2, K_1, and O_1 tide) are adjusted to the measurement result of the tide at several tide gauges [Yano *et al.*, 2009]. Further, the moving wall boundary model for a flat tidal area [Deltares, 2011] 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 [Yano *et al.*, 2009].

The salinity and temperature of water are used as a physical quantities 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 4.1**) 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 sea water, such in our numerical experiment in this paper, 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 thermal properties effect of the mud during spring tide [Moqsud, Hayashi, Du, Suetsugu, 2006].

"No flux mode" [Deltares, 2011] is selected for the physical process of heat transfer. The hourly river discharge data is considered as operational input in this simulation of the baroclinic flows due to freshwater in flow (see **Figure 4.1**) from eight A-class rivers (Chikugo, Yabe, Kase, Rokkaku, Kikuchi, Shira, Midori, and Kuma) and nine B-class streams (Shiota, Kajima, Seki, Tsuboi, Hikawa, Ohtsubo, Sashiki, Yunoura, and Minamata).

4.2.3 Numerical Experiment Condition

In this chapter, numerical simulation was carried out using observed river discharge data from 1st of June till the beginning of Sep, 2012. Further, the numerical analysis is conducted to compare an effect of temperature difference pattern on the baroclinic flow for 20 days from 6th July to 26th July 2012. **Figure 4.3** shows 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 6th July 2012 to 26th July 2012. From the previous study, the momentum of mixing water between sea water and freshwater will be more effectively in low tide [Fischer et al., 2013]. Therefore, observation in the baroclinic structure by using the peak river discharge about 14,000 m^3/s is conducted twice. The first observation was carried out in one hour after the peak river discharge occurred (at 12:00, on 14th July 2012). For the second it was conducted when tide showed low tide after one day from the peak (at 12:00, on 15th July 2012), then the freshwater spread and gave significant effects on the sea area.

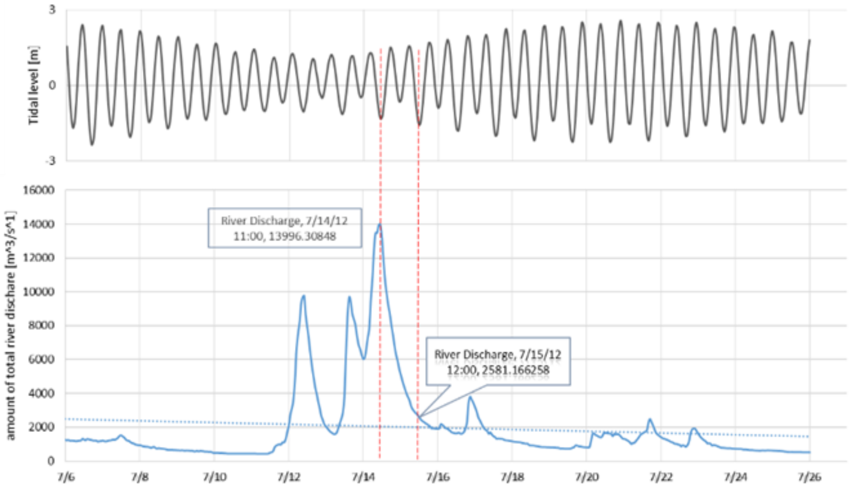
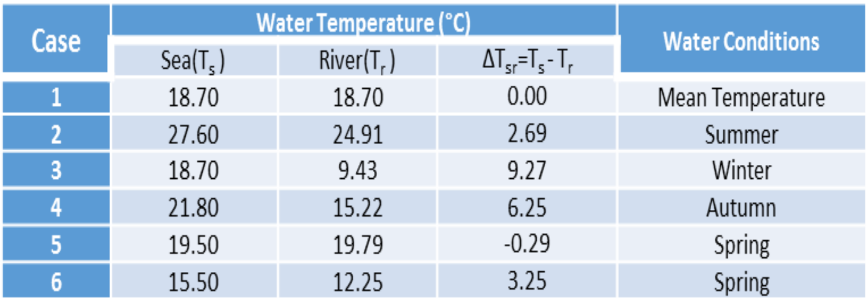


Figure 4.3 Calculated tide at Sta. C and total runoff from A-class rivers during 6th-26th July 2012. [Japan Ministry of Land Infrastructure Transport and Tourism, 2012]

In the present study, the difference temperature $\Delta T_{sr} = 0$ °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.

Table 4.1 Numerical experiment cases.



Case	Water Temperature (°C)			Water Conditions
	Sea(T_s)	River(T_r)	$\Delta T_{sr}=T_s-T_r$	
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

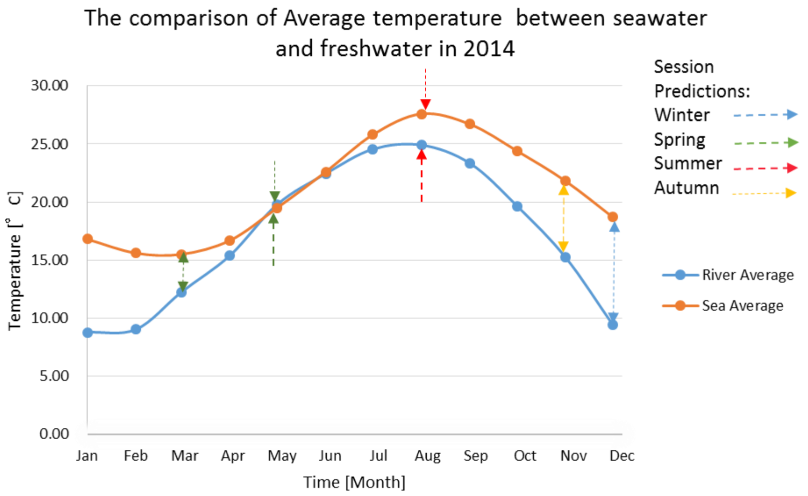


Figure 4.4 The monthly average temperature comparison between seawater and river water in the Ariake Sea. [World Sea Temperatures, 2016] , [Japan Ministry of Land Infrastructure Transport and Tourism, 2012]

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.

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 $\Delta T/\Delta h$ of water in all cases from all observation stations were used to assess how different water temperature can change the baroclinic structure in the ROFIs.

4.3 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 of water color can show an effect of freshwater that flows from the head of the bay where the biggest river (Chikugo River) is located. And also some rivers on the eastern side of the sea (such as Kikuchi River and Shira River) can give an effect in almost all region of the bay.

Figure 4.5 and **Figure 4.6** show the horizontal sea surface temperature distribution pattern from three cases. These Figures show dissimilarity in distribution pattern caused by 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 (at 12:00, on 14th July 2012). This trend can continue for one day after the flood when the freshwater assumed has become widespread at 12:00, on 15th July 2012 in this region. This phenomenon occurs in all cases.

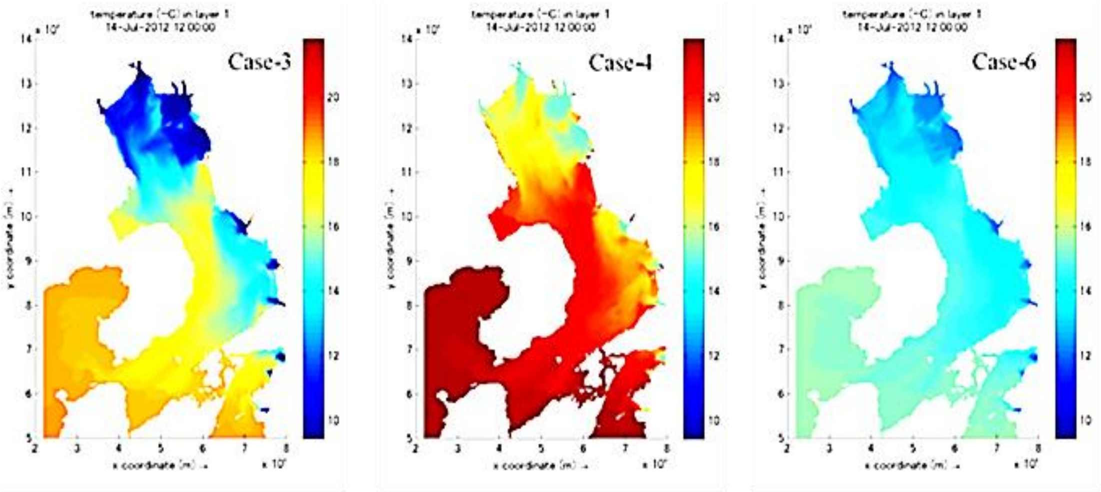


Figure 4.5 Comparison of the computation result of horizontal temperature distribution in the surface layer of the Ariake Sea among case-3, case-4 and case-6 at 12:00 14th July 2012

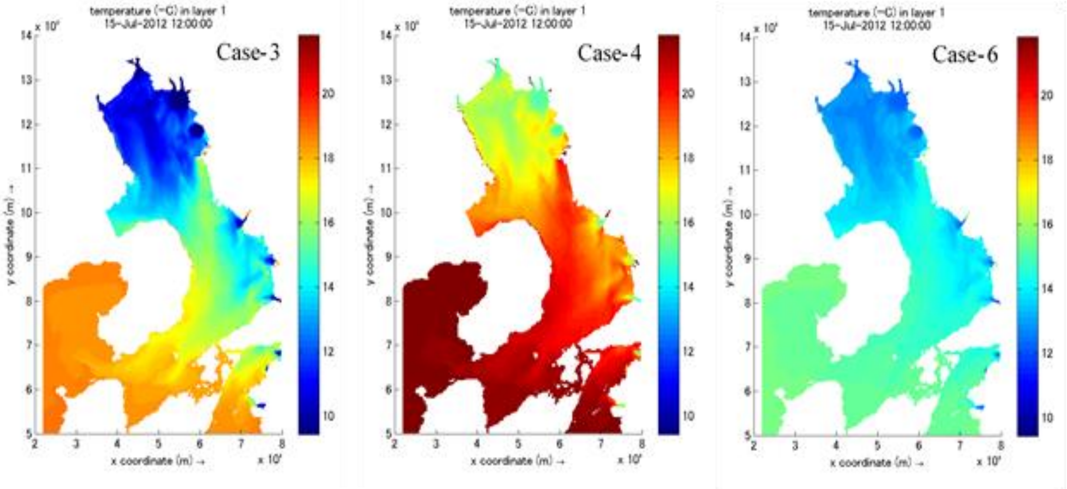


Figure 4.6 Comparison of the computation result of horizontal temperature distribution in the surface layer of the Ariake Sea among case-3, case-4 and case-6 at 12:00 15th July 2012

The variation of difference on the distribution pattern of temperature shows alteration of the baroclinic structure at each case which caused by the difference of water temperature between seawater and freshwater. Therefore, it can be assumed that difference of water temperature is one factor that caused a change of baroclinic structure horizontally in the Ariake ROFIs.

