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Oceanic Water Intrusion into Kagoshima Bay Resulting in Thermal Stratification

Hosotani, K.*[1] and Winarso, G.*[2]

*1 Faculty of Fisheries, Kagoshima University, Shimo-arata 4-50-20, Kagoshima City,Kagoshima Pref., 890-0056, Japan. E-mail: hosotani@mail.goo.ne.jp
*2 Graduate School of Science and Technology, Nagasaki University, 1-14 Bunkyo-machi Nagasaki-shi, 852-8521, Japan.

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Abstract : Kagoshima Bay is an enclosed bay that has the tendency to undergo eutrophication, and a very important site to describe the behavior of open seawater intrusion. According to the results of the satellite SST (Sea Surface Temperature) image analysis or numerical simulation focused on the warm water intrusion into the bay in winter, a warm water mass originates in the meandering Kuroshio Current and reaches the mouth of the bay making the density flow to act like a semi-geostrophic current that is influenced by the Coriolis effect. However, there is still no information on the oceanic intruding flow during the summer, where it is accompanied by thermal stratification. In this research, satellite remote sensing and numerical simulation were employed to investigate the oceanic water intrusion into Kagoshima Bay during the summer season by using satellite chl-a (chlorophyll-a) images instead of SST. As a result, the distribution of the low-concentration chl-a with the oceanic water intrusion was found to be similar to the intrusion that occurs during the winter season. Furthermore, the numerical simulation was performed under the simple assumption that the thickness of the warm water mass that reaches the southern coast of Kyushu also shows the same tendency as in the winter season. Although the characteristics, such as the intruding speed or intruding pattern, are similar in winter, some features such as the generation of the inflow from the middle layer, showed a different tendency.

Keywords : Kagoshima Bay, MODIS/Aqua, Numerical simulation, Oceanic water intrusion, Chlorophyll-a, Sea Surface Temperature.

1. Introduction

Kagoshima Bay is located in the southern tip of Kyushu, Japan. It stretches in a N-S direction with a length of about 75 km. Its mouth opens to the south, forms a sill at a depth of about 100 m. Close to the mouth of the bay flows the Kuroshio Current. In the bay, there are two deep basins connected by Sakurajima channel, which is about 2 km wide and 40 m deep (Fig. 8). Because of the semi-enclosed nature of the bay, the intrusion into the bay water was previously confirmed (Sakurai et al., 1983 and 2000).

During the winter season, there are intermittent warm water intrusions that flow towards the north along the east coast of the bay. Ohtani et al. (1998) reported this phenomenon from field observations and satellite SST (Sea Surface Temperature) images (Fig. 1). Kohno et al. (2004), by using a numerical simulation, reported that this depends on the warm water condition in the mouth of the bay and that this phenomenon was caused by the semigeostrophic gravity flow influenced by the Coriolis effect. Hosotani et al. (2005) investigated details of the intruding patterns and the characteristics of the warm water intrusion using satellite SST images and numerical simulation. Furthermore, they suggested that the characteristics of the intrusion do not change significantly as the temperature conditions at the mouth of the bay change. In addition, the mass conservation law limits the thickness of the intrusion available for the flow inside; therefore, the thickness of the warm water mass is only about 50 m. This result agrees with the observations reported by Sakurai et al. (1983 and 2000). All previous studies mentioned above were done during the winter season. Actually, the oceanic water intrusion into Kagoshima Bay can be clearly seen in the satellite SST image (Fig. 1). During the summer season, however, the SST distribution is uniform due to the increasing surface heating effect (Takahashi and Kawamura, 2005). The oceanic water intrusion is difficult to visualize and the phenomenon cannot be observed by using SST images alone. This is because a strong thermal stratification makes the surface temperature inside the bay lose its gradients (Fig. 2). Thus, the characteristics and mechanism of the oceanic water intrusion into Kagoshima Bay were not described in spite of its actual occurrence.

