Salinity Analysis for Tracking the Behavior of Large Freshwater Discharge into Hakata Bay Due to Heavy Rainfall Using a Three-Dimensional σ-Coordinate Model

Akihiro Fukuda[1], Toshinori Tabata[2], Kazuaki Hiramatsu[2] and Masayoshi Harada[2]

[1]Department of Agro-Environmental Sciences, Graduate School of Bioresource and Bioenvironmental Sciences, Kyushu University, Fukuoka, Japan

[2]Department of Agro-Environmental Sciences, Faculty of Agriculture, Kyushu University, Fukuoka, Japan

Abstract

Massive freshwater discharges due to heavy rainfall have recently caused negative changes such as red tides and anoxic water masses in semi-enclosed bays. Hakata Bay, one of the semi-enclosed bays of Fukuoka, Japan, has experienced red tides and anoxic water masses due to large freshwater inflows after extreme rainfall events. In this research, the impacts of large freshwater discharges were evaluated by analyzing the horizontal and vertical salinity distribution using a three-dimensional σ-coordinate model. Specifically, the bay was examined after the heavy rainfall event that greatly damaged Fukuoka City on 16 September 2002. The calculation period was 11–27 September 2002. River discharge values were calculated using Sugawara's tank models, which were considered to be the river inflow in a hydrodynamic and salinity diffusion model of Hakata Bay. The model was validated, and the results showed high reproducibility; the calculated tidal current and salinity values agreed well with the observed data. The results also showed that: (1) salinities less than 15.0 psu were found at the river mouths just after the heavy rainfall; (2) low-salinity water spread across the surface of the inner part of the bay; and (3) salinity differences between the surface and bottom were large (approximately 4 psu) and lasted for three days after the heavy rainfall. These results indicate that red tides and anoxic water masses could be induced in the inner part of the bay.

Keywords: *anoxic water mass, coastal sea, hydrodynamic and salinity diffusion model, red tide, Sugawara's tank model*

Introduction

In recent years, global climate change has caused more frequent heavy rainfall events. Extreme rainfall can cause significant damage on land, such as through flooding and sediment movement. Similarly, extreme rainfall events cause negative changes in semi-enclosed bays, such as red tides and anoxic water masses. Hakata Bay, which is located in Fukuoka City on the northern end of Kyushu Island, Japan (**Fig. 1**), is a semi-enclosed bay in which environmental problems are reduced by heavy rainfall events. The bay has vast tidal flats, such as the Wajiro Higata and Imazu Higata in its eastern and western parts, respectively, which cultivate rich ecosystems. Moreover, migratory birds from other continents frequent the bay (Babazaki *et al.* 2009); therefore, protection of this environment is important. The bay also contains large-scale developments and has experienced negative changes to its ecosystems and environmental degradation