Figure 4.7 shows the temporal change of vertical thermal gradient $\Delta T/\Delta h$ 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 (see **Figure 4.1**). It can be seen that trend of thermal stratification before the flood events are rather stable for all cases. It means that the water temperature on the surface layer and bottom layer doesn't have a significant differences 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 (at 10:00, 14th July 2012). Its trend continues maximum value, and starts to reduce at one hour after the 2nd observation time (at 13:00, 15th July 2012). 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 opposite that is water temperature in surface is lower than in the bottom layer

Figure 4.8 and **Figure 4.9** show computation results of thermal isopleth in case-3, case-4, and case-6 at Sta. C and Sta. D (see **Figure 4.1**). From this Figures, we can see that there are significant differences on the level of temperature scale at each station area. In general, water temperature level at Sta. C is higher than Sta. D. This is caused by the amount of the freshwater flows into each area. In Isahaya Bay area (Sta.D) has lower water pressure than in the inner part of the bay (Sta. C). This affects the motion of freshwater that flows into this area because freshwater influences in Isahaya Bay area (Sta. D) is higher than in the inner part of the bay (Sta. C).

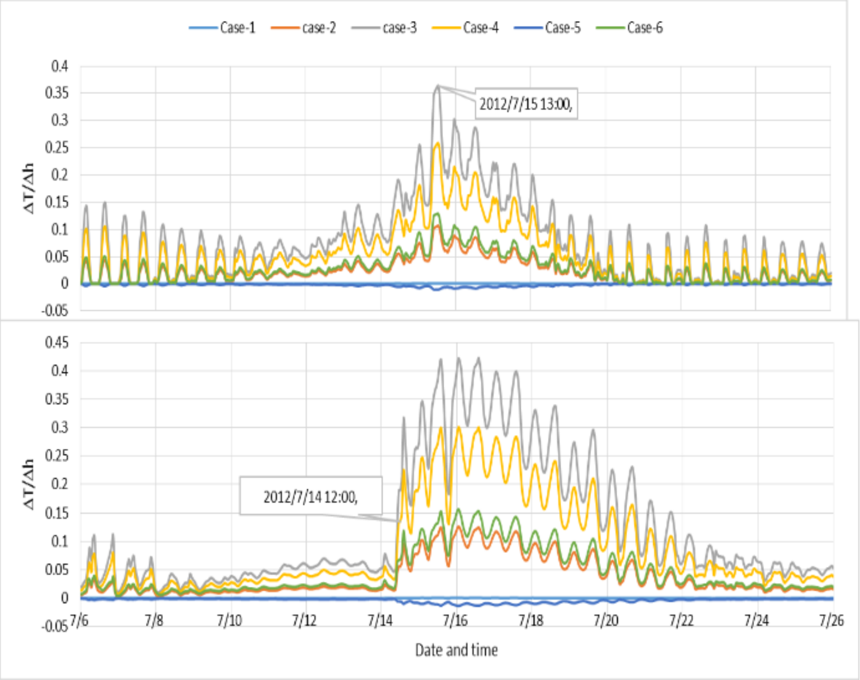


Figure 4.7 The strength of thermal stratification in the six numerical experiment at Sta. C (upper) and Sta. D (lower).

The vast freshwater influences will effect on the deformation of baroclinic structure in ROFIs [de Boer, Pietrzak, Winterwerp, 2005]. It is clarified in this study that all deformation of baroclinic structure in three cases (case-3, case-4, and case-6) is higher in Sta. D than in Sta. C. The freshwater gives an

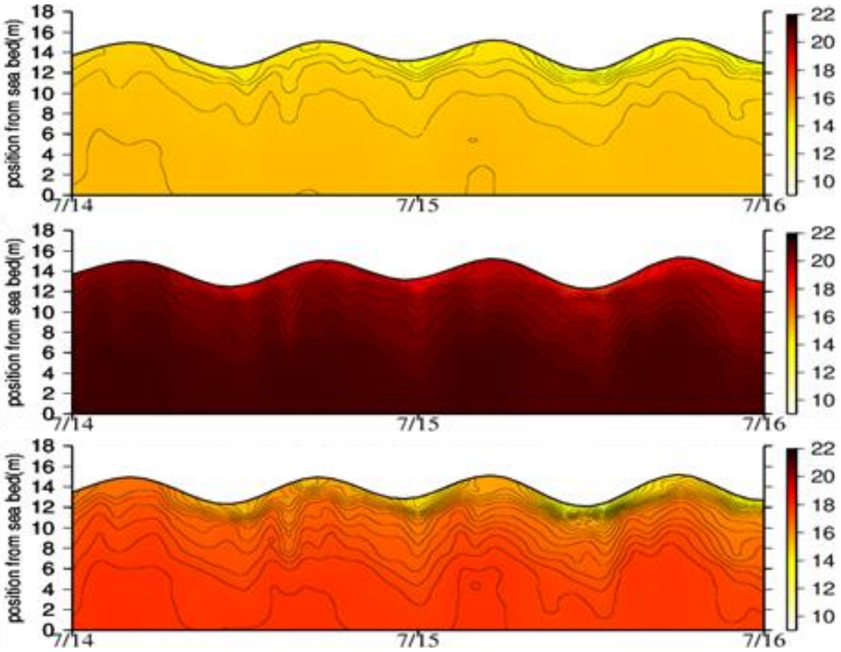


Figure 4.8 Computation results of temperature isopleth in case-3 (upper), case-4 (middle) and case-6 (lower) at Sta. C

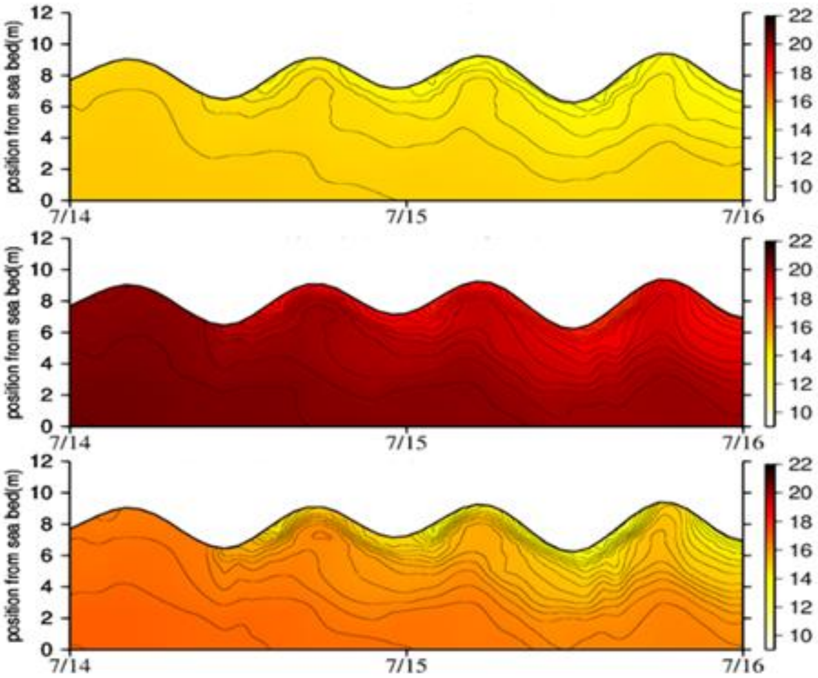


Figure 4.9 Computation results of temperature isopleth in case-3 (upper), case-4 (middle) and case-6 (lower) at Sta. D

impact on the baroclinic structure, as can be seen in **Figure 4.8** and **Figure 4.9**. The deformation of baroclinic structure in Sta. D is higher than in Sta. C.

Meanwhile, changes of baroclinic structure and thermal stratification occur as the implication from differences of water temperature in **Figure 4.8** and **Figure 4.9** in three different cases. We can assume that the difference of water temperature between seawater and freshwater can give an impact on the baroclinic structure and thermal stratification in a region of freshwater influence. Deformation or change of baroclinic structure in a region of freshwater influences (ROFI) can be caused by difference in water temperature between seawater and freshwater, too.

4.4 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. 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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CHAPTER 5

ASSESSING EFFECTS OF TEMPORAL CHANGES IN RIVER WATER TEMPERATURE ON STRATIFICATION IN THE ARIAKE SEA

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. Using the obtained hourly river water discharge and temperature data, numerical simulations were performed on the density stratification in the Ariake Sea 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.

5.1 INTRODUCTION

According to the Working Group I Report of the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) [IPCC, 2013], 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 natural water disaster, water resource (drought and water quality), natural ecosystems, agriculture, heat stroke and infectious diseases [Mimura, 2015]. In the field of civil engineering, the Committee on Adaptation to a Changing Climate of the American Society of Civil Engineers (ASCE) submitted a report [ASCE, 2015] 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 [Panel on Infrastructure Development, Japan, 2015]. 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, increased water temperature has been observed in many public waters [Ministry of the Environment, Japan, 2013]. The IPCC's AR5 [IPCC, 2013] 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 (ROFI) [Simpson, Sharples, 2012] 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.

5.2 CONTINUOUS OBSERVATION OF RIVER WATER TEMPERATURE

To continuously collect water temperature data at rivers that feed the Ariake Sea, small memory-type water-temperature loggers were installed at Class-A rivers from August 2015 onwards. 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 at Tamana for the Kikuchi River (**Figure 5.1**). 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 (Onset Computer, US).

Time-series observation data for river water temperature for 2015 during and after August are shown in **Figure 5.2**, and corresponding data for 2016 in **Figure 5.3**. 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 5.3** 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.

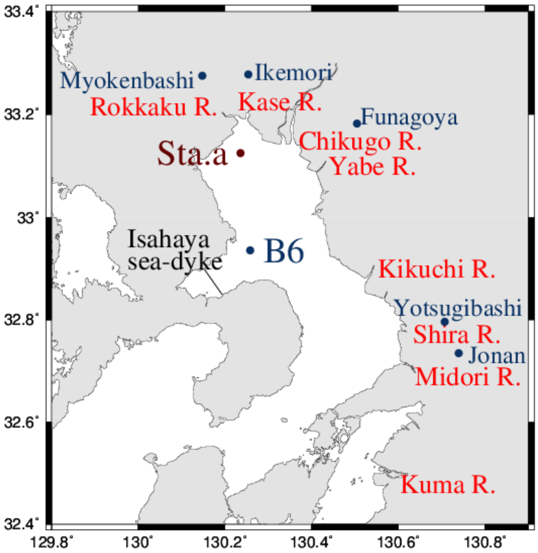


Figure 5.1 Water temperature observation points for the rivers studied and the comparison points for simulation

5.3 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 5.4** shows the correlation between all 2015 water temperature data with 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.