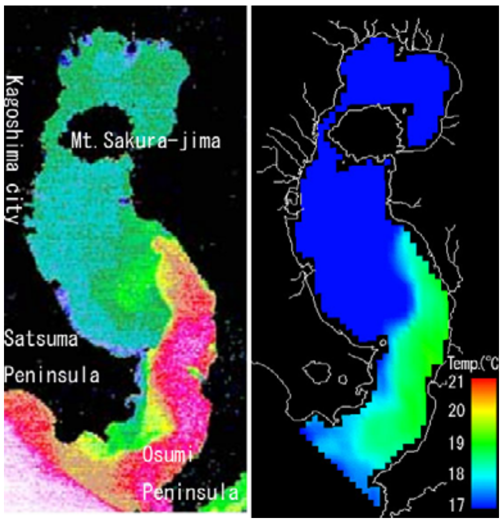


Fig. 1. Oceanic water intrusion in winter. Left figure shows a Landsat-SST image by radiance temperature in which colored high temperature appears red (Ohtani et al., 1998). Right figure shows the results of numerical simulation (Kohno et al., 2004).

Recent developments in satellite remote sensing techniques make it possible to observe the various characteristics on the sea surface, such as chlorophyll-a (chl-a) instead of SST. The different chl-a concentrations between the coastal water and the Kuroshio water show contrast, especially during the summer season as reported by Miyashita (2005) using SeaWiFS chl-a images. Hosotani (2006) reported that the warm ocean filaments, which emanate periodically in winter from the meandering Kuroshio Current at the East China Sea, bring warm water masses to the southern coast of Kyushu. So the source of the water intrusion in the summer season will also exist, as shown by the SST in winter. Takahashi and Kawamura (2005) concluded that the Kuroshio front detection method using chl-a images was effective in the summer season, when the SST images are less sensitive in detecting the front. Therefore, in order to check the oceanic water intrusion during summer (including spring and fall), satellite images focusing on the chl-a concentrations were employed instead of SST. Followed by a numerical simulation that was done to describe the mechanism and to differentiate it from the phenomenon that occurs during the winter season.

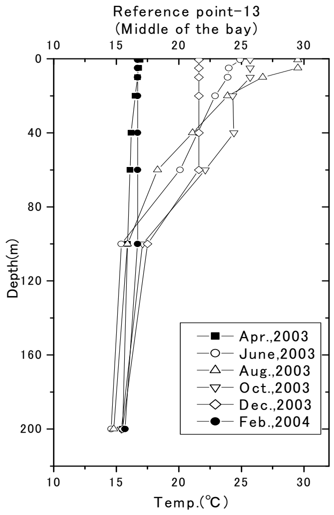


Fig. 2. Vertical water temperature distributions in the middle of Kagoshima Bay (Kagoshima Pref., 2005).

2. Materials and Methods

2.1 Satellite Remote Sensing

To describe the oceanic water intrusion into the bay during the summer season when the SST distribution is uniform due to the increasing surface heating effect, chlorophyll-a images derived from ocean color satellite data were employed. The chl-a and SST images derived from MODIS Aqua/Terra data of the southern Kyushu area with a 4 km resolution during 2005 to 2006 were downloaded from Kagoshima Prefecture Fisheries Technology and Development Center. The intruding speed and distribution patterns were estimated from the time series images. These images are in jpeg format that does not contain an exact geophysical chl-a value. Thus, MODIS Aqua data were processed to find out characteristic patterns or the correlation between chl-a and SST. The HDF formatted MODIS Aqua level 1A data were downloaded from the Goddard Earth Science, Data and Information Service Center, National Aeronautics and Space Administration (NASA), and using SeaDAS data processing software, atmospheric and geometric calibrations were performed.

2.2 Numerical Simulation

There are some reports of a numerical simulation that focused on the warm water intrusion of Kagoshima Bay in winter (Kohno et al., 2004, Hosotani, 2006). These reports showed that the warm water intrusion depends on the warm water mass from the Kuroshio Current touching the mouth of the bay. It causes the semi-geostrophical gravity current flow of the rotation system caused by the Coriolis effect to move northward along the east side coast of the bay. Characteristics of the semi-geostrophical density gravity flow inside a closed bay were studied by Kubokawa and Hanawa (1984). A current is generated as a gravity flow by the warm water mass with low density causing a rise in the water level. This current spreads with a clockwise rotation. As it is common in the Northern Hemisphere, the Coriolis effect transforms the gravity flow into a clockwise flow. After which, the coastal line interferes with the flow so it becomes the intruding current flow, which flows along the right of the coast (i.e., east side). So, the intrusion will go along the coast northward. It is easy to describe the intruding mechanism in the winter season. Vertical water temperature in the bay shows almost the same value regardless of depth, and the warm ocean water, which generates the driving force as gravity flow, spreads into the bay easily. However, in the other seasons that water shows thermal stratification, so it is difficult to describe the intruding mechanism.