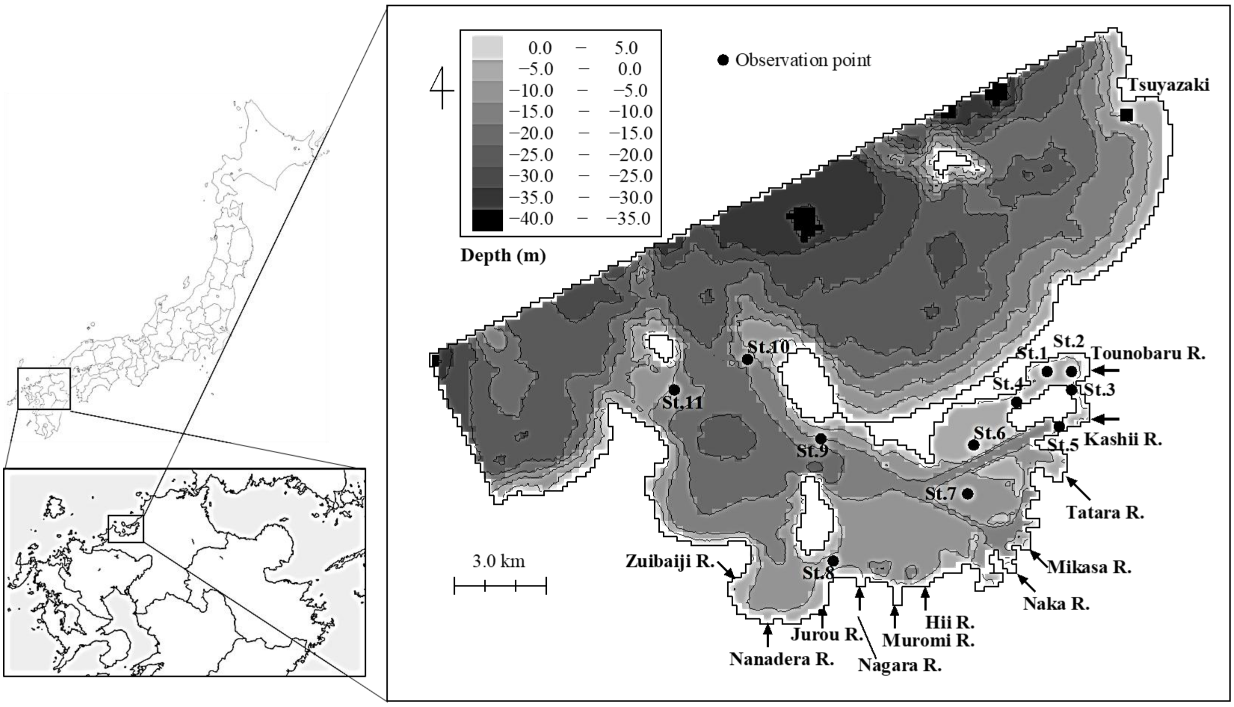

Fig. 1. Bathymetry of the calculation area, as well as the locations of the observation points, river inflow points, and the Tsuyazaki tidal observation station.

of the coastal waters caused by features such as red tides and anoxic water masses, which occur due to extreme rainfall events. They bay also has valuable ecosystems that are worth protecting from environmental issues such as red tides and anoxic water masses, which occur after heavy rainfalls.

However, the process by which heavy rainfall events cause red tides and anoxic water masses has not been quantitatively described. Red tides and anoxia are caused in part by the short-term inflow of large nutrient loads and the strong salinity stratification that result from the massive amount of freshwater discharged from rivers during heavy rainfall events (Tsutsumi *et al.* 2003). Another reason why heavy rainfall results in red tides and anoxia is that flocs release microalgae into the seawater because low salinity seawater decomposes the flocs (Isagai 2014). Hence, salinity regulates the physical and chemical characteristics of a coastal water body after heavy rainfall events. Therefore, three-dimensional salinity modeling is essential, and it is important to evaluate the impacts of heavy rainfall on semi-enclosed bays as these events occur more frequently.

In this study, the authors analyzed the salinity of Hakata Bay after a heavy rainfall event that greatly damaged Fukuoka City in September 2002. This paper used a three-dimensional σ-coordinate model, which has been widely used in numerical modelling studies of coastal seas. Sugawara's tank models (Sugawara, 1985) were used to calculate the river inflow discharge values, which represented the river inflow in a hydrodynamic and salinity diffusion model for Hakata Bay. The validation results of the model were highly reproducible and the impacts of large freshwater discharges were evaluated along both horizontal and vertical distribution of salinity.

Material and Methods

1. Model description

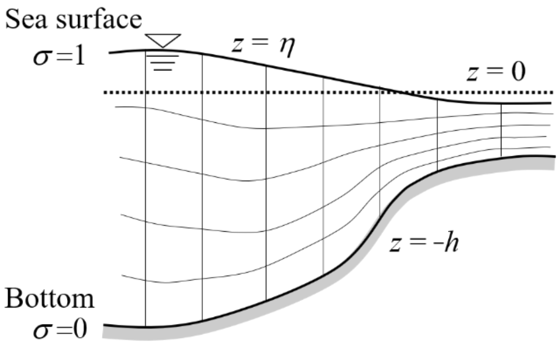

Fig. 2. Conceptual diagram of the σ-coordinate system.