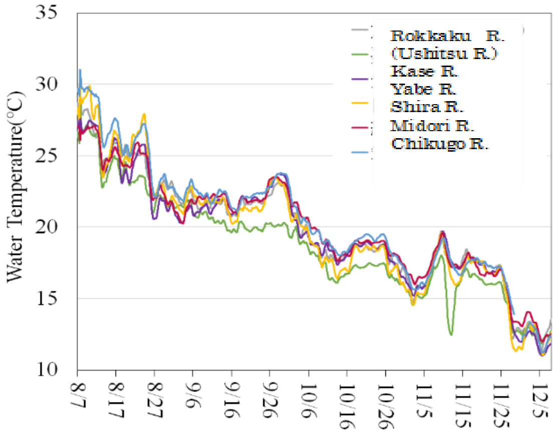


Figure 5.2 Water temperatures for the rivers studied (2015, August and onwards)

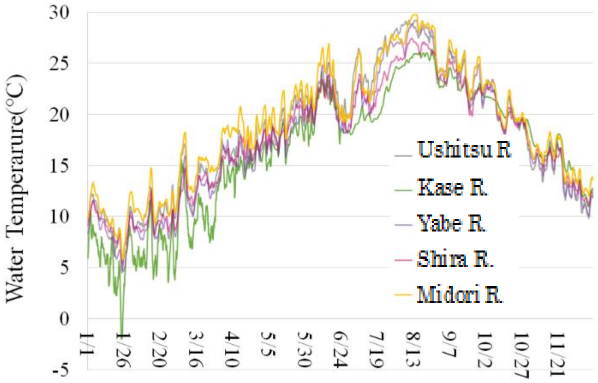


Figure 5.3 Water temperatures for the rivers studied (2016)

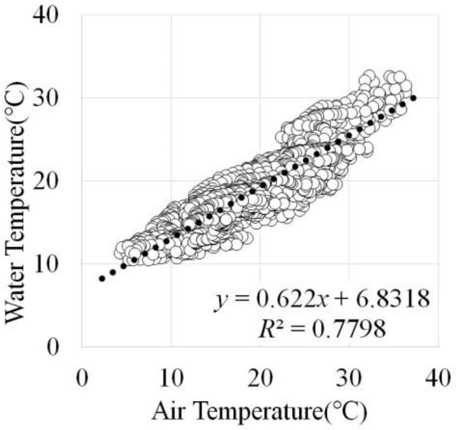
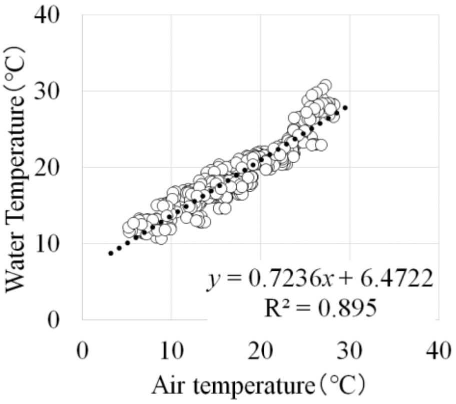
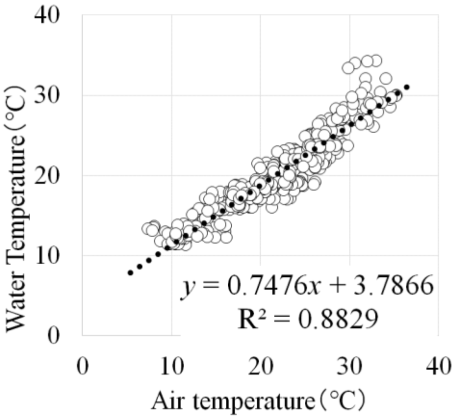


Figure 5.4 Correlation between water temperatures measured at the Shira River (Yotsugi-bashi) and atmospheric temperature (all data for 2015)



a) During 0100–0400 h



b) During 1700–2000 h

Figure 5.5 Correlation between water temperatures measured at the Shira River and atmospheric temperature

Therefore, we divided each day into six 4-h blocks and examined correlations for each block. For example, **Figure 5.5** shows the data from the Shira River for the blocks 0100–0400 h and 1700–2000 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.

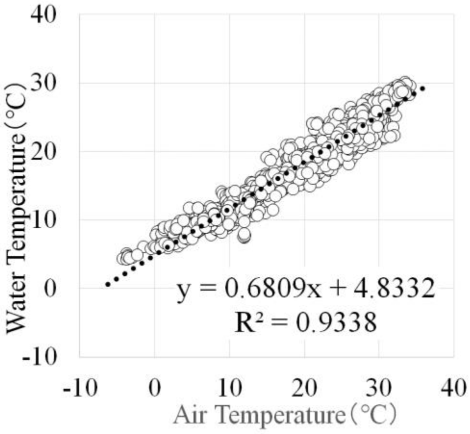


Figure 5.6 Correlation between water temperatures measured at the Ushitsu River (Myoken-bashi) and atmospheric temperature (all 2016 data for the block 0900–1200 h)

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 5.6**).

5.4 NUMERICAL SIMULATIONS

5.4.1 Numerical Model

In the present chapter, numerical simulations were performed using the Ariake Sea–Yatsushiro Sea coupled model which is based on Delft3D [Deltares, 2011], 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 σ-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 to Akune in Kagoshima Prefecture with the north–south and east–west lines. For a tidal flat 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-ε 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. With regard to freshwater inflow, Class-A rivers (**Figure 5.1**), 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 neighboring Class-A rivers were assumed. For heat flux Q_{tot} on the sea surface the following Murakami Model [Murakami, Oonishi, Kunishi, 1985] was used:

$$Q_{tot} = Q_{sn} - Q_{eb} - Q_{ev} - Q_{co} \tag{1}$$

where:

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

Each term was assessed as follows:

$$Q_{eb} = \varepsilon\sigma\bar{T}_a^4\left(0.39 - 0.058\sqrt{e_a}\right)(1.0 - 0.65F_c^2)$$

$$+4\varepsilon\sigma\bar{T}_a^3(\bar{T}_s - \bar{T}_a) \tag{2}$$

$$Q_{ev} = L_V E \tag{3}$$

$$L_V = 2.5 \times 10^6 - 2.3 \times 10^3 T_s$$

$$E = f(U_{10})(e_s - e_a)$$

$$f(U_{10}) = cU_{10}$$

$$e_s = 23.38exp(18.1 - 533.33/\bar{T}_s)$$

$$e_a = \gamma_{hum}23.38exp(18.1 - 533.33/\bar{T}_a)$$

$$Q_{co} = R_b Q_{ev} \tag{4}$$

$$R_b = \gamma(T_s - T_a)/(e_s - e_a)$$

where:

ε = emissivity (0.97),

σ = the Stefan-Boltzmann constant (5.670×10^{-8} W/m^{2}K^4),

$\bar{T}_a$ = atmospheric temperature [K],

F_c = cloud cover,

$\bar{T}_s$ = surface water temperature [K],

c = bulk coefficient (1.2×10^{-9}),

γ_{hum} = relative humidity,

γ = the Bowen constant (0.66) and

U_{10} = wind velocity.

For temperature in ˚C, the symbol does not carry a bar. For Q_{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 5.1**) 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 (http://www1. kaiho.mlit.go.jp/KAN10/kaisyo/suion/06%20yatuari/suion_back06.html) were used as vertically constant data. Separately, the effects on sea water temperature of the Ariake Sea under an open boundary condition were investigated; the sea water 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-month period 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 **5.3**. Comparison with the continuous water temperature distribution data (**Figure 5.7**), collected by the MAFF at the Isahaya Bay Point B6 in late August 2015, showed that the model calculations (**Figure 5.8**) 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 to assess the effects of river water temperature changes on thermal stratification in the coastal sea area.

5.4.2 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.

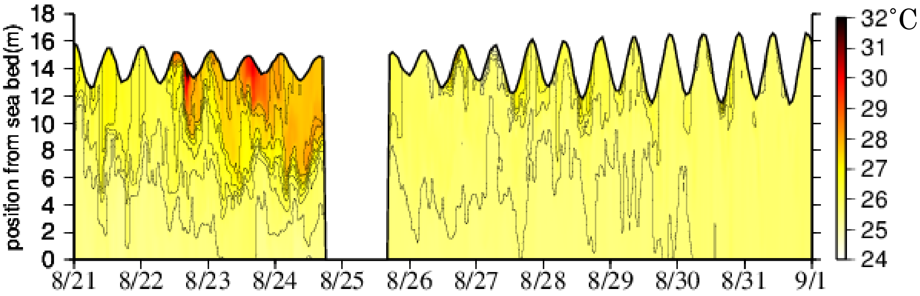


Figure 5.7 Water temperature measured at the Isahaya Bay Point B6 (late August 2015, the blank portion indicates missing data)

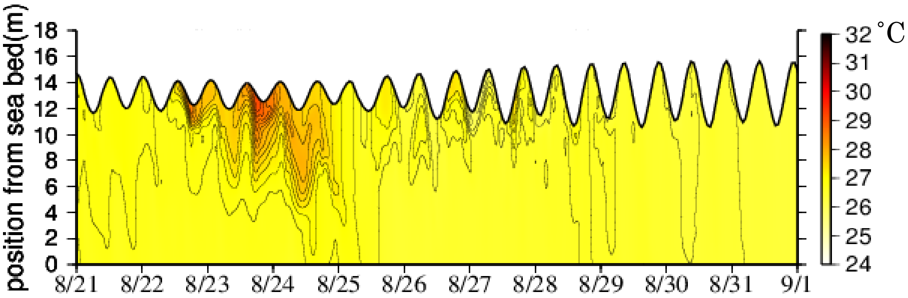
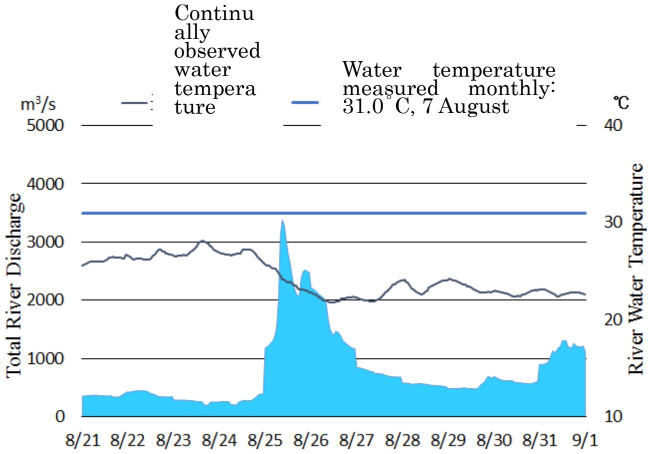
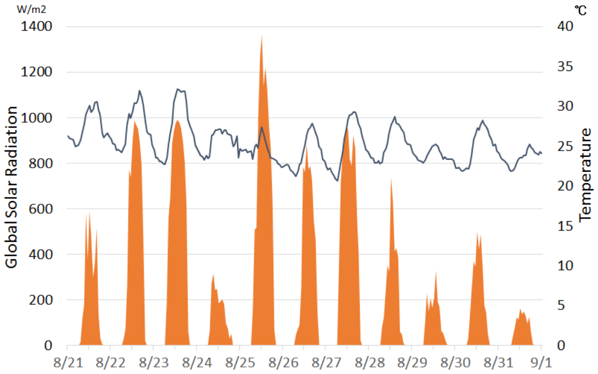


Figure 5.8 Water temperature calculated for the Isahaya Bay Point B6 (late August 2015)

Comparison was made for Sta. A (**Figure 5.1**) 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 basically 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 gray)

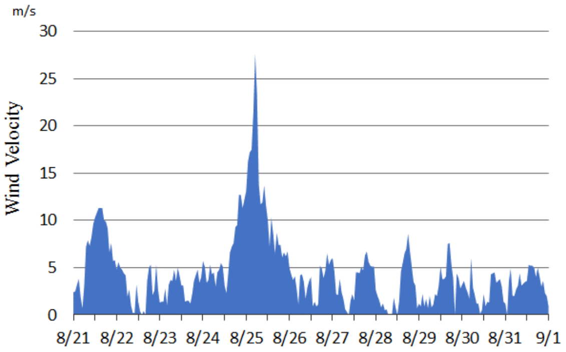


Figure 5.9 River discharge and metrological conditions used for calculation (late August 2015)

The changes in meteorological conditions, river discharge and river water temperature for August when comparisons were made are shown in **Figure 5.9** (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.