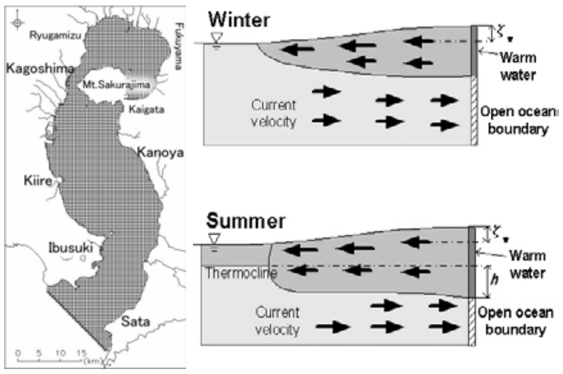


Fig. 3. Division of the bay and the estimated assumptions for modeling during summer and winter.

Table 1. Calculation parameters.

Horizontal grid size	500m	
Level (10 Layer)	1:0-10m	6:80-100m
	2:10-20m	7:100-120m
	3:20-40m	8:120-140m
	4:40-60m	9:140-180m
	5:60-80m	10:18m0-btm
H-eddy visc. ratio	1.0×10^{5}cm^{2}/s	
V-eddy visc. ratio	1.0×10^{0}cm^{2}/s	
H-diffusion ratio	1.0×10^{5}cm^{2}/s	
V-diffusion ratio	1.0×10^{0}cm^{2}/s	
Coriolis parameter	8.0×10^{-5}s^{-1}	
Drag coef. at btm.	2.6×10^{-3}	

Table 2. Boundary conditions.

	Summer	Winter
Initial Boundary condition	1-layer:30 °C 2-layer:27 °C 3-layer:25 °C 4-layer:23 °C 5-layer:20 °C 6-10layer:17 °C	All layers are set as 17 °C
Warm Water condition	Set 30 °C to upper 40m (1-3layer) during 2 days	Set 21 °C to upper 40m (1-3layer) during 2 days
Salinity	Uniformed (34PSU)	
Elevation	Semi-diurnal (Amplitude: 75cm)	

In this research, the same simulation model described above (i.e., Kohno et al. (2004) or Hosotani et al. (2005)) was applied. This model is a three-dimensional finite difference method (Multi-level model) that includes the following assumptions: 1) Hydrostatic approximation for the vertical momentum equation, 2) Boussinesq's approximation and 3) F-plane approximation. Then, the thickness of the warm water mass, which comes near the mouth of the bay, is assumed to act as shown in Fig. 3. The procedure to solve this model is to first calculate the current flow field and the water temperature field using advection-diffusion equations. The chl-a field is calculated by applying the diffusion equation which incorporates the current flow data.