Three-dimensional σ-coordinate models (Phillips 1957) are generally used to analyze salinity in coastal seas (*e.g.*, Irie *et al.* 2003, Serio *et al.* 2007). In this research, a σ-coordinate system was combined with a hydrodynamic and salinity diffusion model to accurately represent how the shallow inner part of the bay was influenced by freshwater river discharge.

In the Cartesian z-coordinate system, the sea surface and bottom are defined as $z = \eta$ and $z = -h$, respectively. In the σ-coordinate system, the sea surface and bottom are defined as $\sigma = 1$ and $\sigma = 0$, respectively (**Fig. 2**), wherein the coordinate conversion formula is defined as $\sigma = (z+\eta)/(h+\eta)$.

The model-governing equations were composed of the continuity equation for an incompressible fluid (Eq. 1), the Reynolds equation using a hydrostatic pressure approximation (Eqs. 2 and 3), and the diffusion equation of salinity (Eq. 4) with the σ-coordinate conversion, as follows:

$$\frac{\partial \eta^*}{\partial t} + \int_0^1 \frac{\partial \tilde{u}^*}{\partial x} d\sigma + \int_0^1 \frac{\partial \tilde{v}^*}{\partial y} d\sigma = 0 \tag{1}$$

$$\begin{aligned} &\frac{\partial \tilde{u}^*}{\partial t} + \frac{\partial (Huu)}{\partial x} + \frac{\partial (Huv)}{\partial y} + \frac{\partial (w_s \tilde{u}^*)}{\partial \sigma} \\ &= Hfv - \frac{gH}{\rho}\left[(\rho_0 + \rho'\sigma)\frac{\partial \eta^*}{\partial x} + \rho'(\sigma - 1)\frac{\partial h}{\partial x} + \frac{\partial}{\partial x}\left\{ (\eta^* + h)\int_\sigma^1 \rho' d\sigma \right\} \right] \\ &+ \frac{1}{H^2}\frac{\partial}{\partial \sigma}\left(A_\sigma \frac{\partial \tilde{u}^*}{\partial \sigma} \right) + HA_H\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \end{aligned} \tag{2}$$

$$\begin{aligned} &\frac{\partial \tilde{v}^*}{\partial t} + \frac{\partial (Huv)}{\partial x} + \frac{\partial (Hvv)}{\partial y} + \frac{\partial (w_s \tilde{v}^*)}{\partial \sigma} \\ &= -Hfu - \frac{gH}{\rho}\left[(\rho_0 + \rho'\sigma)\frac{\partial \eta^*}{\partial y} + \rho'(\sigma - 1)\frac{\partial h}{\partial y} + \frac{\partial}{\partial y}\left\{ (\eta^* + h)\int_\sigma^1 \rho' d\sigma \right\} \right] \\ &+ \frac{1}{H^2}\frac{\partial}{\partial \sigma}\left(A_\sigma \frac{\partial \tilde{v}^*}{\partial \sigma} \right) + HA_H\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) \end{aligned} \tag{3}$$

$$\frac{\partial(HS^*)}{\partial t}+\frac{\partial(HuS)}{\partial x}+\frac{\partial(HvS)}{\partial y}+\frac{\partial(Hw_sS^*)}{\partial \sigma}=\frac{1}{H^2}\frac{\partial}{\partial \sigma}\left(K_\sigma\frac{\partial(HS^*)}{\partial \sigma}\right)+HK_H\left(\frac{\partial^2 S}{\partial x^2}+\frac{\partial^2 S}{\partial y^2}\right) \quad (4)$$