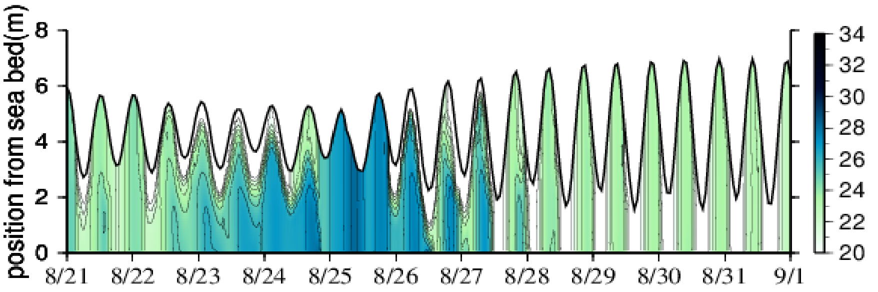
The isopleths for salinity for Sta. A (northern Ariake Sea) and Point B6 (Isahaya Bay) show that in this area into which several rivers including the Chikugo River feed water, salinity is low especially in the surface layer (**Figure 5.10**).

Water temperatures for Cases 1 and 2 are shown in **Figure 5.11** and the isopleths showing the differences (i.e., Case 1 subtracted from Case 2) in **Figure 5.12**. Water temperature was generally low in Case 1; and differences in water temperature stratification during 26–27 August when flood water reached the area and differences in water temperature after 29 August when vertical mixing was strong due to a strong tide were clearly 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.

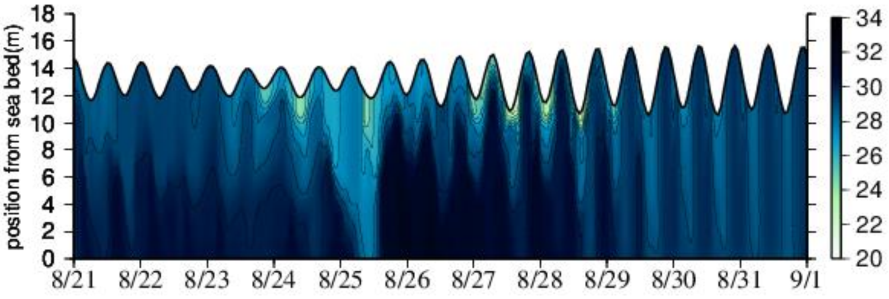
Comparisons of Cases 1 and 2 were also made for September when thermal stratification came to an end and the transition to the mixing period started (data not shown). At this time, heating weakened in both cases and stratification weakened due to a decrease in river water inflow, and there was a base 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 *et al*. 2017] assessed the distribution of dissolved oxygen in the Ariake Sea using an 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, in relation to 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 in relation to 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.

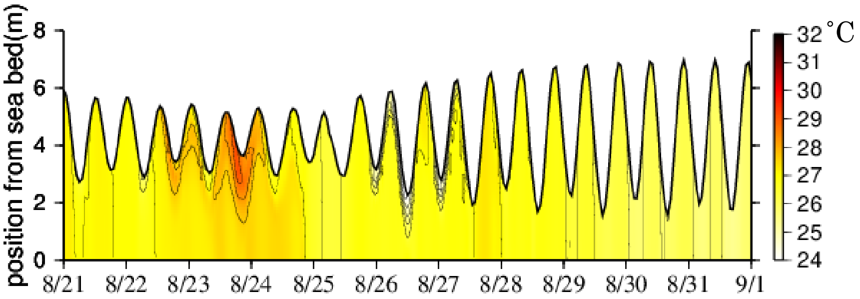


a) Sta. A (northern Ariake Sea)

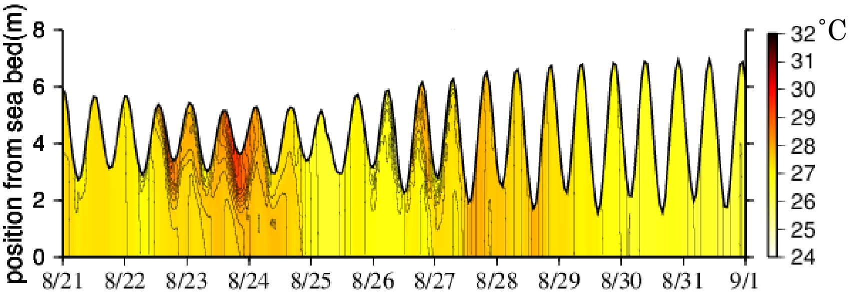


b) B6 (Isahaya Bay)

Figure 5.10 Salinity calculated for Case 1 (late August 2015)



a) Case 1



b) Case 2

Figure 5.11 Water temperature calculated for Sta. A (northern Ariake Sea in late August 2015)

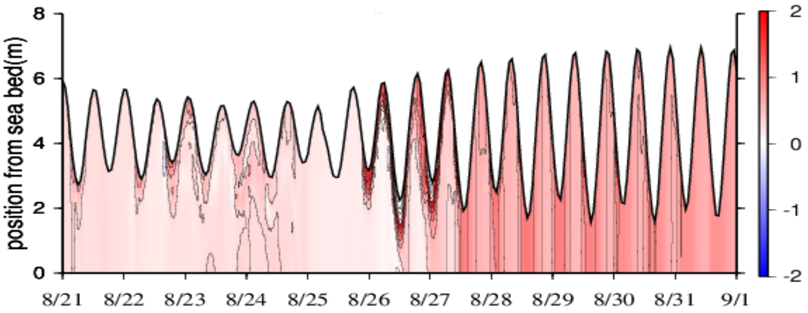


Figure 5.12 Difference in water temperature (Case 2 minus Case 1) calculated for Sta. A (northern Ariake Sea) results

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.

5.5 CONCLUSION

The effects of river water temperature on stratification in sea water 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.

In the future, it will be necessary to make detailed assessment by incorporating an ecological model or other means using downscaling data for post-warming climate prediction and to propose adaptation measures feasible in terms of cost and benefit and assessing their effects.

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CHAPTER 6
THE THREAT OF WATER TEMPERATURE ALTERATION DUE TO CLIMATE CHANGE IN REGION OF FRESHWATER INFLUENCE (ROFI)

ABSTRACT

Generally, alteration of water temperature is defined as increase or decrease in temperature of a natural body of water which possible in the ocean, lake, river or pond. Water temperature plays an important role in determining the environmental quality of aquatic ecosystems, with significant effects of changes in water temperature. The activity of water temperature interaction between seawater and freshwater will be strongly influenced by future global climate change.

The region of freshwater influence (ROFI) is the seawater–freshwater interface, and is an area vulnerable to degradation of water quality. Water temperature in the ROFI is determined by the mixing process between seawater and freshwater from rivers. This is a natural process; however, as an effect of climate change, this process can be harmful to water quality when extreme differences in water temperature occur.

To study differences of water temperature in the ROFI associated with global warming, we developed some numerical experimental conditions for water temperature simulations using extreme differences in temperature (10 to –8°C) in the Ariake Sea, Japan. The three-dimensional hydrodynamic model Delft3D was used to assess how alteration of water temperature developed and its spread during flood events in this coastal area.

The results show how global warming can be a problem in aquatic environments and how the distribution pattern of potential threats of water temperature change in seawater–freshwater mixing relate to water temperature in aquatic ecosystems. This is important because changes in water temperature have implications for aquatic biota such as seaweed (Porphyra yezoensis), fish and other organisms especially in the ROFI. The results can be utilized to determine some methods to mitigate the effects of global warming on aquatic environments and marine ecosystems in coastal regions generally.

6.1 INTRODUCTION

Warming that results in climate change is a global issue of this century [IPCC, 2014]. The increase in global surface temperature is likely to exceed 1.5°C relative to 1850–1900 for all Representative Concentration Pathway (RCP) scenarios and this trend will be followed by an increase in seawater surface temperature (SST) [IPCC, 2014]. The SST during 1961–1990 was on average 0.44, 0.38 and 0.37°C warmer according to the HadSST2, NCDC and COBE-SST models, respectively [IPCC, 2014]. Temperature is one physical quality of water with an important role in determining the environmental quality of aquatic ecosystems [Ozawa, Kamiya, Itoh, 2004]. Increasing water temperatures as a result of climate change will alter fundamental ecological processes and the geographic distribution of aquatic species [Bates, Pecl, Frusher, 2014].

Aquatic ecosystems are critical components determining the quality of the global environment. In addition to being essential contributors to biodiversity and productivity, they also provide a variety of services for humans. Climate change will probably significantly affect biodiversity of aquatic ecosystems throughout the water regions (i.e. sea and wetlands) [Poff, Brinson, 2002]. Aquatic ecosystems have a limited ability to adapt to effects of climate change [Poff, Brinson, 2002] and so are directly and indirectly increasingly threatened [Scavia, Field, Boesch, 2002]. Aquatic ecosystems will be significantly altered by changes in water temperature and, although warmer waters are naturally more productive, the particular species that flourish may be undesirable or even harmful [Brander, 2010].

Extreme events such as high temperatures, heat waves, high or low precipitation, droughts or dryness, change in tropical cyclone activity and increases in sea level are some of the impacts of climate change [IPCC, 2014]. For aquatic ecosystems, increased water temperature, precipitation intensity and longer periods of low flows are projected to exacerbate many forms of water pollution including sediments, nutrients, dissolved organic carbon, pathogens, pesticides, salt and thermal pollution [Bates B. Z., 2008].

The anomalies in water temperature caused by storms, heat waves and heavy rainfall can alter water temperature of the sea and wetlands, threatening the aquatic ecosystems and ecology. Sudden change in water temperature can have a negative impact on aquatic ecosystems by decreasing dissolved oxygen, loss of biodiversity and sudden thermal shock that can lead to mass killings of fish, insects, plants or amphibians [Wrona, Prowse, Reis, 2006].