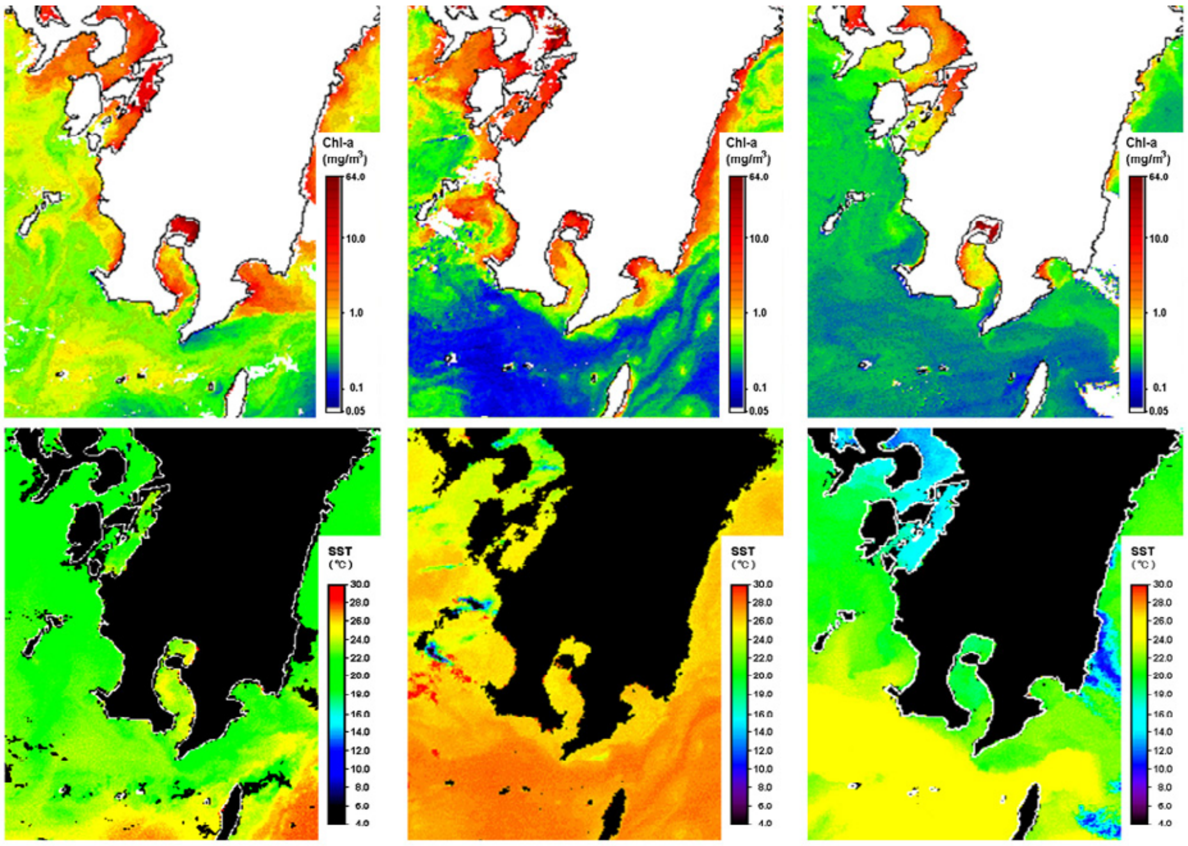
The calculation parameters are given in Table 1. Table 2 shows the open boundary conditions. Here, it was checked that this calculation model and the calculation parameters have the validity and stability under various conditions by preliminary calculations. The boundary condition of thermal stratification was applied based on observation results obtained in October, in which the water thermocline forms the strongest gradient (Fig. 2). During the summer season, the thickness of a given thermal stratification is set at 20 m. According to the SST images of the NOAA satellite of time series, the warm water will be brought to the southern coast of Kyushu for two or three days by the Kuroshio Current frequently. So, a 30 ^{o}C warm water condition, which has 40 m thick, was given at the boundary grid for two days. On the other hand, during the winter season, the calculation parameters and warm water condition were set as in Hosotani et al. (2004). The chl-a calculation is based on a simple concentration diffusion model, which does not pass through a strict biochemical process. It was based on the observation report of Kobari et al. (2002) and the concentration value of 15 mg/m^3 was given as the initial condition at the upper 60 m. The value 0 mg/m^3 is given as the boundary condition below 60 m. The only condition added to these is the semi-diurnal tide level which is of a very large intensity in Kagoshima Bay, and is forced at the mouth of the bay. Although the assumptions of the boundary conditions are rough, they are surmised that it is not significantly different from the real conditions.

3. Results and Discussion

3.1 Visualization of the Oceanic Water Intrusion and Seasonal Variation

The satellite images representing the oceanic water intrusions for each season are shown in Fig. 4. Upper images show chl-a on the sea surface, and lower images show SST, respectively. These images focused on the spring season, that is, when plankton increases explosively. In the fall season the thermal stratification becomes the most remarkable, and in winter it shows clearly the warm water intrusion. First, in spring season as shown in Fig. 4(a), SST shows that the higher temperatures were along the east and west side coasts of the central bay section and in the northern section. While the oceanic water intrusion cannot be clearly visualized. On the other hand, the chl-a image shows the distribution of low concentration according to the oceanic water intrusion, which shows clearly the intrusion from the mouth of the bay to southern Mt. Sakurajima. During the fall season, when a stronger thermocline is formed, although SST inside the bay cannot be distributed almost uniformly at 26 ^{o}C (Fig. 4(b)), the oceanic water intrusion is still not visualized. The chl-a image shows signs that the open seawater with a low concentration intrudes towards the central part of the bay. Finally, in winter (Fig. 4(c)), the oceanic water intrusion (probably, in the case of this example, it could be called warm water intrusion) can be seen both in the SST and chl-a images. It is important to note that chl-a is greatly dependent on water temperature, observation time, and the nutrients that flow in from fresh water and land, rivers and other waters. Therefore, each image shows a high concentration of chl-a at the northern section of the bay, where many fish farms are located; and at the west side of the central section, where the offshore area of the city is located. Thus, after the intruding water has been fully distributed, the chl-a distribution pattern should differ from the advection-diffusion of SST. Although the low-concentration chl-a water seems to split in to two forks by the chl-a image of the central part in fall season, it is still an assumption whether the flow has separated, and that this is where light seawater, mostly including fresh water from the offshore of Kagoshima-city, experienced eutrophication. The existence of this eutrophication in the water distribution offshore of the city area can be gathered also from reports on environmental assessment, which are performed periodically for the evaluation of water quality and for the numerical simulation of the ecosystem.