where t is the time (s); u, v are the velocity components in the x- and y-directions, respectively (m/s); w_s is the velocity component in the σ-direction (1/s); $H(=\eta+h)$ is the depth from the bottom to the sea surface (m); $\rho(=\rho_0+\rho')$, ρ_0, and ρ' are the density, the standard density, and the difference between ρ and ρ_0, respectively (kg/m^3); g is the gravitational acceleration (m/s^2); f is the Coriolis parameter (1/s); $\tilde{u}$ and $\tilde{v}$ are the line discharges in the x- and y-directions, respectively (m^2/s; $\tilde{u}=uH$ and $\tilde{v}=vH$); A_H and K_H are the horizontal eddy viscosity and diffusivity coefficients, respectively (m^2/s); A_σ and K_σ are the vertical eddy viscosity and diffusivity coefficients, respectively (m^2/s); and S is the salinity (psu).

To solve the model numerically, the semi-implicit method algorithm of Sasaki *et al.* (1996) was utilized. This method implicitly discretizes variables with *, such as the sea surface elevation, line discharges, and the vertical convective and viscosity (diffusive) salinity terms.

The horizontal eddy viscosity (A_H) and diffusivity (K_H) coefficients were determined using the Smagorinsky model (Smagorinsky 1963), as follows:

$$A_H=K_H=\frac{1}{2}S_mA_G\left\{\left(\frac{\partial u}{\partial x}\right)^2+\frac{1}{2}\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right)^2+\left(\frac{\partial v}{\partial y}\right)^2\right\}^{\frac{1}{2}} \quad (5)$$

where S_m (=0.2) is the model parameter and A_G (m^2) is the mesh size.

The vertical eddy viscosity (A_σ) and the diffusivity (K_σ) coefficients were determined using Kolmogorov's hypothesis (*e.g.*, Kowalik and Murty 1993), as follows:

$$A_\sigma=l^2\left[\left(\frac{\partial u}{\partial z}\right)^2+\left(\frac{\partial v}{\partial z}\right)^2\right]^{\frac{1}{2}}\sqrt{1+\frac{R_i}{P_r}} \quad (6)$$

$$K_\sigma=A_\sigma/P_r \quad (7)$$

where R_i is the Richardson number, P_r is the turbulent Prandtl number determined following Kondo *et al.* (1979), and l (m) is the mixing length determined following Blackadar (1962).

Finally, a wet-and-dry method proposed by Uchiyama (2004) was introduced to represent the appearance and disappearance of tidal flats.

3. Calculation conditions

Figure 1 shows the bathymetry of the calculation area and the river inflow points in Hakata Bay, which has a sea surface area of 133.3 km^2, a mean depth of 10.8 m, and a maximum depth of approximately 23 m (Fukuoka City Environmental Bureau 2016). The bay has six main rivers: the Tatara, Mikasa, Naka, Hii, Muromi, and Zuibaiji. The calculations were conducted with a spatial discretization of Δx, Δy = 100 m, and 7 vertical layers. A temporal discretization of Δt was set at 20.0 s for the low river discharge and 1.0 s for the high river discharge; these values were used to stabilize the calculation near river mouths. At the