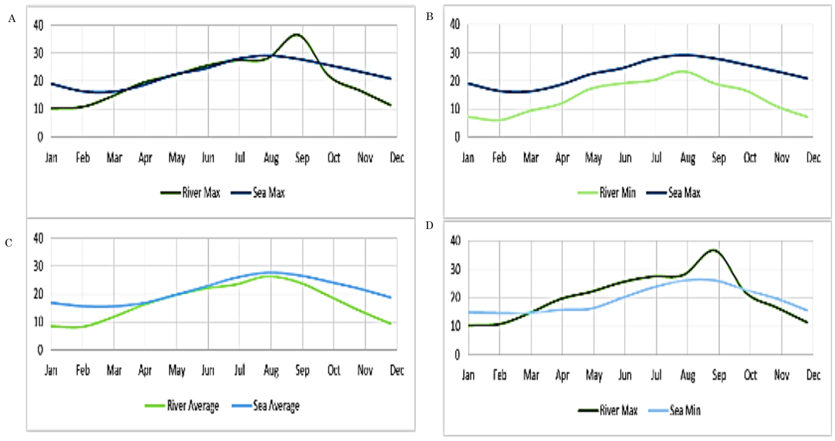

Figure 6.1 Comparison of water temperature between seawater (Shimabara Bay Observation Station) and freshwater (Chikugo River) in four different scenarios. Data source: [Global Sea Temperature, 2016] and [Japan Ministry of Land, Infrastructure, Transport and Tourism, 2016]

The rising trend of precipitation, generally seen in increasing river runoff flowing into coastal regions, and increasing seawater level are two phenomena resulting from global warming that have a significant influence on aquatic environments, especially in ecosystems of the region of freshwater influence (ROFI). The potential of interaction in extreme temperature differentials between seawater and freshwater is predicted to occur in the ROFI and makes such areas vulnerable to degradation of water quality.

During 11th–14th July 2012, heavy rain fell on the northern part of Kyushu, Japan. This record-breaking rain caused floods and landslides, especially in Kumamoto, Oita, Fukuoka and Saga Prefectures. Some rivers exceeded the highest discharges ever recorded. These events are not evidence of global warming; however, as anomalies they are of interest to researchers as a source of data for future protection of the aquatic environment and ecosystem.

The ROFI proposed by Simpson has an important role in determining conditions of the marine environment and ecosystem in coastal areas [Simpson, Sharples, 2012]. These areas are interfaces between seawater and freshwater, and are vulnerable to effects of altered water temperature. In the ROFI, water temperature fluctuation is determined by the interaction between seawater and freshwater from rivers in estuary areas before they mix fully. This is a natural process; however, as the effects of climate change increase, we assume that this process will become more harmful as the water temperature differences become more extreme.

Numerical simulation of the effect of climate change on the ROFI in the Ariake Sea was carried out using data from runoff of some surrounding rivers in mid-July 2012. The change of baroclinic structure and stratification of salinity caused by altered rain intensity demonstrated the impact of climate change on the ROFI [Yano, Arifin, 2015]. The assessment of water temperature interaction in the Ariake Sea ROFI shows that the difference in water temperature between seawater and freshwater affects the stability of the baroclinic structure of water and its stratification in the ROFI area. Therefore the strength of alteration of the baroclinic structure is affected by the difference in water temperature between seawater and freshwater for some numerical simulation cases, with implications for the variations in horizontal and vertical distribution patterns of water temperature [Arifin, Yano, Nakamura, 2016]. The alteration of water temperature distribution pattern can predict the potential threat when the differences in water temperature are extreme.

The purpose of this study is to assess the effect of several extreme water temperature differences before mixing on the ROFI during flood events. This uses some numerical experiment cases to determine alterations in thermal stratification, the horizontal and vertical distribution pattern of water temperature and the residence time of water temperature change.

6.2 METHODOLOGY

6.2.1 Numerical Model

This chapter research also applied the Delft3D model, three-dimensional hydrodynamic model commonly used for coastal areas, to perform all calculations in the numerical model developed by Yano *et al*. (2010). The Ariake Sea and the Yatsushiro Sea, two of the largest semi-enclosed bays in Japan, were used as the computational domain (**Figure 6.2**), and the linear orthogonal coordinate system of 10″-interval resolution (Δx=250 m) horizontally and the five-layer σ-coordinate system vertically were applied on this. Furthermore, to carry out the calculation, the open boundary was set as a line connecting Akune to Kabashima. There were 40 tide components given as an open boundary condition, based on the known harmonic constant of both edges. The harmonic constants (amplitude and lag) only for the four major tidal components (M_2, S_2, K_1 and O_1 tide) were used to adjust the tide measurement results at several tide gauges [Yano *et al*., 2010], and the moving wall boundary model for a tidal flat area [Deltares, 2011] was adapted.

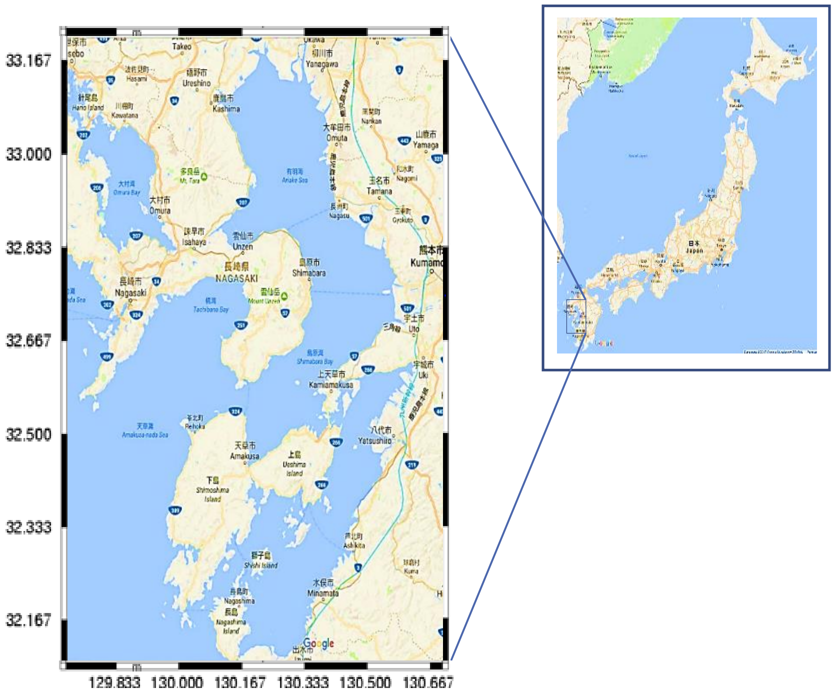

Figure 6.2 Japan and location of the Ariake Sea. Data source: Google maps

The Murakami Model was selected for the physical process of heat transfer because this model is very reasonable to express the actual Japanese water conditions associated with the relative humidity, air temperature and the net (short wave) solar radiation – the effective back radiation and the heat losses due to evaporation and convection are computed by the model [Deltares, 2011]. Furthermore, the hourly river discharge data were considered as operational input in this simulation from eight A-class rivers (Chikugo, Yabe, Kase, Rokkaku, Kikuchi, Shira, Midori and Kuma) and nine B-class rivers (Shiota, Kajima, Seki, Tsuboi, Hikawa, Ohtsubo, Sashiki, Yunoura and Minamata) (**Figure 6.3**). The accuracy of calculation of the model is not discussed in detail in the present paper, because this was confirmed in our previous paper that discussed salinity stratification, tide and tidal currents [Yano *et al.*, 2010].

6.2.2 Numerical Experiment Conditions

In this study, numerical simulations were performed using a simulation time starting from 1 January until the end of December 2012. To obtain calculation results close to the real conditions, the simulation was conducted twice: for the first simulation, the average seawater temperature and salinity average were used to get water conditions in December 2012; in the second simulation, initial conditions were set using the “restart file” (i.e. the calculation result at end of December 2012) as input, because at this time the water conditions

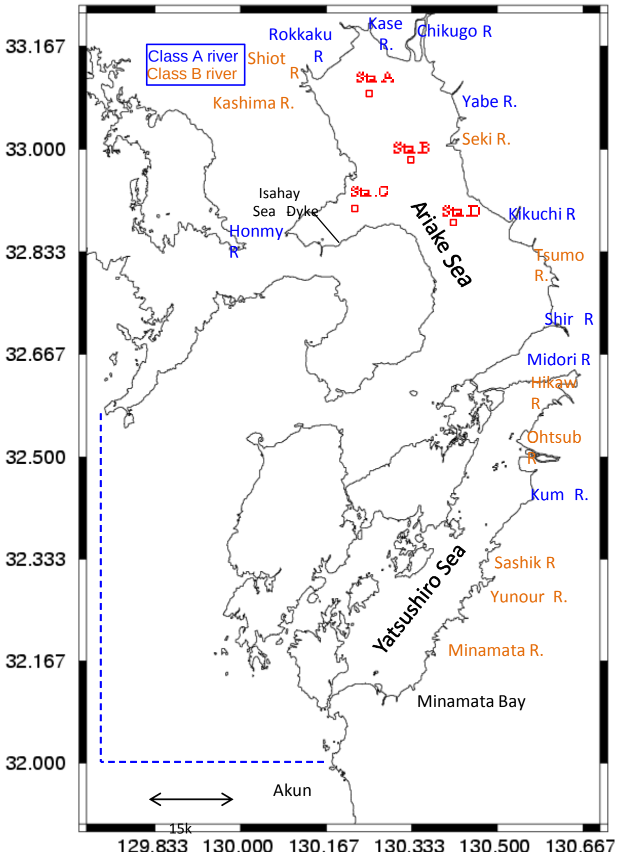

Figure 6.3 Computational domain

were closer to the conditions in January than were the average values. The preliminary numerical simulation was carried out for approximately 3 months (1 July to 1 September 2012). Furthermore, we conducted the numerical analysis to compare the effect of river runoff pattern on the baroclinic structure and alteration of water temperature in three conditions: before, during and after flood events in mid-July 2012.

Four observation stations were used to simultaneously assess alteration of baroclinic structure and thermal stratification for each case. Observation stations were located according to a prediction of the direction of water runoff flow from Chikugo River to the mouth of the bay. This allowed comparison of the altered baroclinic structure and thermal stratification with different amounts of freshwater influence in the bay. Stations A–D were located in the head area, the center of the bay, Isahaya Bay and the mouth of the Kikuci River, respectively (**Figure 6.3**).

Water temperature was the main parameter in this study. The initial values used for all cases were seawater average temperature $(\overline{T_s})$ of 18.70°C and average salinity of 29.26 ppt for the Ariake Sea [Tabata Hiramatsu, 2015]. In order to create constant temperature differences between seawater and freshwater (i.e. $\Delta T_{sr1} = 10$°C, $\Delta T_{sr2} = 6$°C, $\Delta T_{sr3} = 2$°C, $\Delta T_{sr4} = -2$°C and $\Delta T_{sr5} = -8$°C), freshwater temperatures from rivers were set at different constant values for each of five cases (**Table 6.1**).

6.2.3 Ariake Sea ROFI

All ROFI systems have the distinctive feature of the input of a significant amount of buoyancy from river runoff [Simpson J. H., 1997]. Freshwater from river runoff contributes an important input of buoyancy to large areas of the shelf seas adjacent to estuaries. This buoyancy input is responsible for producing physical characteristics in ROFIs that are radically different from the other parts of the shelf seas and estuaries.