The correlation diagram, which shows the relationship between SST and chl-a under intruding condition, along the survey line (A-A') is shown in Fig. 5. The results show that fall and winter seasons are significantly correlated although the plot of spring was not clear. Also, this result shows that the chl-a value tends to be lower with a rise in SST, and this characteristic shows that the water mass with low chl-a concentration intrudes simultaneously with the warm oceanic water. It is clearly shown that chl-a depends on many parameters (such as water temperature, salt concentration, rain or nutrient concentration) and it shows dramatic changes on a daily basis.



(a)Spring (07,May,2005) (b)Fall(18,Oct.,2005) (c)Winter(21,Feb.,2006)

Fig. 4. Chl-a and SST images by MODIS satellite. Every chl-a image shows ocean water intrusion for each season, SST image shows only for winter.

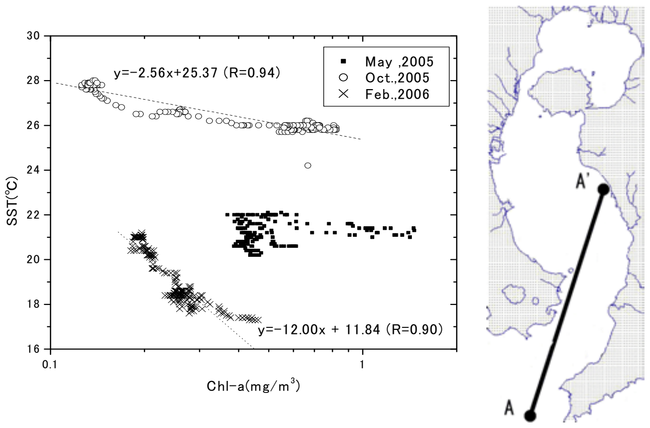


Fig. 5. The correlation graph of chl-a vs. SST on the survey line "A-A'".

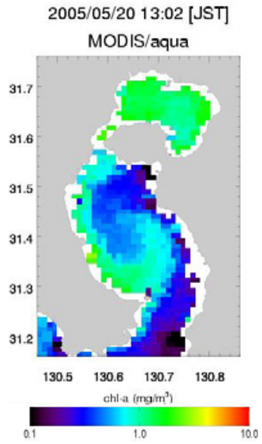


Fig. 6. Typical intruding pattern. (Taken by Kagoshima Prefectural Fisheries Technology and Development Center.)

However, since the intruding phenomenon will also progress for about one week and the chl-a concentration of oceanic water is too low, the oceanic water intrusion can explain the intruding pattern or characteristics (such as in winter). Thus, the intruding speed was estimated by dividing distance traveled by the time interval obtained from the time series of chl-a images. Since chl-a tends to be influenced by environmental factors as described above, the estimated intruding speed was calculated using the traveled distance of the front of the chl-a low-concentration water. Therefore, intruding speed should be considered as a rough estimate. The estimated speed was about 15 cm/s, which is the same found during the warm water intrusion in winter (Kohno et al., 2004). The representative examples that show clear intruding patterns by chl-a are shown in Fig. 6. This image shows the anti-clockwise rotation in the central part of the bay that has two patterns, i.e., the first pattern shows anti-clockwise rotation at the north side of the central section of the bay after it has reached Mt. Sakurajima, and another pattern forms a similar rotation at the center of the bay.