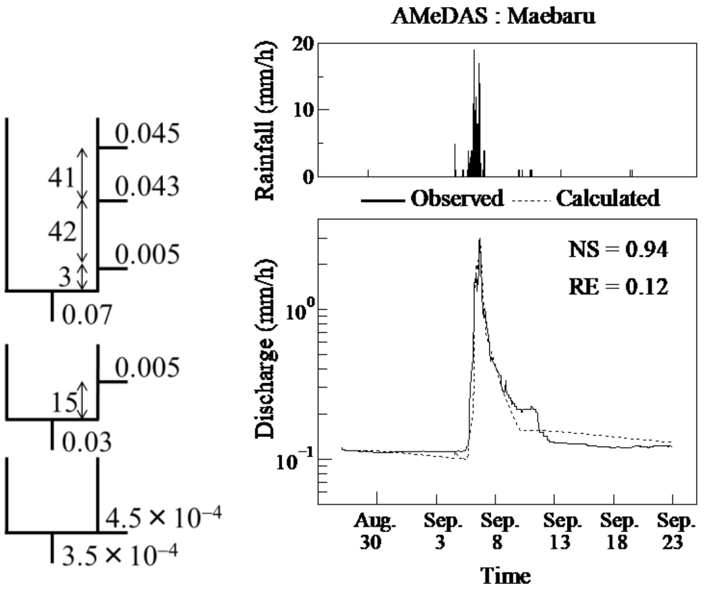

Fig. 3. Sugawara's tank model used to calculate the rainfall-runoff value for the Zuibaiji River watershed; the comparison of observed and calculated discharges from 25 August to 23 are also shown September 2002.

bay entrance, the tidal level was calculated using harmonic constants obtained from the Tsuyazaki tidal observation station; the tidal level was deemed an open boundary condition in the calculation.

In general, it is difficult to observe river discharges, especially after heavy rainfall events. The tank model proposed by Sugawara (1985) was used to determine discharges of the rivers that flow into Hakata Bay during flood events. The tank model parameters were identified from hourly observed discharges using a trial-and-error method. As an example, **Fig. 3** shows the structure and parameters of the tank model for Zuibaiji River and a comparison between the observed and calculated discharges for Zuibaiji River during 25 August–23 September 2005. A Nash–Sutcliffe (NS) coefficient of 0.94 and a Relative Error (RE) of 0.12 indicated that the tank model accurately reproduced the observed data.

In this research, the impact of a massive amount of freshwater discharging from rivers due to heavy rainfall in the Hakata Bay region was analyzed using a three dimensional σ-coordinate model. The calculation period was from 11 to 27 September 2002 because an extreme rainfall event producing 163.5 mm/d occurred on 16 September in Fukuoka City.

Prior to simulating the impacts of heavy rainfall events, a hydrodynamic and salinity diffusion model was validated over a two-week period. The validation period for which observed tidal current vectors and salinities were available was from 18 July to 2 August 2007.

Results and Discussion

1. Model validation

Observation points for the velocity and salinity are indicated in **Fig. 1**. **Figure 4(a)** compares the observed and calculated tidal current vectors in one-hour intervals at several observation points from 0:00 to 23:00 on 30 July 2007. The tidal current vectors calculated exhibited good agreement with observed ones. **Figure 4(b)** compares observed and calculated salinity values at several observation points for the same period as the tidal current vectors. The calculated salinities at St. 5 were slightly higher than the observed values due to the nearby small rivers that could not be considered in the model. However, the other calculated salinities demonstrated good agreement with observed values. Overall, the model