According to the characteristics of the scheme shelf marine and estuarine by Simpson, during the stirring process, the ROFI area lies between the mixing water and freshwater from the estuary. The stirring mechanisms provided by tides, winds and waves, and in a variety of different topographic settings provide the essential subtlety and variety of ROFI [Simpson J. H., 1997]. The changes in baroclinic structure and the strength of density stratification ($\Delta\rho$), as a result of the effect of freshwater, can be used to identify the changes in water physical characteristics before the water is fully mixed (low stratification) in aquatic areas. $\Delta\rho$ was obtained using the equation below:

$$\Delta\rho = \frac{\delta\rho}{\Delta h} = \frac{\rho_b - \rho_s}{\Delta h} \dots\dots\dots\dots\dots..(1)$$

Where: $\Delta\rho$ = The strength of density stratification (kg/m^3),

ρ_b = Water density on the bottom layer (kg/m^3),

ρ_s = Water density on the surface layer (kg/m^3) and

Δh = Water depth (m)

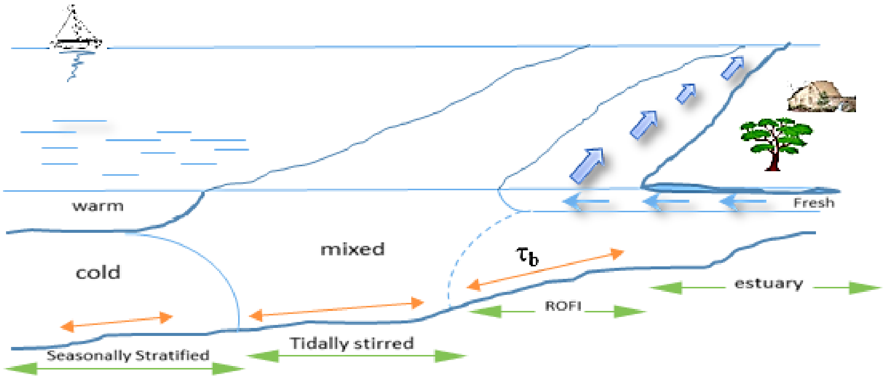

Figure 6.4 Schematic of the characteristic regimes of shelf, estuary and ROFI [Simpson, 1997]

The density of water as a physical parameter was used to assess changes in baroclinic structure and water stratification, and so to identify the ROFI area during flood events in the Ariake Sea. As a semi-enclosed bay, water in the Ariake Sea has a long rotation period [Tabata, Hiramatsu, 2015]. Therefore, the physical characteristics of this seawater are strongly influenced by the quantity and quality changes in freshwater entering from the surrounding rivers.

6.2.4 Assessment of Alterations in Water Temperature

Water temperature change is the main issue for this chapter. The potential threat of altered water temperature in this ROFI, the physical assessment of water temperature and the effect of water runoff from rivers was conducted throughout 2012, particularly during and after heavy rainfall in mid-July. Physical measurement of water temperature was needed to assess the natural water temperature fluctuation and the associated time period in each case for before, during and after flood events at each observation station. We assumed that this method was a reasonable assessment of the numerical simulation of water temperature change.

Table 6.1 Numerical experiment cases.

Case	Water temperature (°C)		
	T_s	T_r	$\Delta T_{sr} = T_s - T_r$
1	18.70	8.70	10
2	18.70	12.70	6
3	18.70	16.70	2
4	18.70	20.70	–2
5	18.70	26.70	–8

In general, effects on the aquatic environment caused by sudden changes in water temperature indicate the adaptation capacity of aquatic biota. Each biota has a different ability to adapt to changes in water temperature, and changes in temperature can be catastrophic if they exceed the thermal tolerance capacity (either higher or lower) for some species.

The Ariake Sea in the west of Kyushu Island, a semi-closed and macro-tidal shallow sea with the largest tidal flat ecosystems in Japan, was used in this study of water temperature effect on aquatic biota. A large mud tidal flat with a productive ecosystem along the western shoreline of the sea makes this area ideal as a major production site of nori seaweed (*Porphyra yezoensis*). The most important nutrient for the production of nori is nitrogen. The nitrification rates, which are related to water temperature, were previously used to assess nitrogen levels for the nori ecosystem; and were relatively high at 20–35°C (optimum at 29.5°C), but very low at 5, 10 and 40°C [Isnansetyo, Getsu, Seguchi, Koriyama, 2014].

The water temperature average $(\overline{T_s} = 18.70°\mathrm{C})$ used in this simulation was assumed to be representative of water in the Ariake Sea [Tabata Hiramatsu, 2015]. The large number of rivers that empty into the Ariake Sea causes the physical and chemical conditions of the seawater to be strongly influenced by those of the freshwater. We assume this results in a vulnerable condition for thermal pollution if water temperature suddenly changes due to mixing triggered by global warming effects such as extreme rainfall or cyclone.

6.3 RESULTS AND DISCUSSION

6.3.1 ROFI Area

Water density as a physical parameter was used to identify distribution of the ROFI area, and $\Delta\rho$ was high during flood events (**Figure 6.5**). During flood events, the largest ROFI area developed in the head area of the bay (Sta. A) and began to slowly decrease at Sta. B and Sta. C. At Sta. D the stratification of water density tended to be flat, indicating that the water density was already uniform or the water was fully mixed.

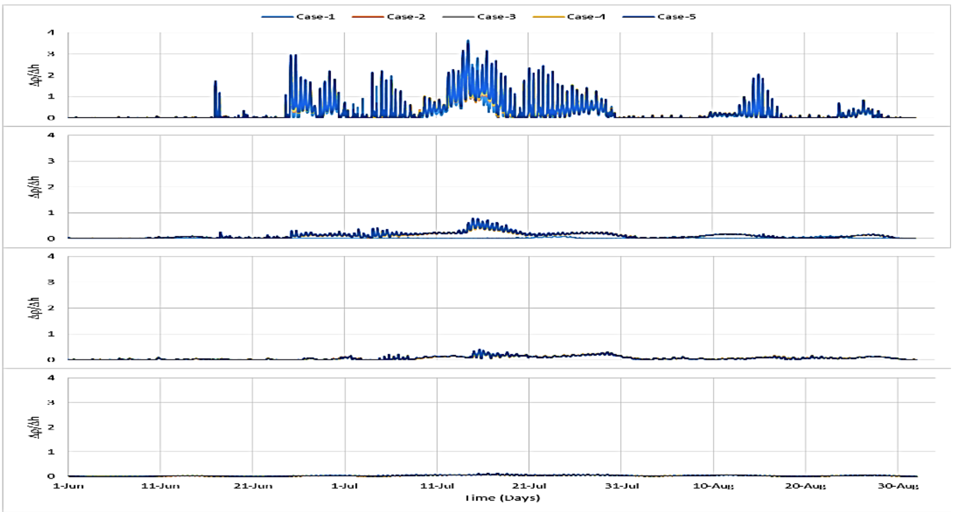

Figure 6.5 The strength of water density stratification ($\Delta\rho$) for all numerical experiment cases at Sta. A, Sta. B, Sta. C and Sta. D from 1 June to 1 September 2012

The calculation results showed that size of the ROFI area was similar in all cases except for case-5. In case-5, the freshwater temperature was set at a higher value than for the other cases, creating a lower density of freshwater than the other cases. Therefore, in case-5, the area of freshwater influence was greater than the other cases, consistent with the changes in water density caused by water temperature.

6.3.2 Extreme Rainfall and Water Temperature

Heavy or extreme rainfall is one climate change indicator that causes an increasing trend of river runoff flowing into the sea. This condition implicates to interaction pattern between freshwater and seawater, include they are physical parameter difference both. In 2012, the water temperature fluctuation in the Ariake Sea tended to be stable, with little thermal stratification found at all the observation stations, as shown in the calculation results in each case. Therefore, it can be assumed that there was no threat of thermal pollution except in the middle of the year.

The extreme river runoff during 12–14 July 2012 [Haeseler, 2012] was caused by a peak in rainfall intensity. This had a significant impact on the amount of river runoff for the four A-class rivers (**Figure 6.3**), including the Chikugo River (the largest river) located close to Sta. A. This heavy rain resulted in an extreme amount of river runoff flowing into the sea (**Figure 6.6**). This condition caused the thermal stratification of seawater, with temperature in surface layers tending to be lower than in deeper water. The greatest differences in water temperature for each layer were for case-1 and case-2 during 12–19 July 2012. These phenomena indicate the potential threat of thermal stratification caused by nature.

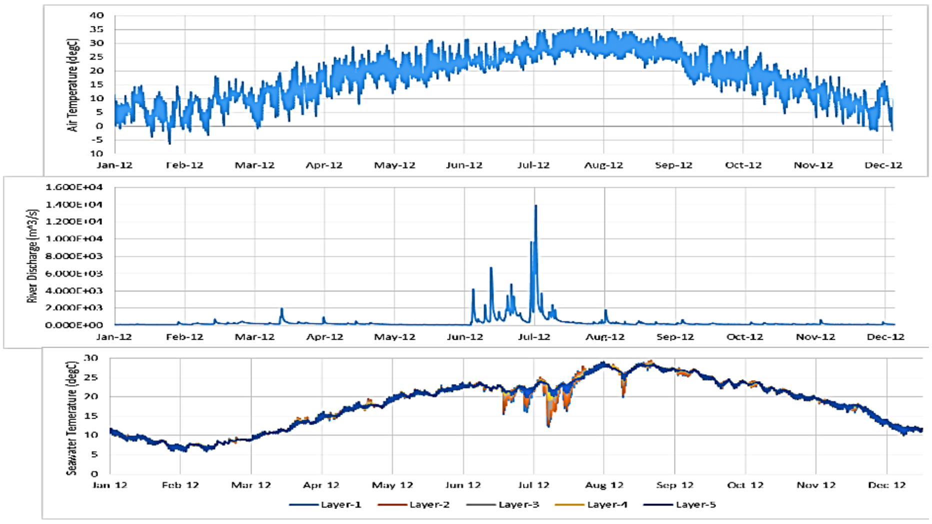

Figure 6.6 The total runoff from A-class and B-class rivers flowing into the Ariake Sea and the Yatsushiro Sea in 2012, and the calculated water temperature of case-1 for Sta. A [Japan Ministry of Land, Infrastructure, Transport and Tourism, 2016]

6.3.3 Thermal Assessments

Water temperature is one indicator of water quality in an aquatic environment. In this chapter, the calculated water temperature from all numerical cases was used to compare and assess how alteration in water temperature developed in each case.