3.2 Numerical Calculation Results.

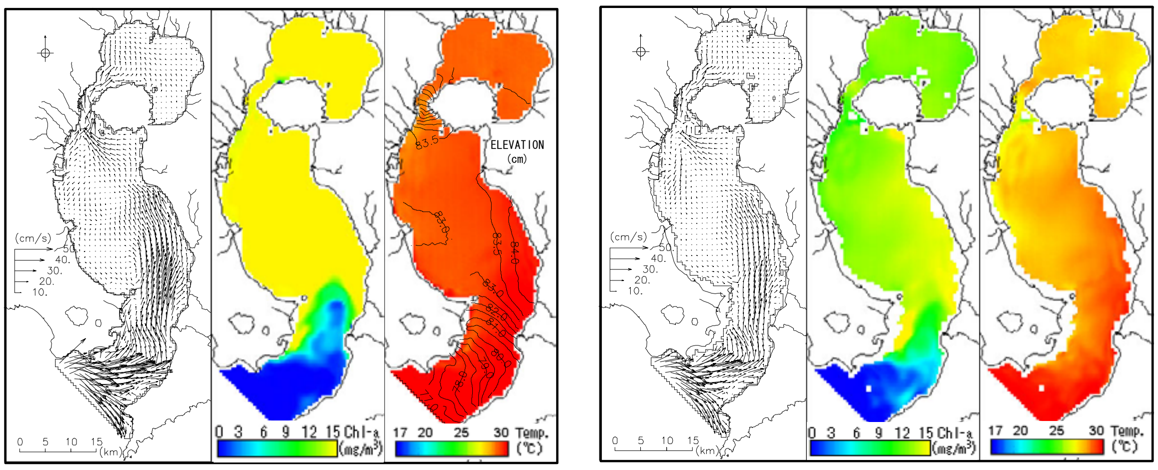
The oceanic water intrusions observed in summer from the satellite images showed that their distribution and characteristics were similar to those observed in winter. But are these advection-diffusion processes really having the same mechanisms as assumed for winter? To check this assumption, a numerical simulation was performed which employed the same warm water boundary conditions as in winter.

The current velocity vector, chl-a distribution, and the seawater temperature distribution of the 1st and 2nd layer on the 3rd, 4th, and 5th day, chl-a, and the water temperature distribution are shown in Fig. 7. As a result, the calculated current flow distributions showed the intrusion, which happens along the east side coast of the bay, similarly to the warm water intrusion that occurs in winter, although a thermal gradient was not seen. The calculated low-concentration water distribution of the assumed chl-a also showed the oceanic water intrusion as shown in the satellite images, and it goes northward along with the flow. After the front reaches the coasts near Kanoya (see location in Fig. 3), the diffusion pattern branched out. The calculated intruding speed offshore of Kanoya is about 15 cm/s, which is similar to the estimated value calculated from satellite chl-a images. Moreover, this value is also similar to 10 cm/s - 15 cm/s as found in winter. Here, the detailed results of the calculations in winter were in agreement with other results reported in the literature (Kohno et al., 2004; Hosotani et al., 2005).

3.3 Comparison with Winter, and Discussion for the Driving Mechanism

As explained above, the oceanic water intrusion was described and visualized by satellite chl-a images and numerical simulation, and they showed that the oceanic water could intrude even under the thermal stratification condition. In this section, the mechanism of this phenomenon will be discussed by comparing it with the analogous one found in winter. The point is that a warm water mass exists in the middle layer at the boundary in summer (Fig. 3, summer, labeled as *h*), which makes the warm water intrusion extend to the depth of 40 m, much thicker than the 20 m found in winter (i.e., a thickness of warm water = 40 m – 20 m = 20 m acts as a driving source). As shown in Fig. 7, the less dense warm water makes the water level rise up like in winter, so that a gravity flow is also generated. The difference of oceanic water intrusion between winter and the other seasons will be shown in the vertical water temperature and current velocity distribution.