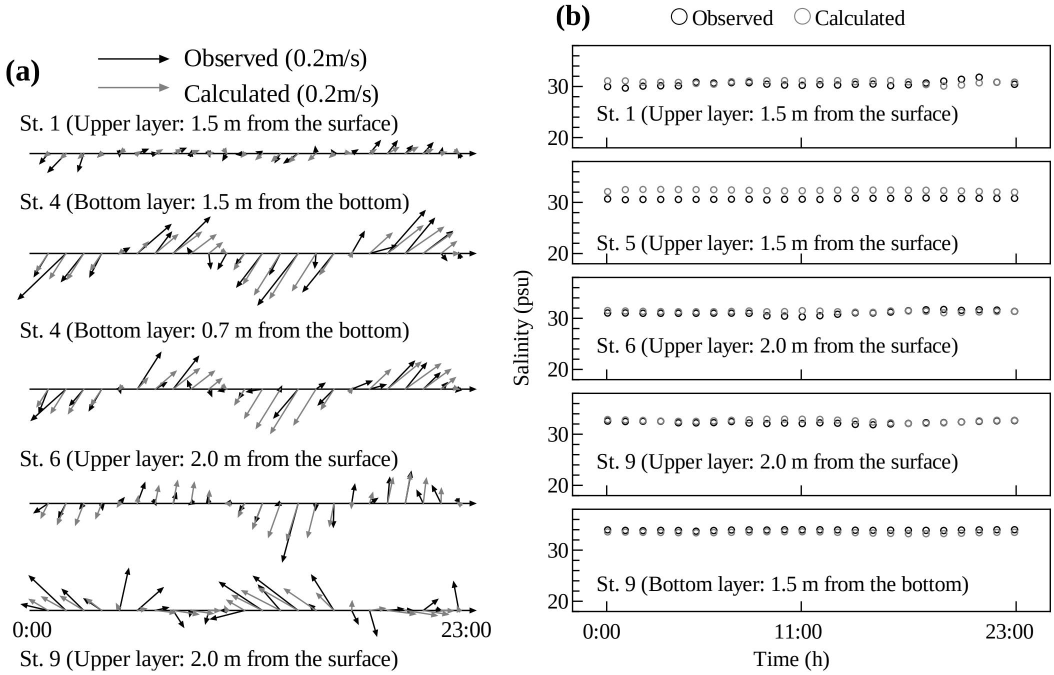

Fig. 4. Comparisons of observed and calculated (a) tidal current vectors and (b) salinities, in one-hour intervals from 0:00 to 23:00 on 30 July 2007.