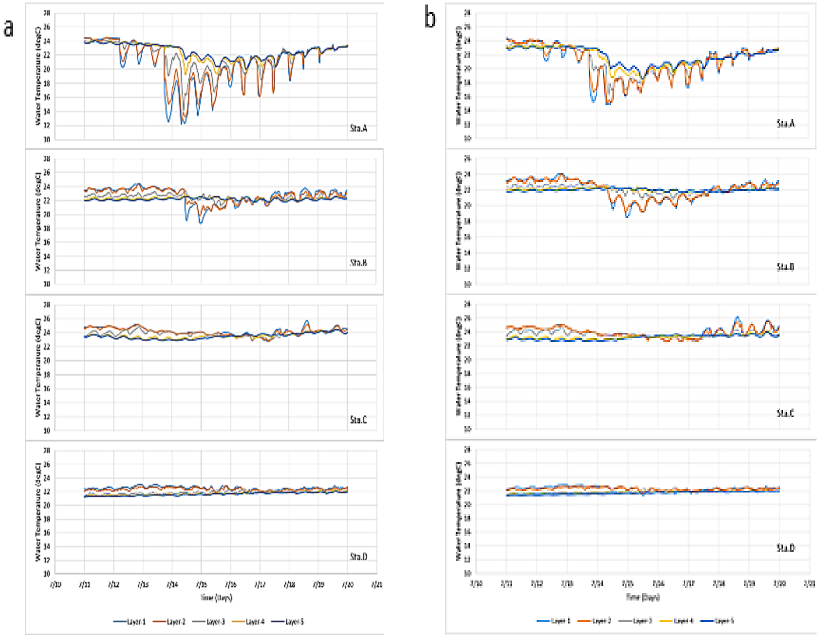

Figure 6.7 Water temperature fluctuation at all observation stations (Sta. A, Sta. B, Sta. C and Sta. D) for case-1 (a) and case-2 (b)

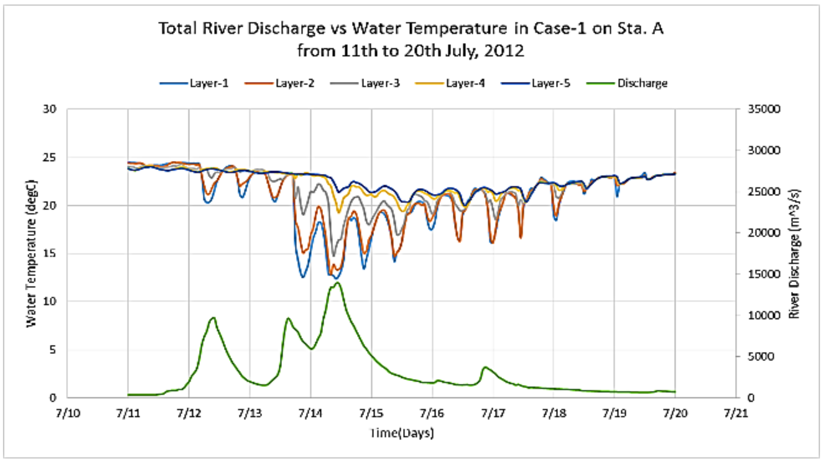

Figure 6.8 River discharge and water temperature for case-1

at Sta. A, Sta. B and Sta. C due to approximate ROFI area develop in that area only. The highest threat of degradation of water quality was in the head of the bay for case-1 and case-2 and sometimes for case-3 (**Figure 6.7**). For case-4 and case-5, low threats were found due to smaller differences between seasonal seawater temperature and freshwater temperature. Particularly for case-1 and case-2, the stratification of water temperature was caused by an increase in river discharge caused by heavy rainfall in the areas surrounding the Ariake Sea during 12–14 July 2012 [Haeseler, 2012]. The freshwater from river runoff delivered all the physical components including water temperature and density.

The changes in water temperature in each layer were combined with river discharge during the same period (**Figures 6.8** and **6.9**). The rivers surrounding the bay had three peak times of discharge: 12 July at 09:00 (9,700 m^3s^{-1}), 13 July at 16:00 (9,000 m^3s^{-1}) and the highest on 14 July at 10:00 (14,000 m^3s^{-1}). The altered temperature and stratification of water temperature followed the increase in river runoff (**Figures 6.8** and **6.9**), indicating that the runoff caused thermal stratification in the ROFI area.

In addition to river runoff, there was fluctuation in seasonal seawater temperature with tidal movement (**Figures 6.10** and **6.11**). The decreasing trend of water temperature for each layer was at a maximum for low tide, such as on 11 July 2012 at 19:40 (–0.73 m) to 12 July 2012 at 08:40 (–1.03 m), when the amount of river runoff flowing into the sea tended to increase. This condition was supported by decreasing trend of air temperature (**Figure 6.6**) over the sea in same period, and the lowest temperature for layer-1 occurred in three cases: case-1 (ΔT = 4.01°C), case-2 (ΔT = 2.89°C) and case-3 (ΔT = 1.91°C).

Although the temperature changes in water bodies occur over rather short periods, this can have a great effect on some aquatic biota. The change in water temperature in some cases (e.g. case-1 and case-2) was higher than the preferred temperature range of some marine biota, for which a maximum tolerated change can average about 2.66°C [Richardson et al., 2010].

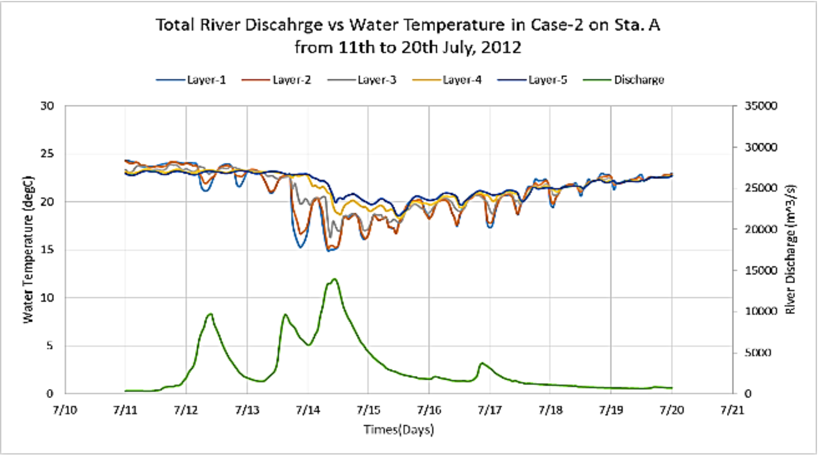

Figure 6.9 River discharge and water temperature for case-2

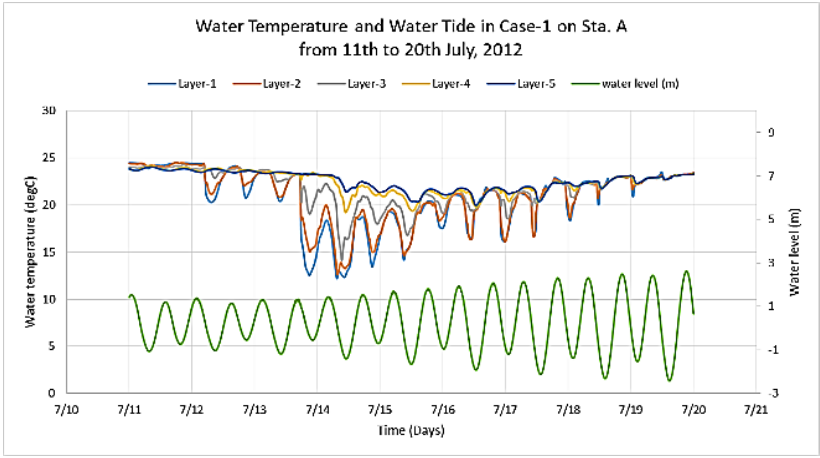

Figure 6.10 Water temperature and tide water level for case-1 during flood events

At 10:30–22:20 on 13 July 2012, there was a low tide and river runoff into the sea at 16:00 reached 9,000 m^3s^{-1}; this was followed by the greatest runoff at 10:00 on 14 July of 14,000 m^3s^{-1}. This condition caused significant decreases in water temperature. The decreasing trend of water temperature occurred for all numerical cases and all layers: case-1 (ΔT = 11.10°C), case-2 (ΔT = 8.51°C) and case-3 (ΔT = 4.82°C). The decrease of water temperature started at this point and reached a minimum at 10:50 on 14 July. Low water temperatures continued until the end of 19 July 2012.

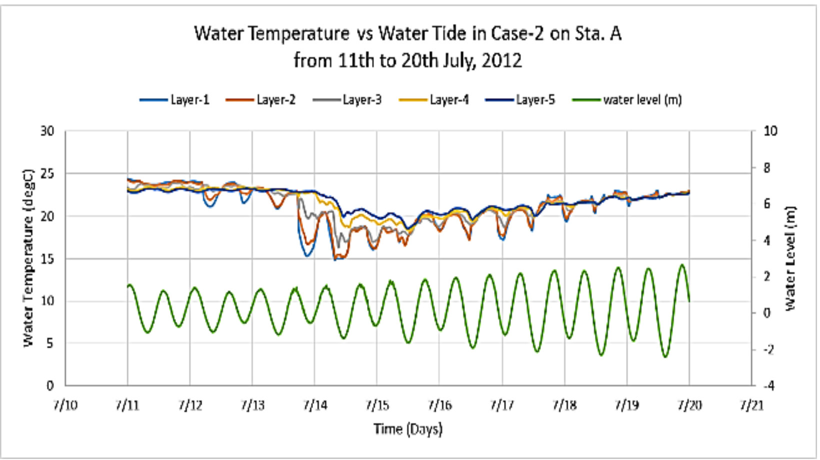

Figure 6.11 Water temperature and tide water level for case-2 during flood events

The water temperature calculations caused by the difference in temperature between seawater and freshwater show that heavy rainfall is one outcome of climate change that could be a problem for aquatic ecosystems by inducing thermal shock. Analysis using the critical thermal maximum method has shown acute thermal stress on some aquatic biota with the rate of water temperature change in the range of 0.2–0.5°C/min [Olsen *et al.*, 2012]. The water temperature calculation for case-1 showed a rate of water temperature change of 0.28°C/min for layer-1 and 0.20°C/min for layer-2 at 17:30 on 13 July 2012, indicating possible thermal shock in this ROFI during flood events. Such conditions would become worse if water temperature differences were greater.

Specific to the Ariake Sea ecosystem, the effect of water temperature change is evident in the nitrification of seawater above mud sediment. The calculations showed that decreases in water temperature caused by heavy rainfall in mid-July 2012 were greatest for layer-1 in case-1 (7:40 on 14 July; 11.49°C) and case-2 (7:40 on 14 July; 14.85°C) at Sta. A. These results show that water temperature was below the optimum for nori ecosystems (20–30°C), and will have implications for lower nitrogen levels and consequent reduced growth of nori.

6.3.4 Thermal Distribution

Horizontal distribution

Horizontal thermal distribution was used to investigate the thermal spread during flood events and is shown in **Figure 6.12** for case-1, case-2 and case-5. The spread of thermal distribution was at a maximum at low tide.

The seasonal range of seawater temperature in the surface layer for all cases was 22– 23°C (**Figure 6.12**). This was affected by air temperature (~25°C) during this period; however, the freshwater temperature as operational input in the simulations was a constant value for all periods. This condition affected the differences in thermal distribution pattern among cases.

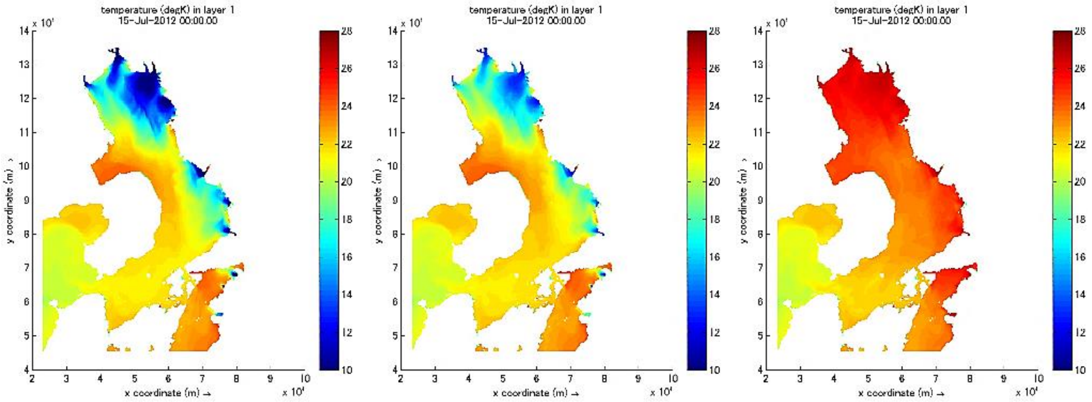

Figure 6.12 The horizontal propagation of thermal distribution in the surface layer for case-1 (a), case-2 (b) and case-5 (c)

For the surface (layer-1) in case-1 and case-2, the freshwater temperature was set below the seasonal seawater temperature. The distribution of freshwater temperature was greater for case-1 than case-2 due to higher difference ratio of temperature for case-1 than case-2, indicating that differences in temperature between seawater and freshwater affected the size of the area of influence of freshwater temperature. For case-5, the area of thermal distribution was smaller than for the other cases, caused by a smaller difference ratio of temperature between seasonal seawater and freshwater temperatures, although the initial condition of difference in water temperature in this case was set higher (ΔT_{sr} = –8°C) than for the other cases. Therefore, the threat of thermal pollution was lower for case-5 than for the other cases.

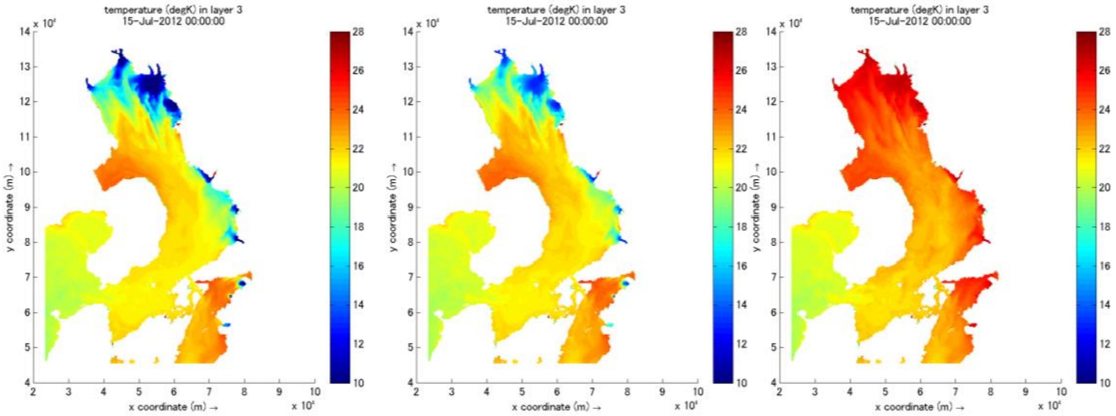

Figure 6.13 The horizontal propagation of thermal distribution in layer-3 for case-1 (a), case-2 (b) and case-5 (c)

In layer-3, the difference of water temperature distribution was the same as for layer-1, with the thermal distribution pattern greater for case-1 than case-2, moreover in case-5, this is influenced by difference ratio of temperature in each case during this period (**Figure 6.13**).

The impact of heavy rainfall during this period on the thermal distribution pattern in the ROFI area was affected by the difference ratio of temperature between seawater and water from river runoff **(Figure 6.12** and **Figure 6.13**). The horizontal distribution of water temperature differed for each ROFI area during the flood events, this condition causes propagation of thermal in the same layer become different on each region horizontally in an aquatic area.

Vertical distribution

The calculation showed that vertical thermal distribution was similar to the horizontal distribution, with case-1 and case-2 showing greater differences than the other cases. In case-1, the thermal distribution patterns showed lower water temperature than for the other cases. Furthermore, the seasonal alteration of seawater temperature caused greater thermal stratification for case-1 and case-2 than the other cases, this condition is showed by the difference of water temperature has occurred on a different layer in each case. Case-5 showed weaker thermal stratification than the other cases, caused by seawater temperature being closer to freshwater temperature in this case. The thermal stratification developed more strongly in case-1 and case-2 than for the other cases (**Figure 6.14** and **6.15**). This can be assumed to result in a greater thermal pollution threat following increased river runoff during flood events.

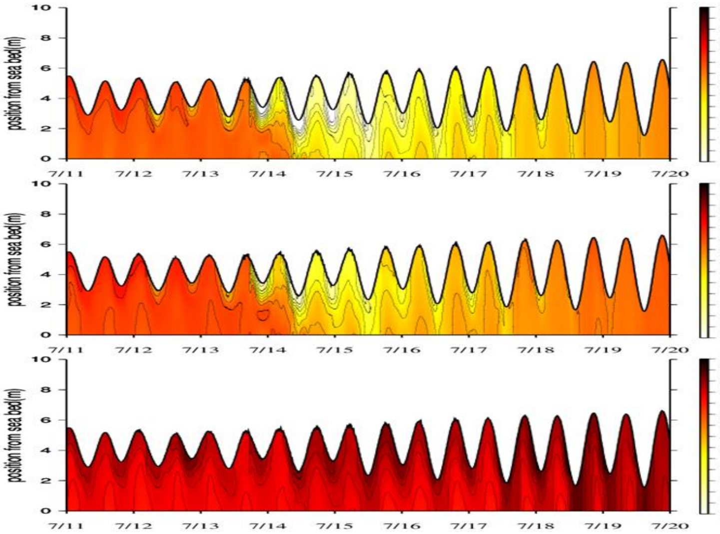

Figure 6.14 Computation results of thermal vertical distribution for case-1 (upper), case-2 (middle) and case-5 (lower) at Sta. A

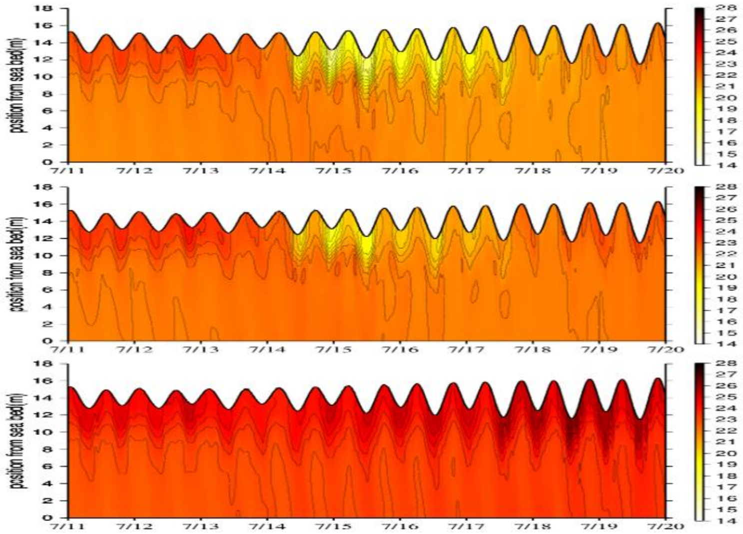

Figure 6.15 Computation results of thermal vertical distribution for case-1 (upper), case-2 (middle) and case-5 (lower) at Sta. B

6.4 CONCLUSION

The calculation results from the extreme river runoffs caused by heavy rainfall (one possible result of climate change) on Kyushu Island in the middle of 2012, using the numerical experiment cases of water temperature differences between seawater and freshwater temperature, indicated possible problems in the aquatic environment of ROFI areas. These results show that threatening activity from changes in water temperature can lead to degradation of water quality, especially in nori ecosystems in ROFI Ariake Sea, due to a decrease in water temperature has a significant effect on the supply of nitrogen as primary nutrients role to the biological growth processes of Nori.

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CHAPTER 7

CONCLUSION

According to the result of all researches that discuss the climate change impact on Region of Freshwater Influences (ROFI) in the Ariake Sea, Japan, some conclusions were obtained as follows:

1. From the comparison between numerical experiments for some extreme flood simulations considered as an indication of climate change, the alteration of precipitation patterns may alter the baroclinic flow and its structure in the Ariake Sea coastal region.

2. The result of horizontal salinity distribution indicates that the extensive alteration of baroclinic flow in Ariake Sea is strongly influenced by the rain intensity rate that occurs in surrounding the bay.

3. The alteration of rainfall patterns as an indicator of climate change led to the evolution in baroclinic flow on characteristic each regime of shelf sea, mixing zone, estuary, and the region of freshwater influences (ROFI) in the Ariake Sea.

4. The alteration of baroclinic flow due to climate change impact causes deformation of ROFI area in the Ariake Sea. This result suggests that the regime of marine environment and ecosystem can be altered due to climate change.

5. From the comparison of results from numerical experiments in several experiment cases of water temperature difference between seawater and

freshwater temperature, we deduce that dissimilarity of water temperature can give effect on the baroclinic structure in the regions of freshwater influence (ROFIs).

6. The large deformation of baroclinic structure in ROFI can be affected by two factors. First one is difference ratio of water temperature between seawater temperature and freshwater one. Second is river runoff around ROFI.

7. Flood events that are considered an indicator of climate change may lead to a change of baroclinic structures in ROFI of the Ariake Sea.

8. The magnitude of water temperature difference between seawater and freshwater effect causes thermal stratification problem in ROFI during flood events.

9. The effects of river water temperature on stratification in seawater are 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 deprivation.

10. The calculation results from the extreme river runoffs caused by heavy rainfall (one possible result of climate change) on Kyushu Island in the middle of 2012, using the numerical experiment cases of water temperature differences between seawater and freshwater temperature, indicates possible problems in the aquatic environment of ROFI. These results show that threatening activity from changes in water temperature can lead to degradation of water quality, especially in nori ecosystems in the ROFI of

the Ariake Sea.

11. The decrease in water temperature has a significant effect on the supply of primary nutrients to the biological growth processes in the Ariake Sea ROFI during flood events.

12. The thermal shock as a potential threat on the Ariake Sea ROFI, if the difference water temperature in extreme one.

From these conclusions, we can say that climate change phenomena have a significant impact on the marine environmental system due to sensitivities of them on each alteration of climate. The region of freshwater influence (ROFI) as the primary component to determine aquatic environmental quality can become a vulnerable area against to climate change impact in the marine ecological system. Extreme events, such as heavy rainfall and anomaly of temperature over the land and the ocean are two climate change indicators that can indicate a significant impact on water quality in a ROFI.

Considering the increasing threat of climate change impacts to human activity and aquatic environmental system, the importance of the ROFI’s primary role in the marine ecological system and limited time of us to explore more deep research about climate change impact on the ROFI. Therefore, the continuation of investigation topic about climate change impact on ROFIs on all aspects is needed to obtain the precise description of the climate change impact in ROFIs.

For further research, we recommend many research topics related to the following questions:

A) How can ROFI response to some indicators of climate change?
B) How is climate change impact on all water nutrition components in ROFIs?
C) How can aquatic organisms respond on alteration of ROFI condition related to climate change phenomena?
D) How may ROFI area respond on sea level rise?

E) How is climate change impact on environments in bottom layer in ROFIs?

F) How may the climate change impact on economic sustainability in ROFIs?

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