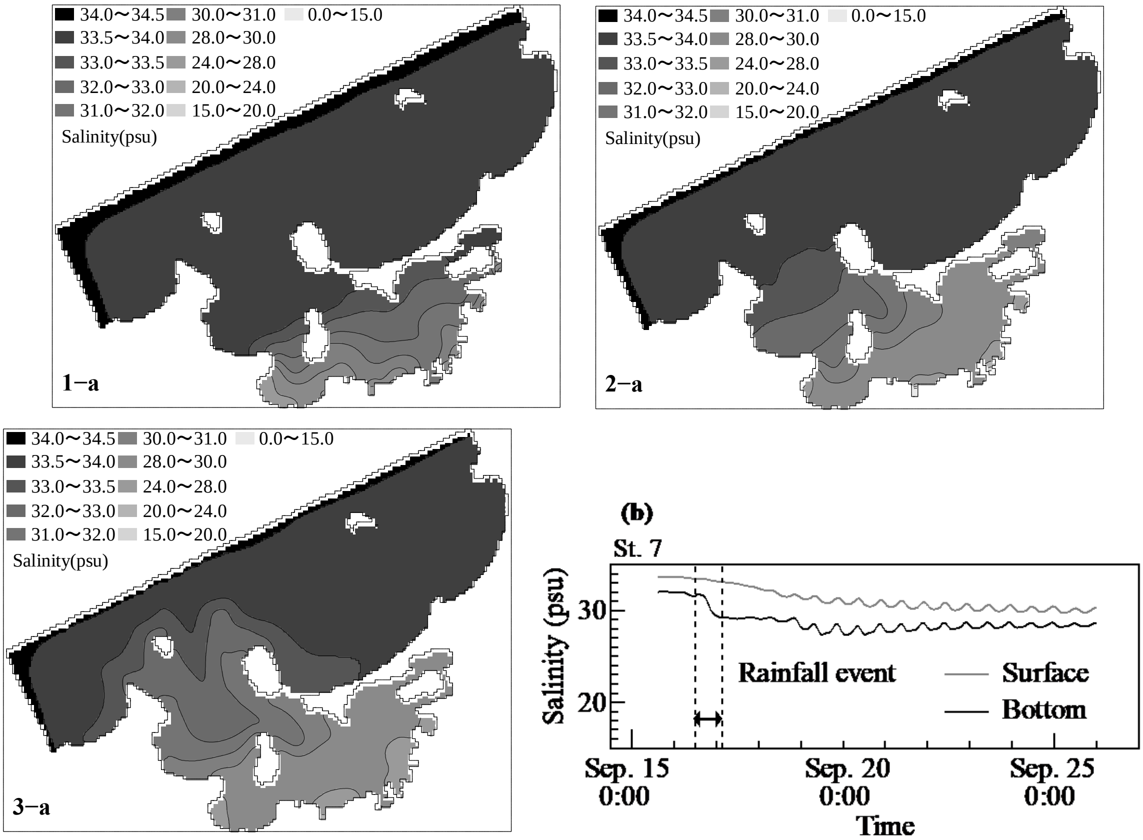

Fig. 5. Salinity distribution at the surface at (1-a) 0:00 16 September, (2-a) 20:00 17 September, and (3-a) 23:00 24 September 2002, respectively, and (b) time series of calculated salinity at St.7 from 15:00 15 September to 0:00 26 September 2002 (See also Fig. 1)

validation period results indicated that the hydrodynamic and salinity diffusion model performed well in simulating tidal currents and salinity diffusion in Hakata Bay.

2. Post-rainfall salinity analysis

Figure 5 shows the results of the salinity calculations. The horizontal distribution of salinity is shown for the surface (1-a) before the heavy rainfall event (0:00 16 September), (2-a) after the heavy rainfall event (20:00 17 September), and (3-a) one week after the heavy rainfall event (23:00 24 September). Comparing **Fig. 5(1-a)** and **Fig. 5(2-a)**, very low salinity values of less than 15.0 psu were found at the river mouths where a large amount of fresh water flowed into the bay over a short period. However, the differences between **Fig. 5(2-a)** and **Fig. 5(3-a)** were larger; low-salinity water covered the entire inner part of the bay, reaching the outer bay, one week after the heavy rainfall event [**Fig. 5(3-a)**]. Freshwater flowing into the bay took time to spread out and the low-salinity water (< 28.0 psu) was concentrated at the large river mouths (**Fig. 1**). **Figure 5(b)** shows a salinity time series for the period of calculation at St. 7 (**Fig. 1**). Just after the heavy rainfall event, the salinity difference between the surface and bottom became large (approximately 4 psu). Surface salinity suddenly decreased just after the heavy rainfall event and then slowly increased, with evident tide fluctuations. However, the bottom salinity slowly decreased and the difference became gradually smaller over the week.

According to Fukuoka Fisheries and the Marine Technology Research Center (2016), red tides have frequently occurred in the inner Hakata Bay, especially near the mouths of the Tatara, Mikasa, Naka, Hii and Muromi rivers. Low-salinity water spread across the inner part of Hakata Bay one week after the heavy rainfall event [**Fig. 5(3-a)**]. Therefore, nutrients such as nitrogen and phosphorus might similarly spread, allowing microalgae that absorb nitrogen and phosphorus to also spread throughout the inner bay. Furthermore, salinity stratification occurred approximately 3 days after the heavy rainfall event [**Fig. 5(b)**]. Because salinity stratification reduces vertical mixing, dissolved oxygen at the bottom might become depleted if red tides on the surface prevented sunlight penetration.

Conclusions

In this study, a three-dimensional σ-coordinate model was used to analyze the salinity in Hakata Bay after a heavy rainfall event. Sugawara's tank model was used to determine the discharge from the eleven rivers that flow into the bay. The tank model accurately reproduced the observed data. The modeled tidal current vectors and salinities also agreed well with the observed data.

The numerical model results for the salinity of Hakata Bay following heavy rainfall indicated that: (1) very low salinity (< 15.0 psu) values were found at the river mouths just after the heavy rainfall event; (2) low-salinity surface water spread across the inner part of the bay; and (3) the salinity difference between the surface and the bottom was large (approximately 4 psu) just after the heavy rainfall event. These results suggested that the nutrients in the rivers likely behaved similarly and the salinity stratification lasting approximately three days, which likely reduced vertical mixing in the inner bay. Consequently, a relationship between salinity and the occurrence of red tides and anoxic water masses was determined.

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