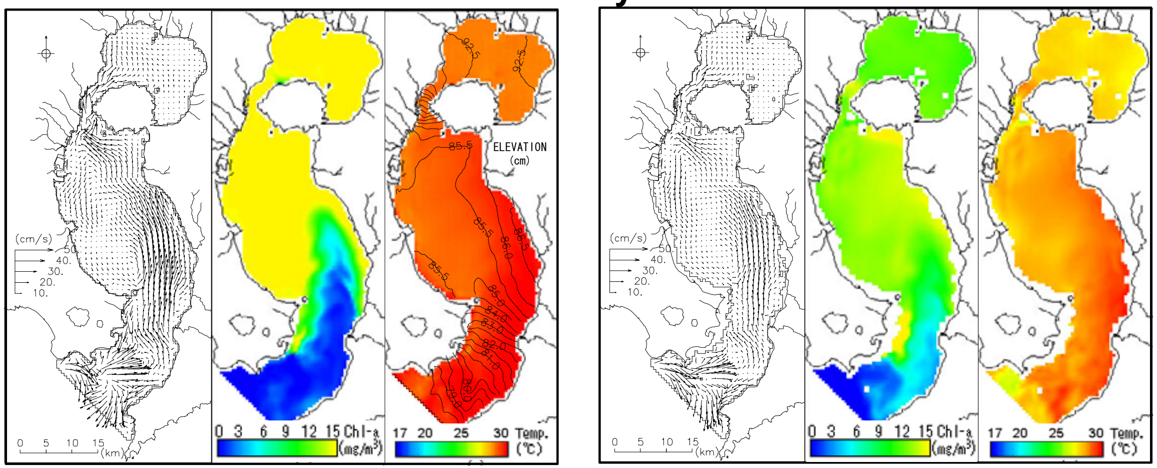
The two dimensional (horizontal-vertical) water temperature distributions and the current velocity vectors are plotted through the centerline of the bay (Fig. 8). In addition, in order to compare it with the case in winter and summer, both results are indicated. Here, the flow velocity vector of each figure is shown for high tide. On the other hand, water temperature distributions are one tide averaged in order to remove the detailed perturbation and to make it simpler. It is noted that the velocity vectors always appeared outward near the mouth of the bay because the survey line crosses the turbulent flow field front in this area as shown in the horizontal vector plots in Fig. 7.



Current velocity Chl-a Water temp.
1st layer (0m-10m)

Current velocity Chl-a Water temp.
2nd layer (10m-20m)

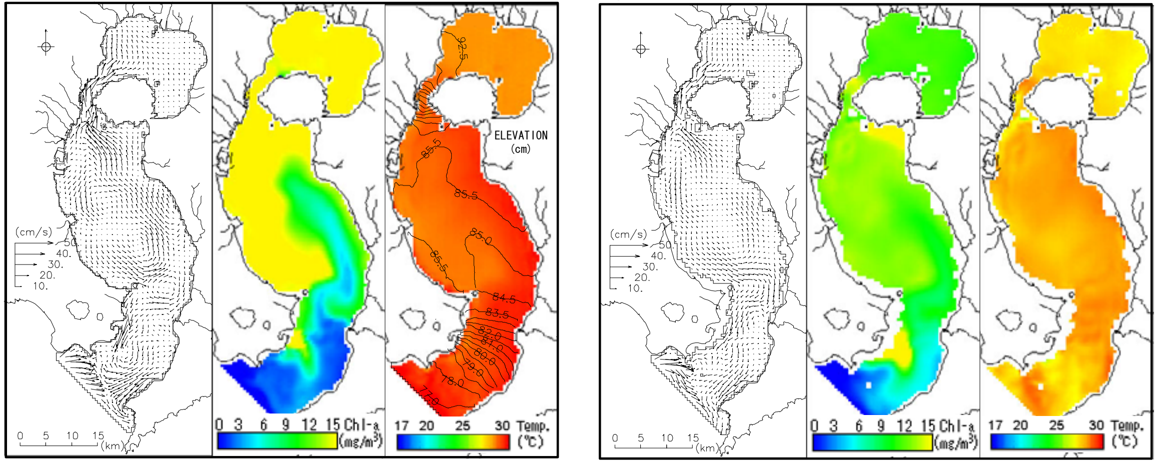
3rd day



Current velocity Chl-a Water temp.
1st layer (0m-10m)

Current velocity Chl-a Water temp.
2nd layer (10m-20m)

4th day



Current velocity Chl-a Water temp.
1st layer (0m-10m)

Current velocity Chl-a Water temp.
2nd layer (10m-20m)

5th day

Fig. 7. Simulated horizontal velocity vector, Chl-a and water temperature distributions of upper two layers, which are focused on summer. Note that these figures show the high tide conditions only. In the figure of water temperature, tide level contour plots are added.

As shown in Fig. 8, water temperature distribution in winter indicates that there is an upper inflow and an undercurrent outflow. On the other hand, in the case of summer, although the water temperature does not change near the surface layer, in the middle layer the effects of thermal stratification make gravity flow to cause the intrusion, so that the upper layer inflow and undercurrent outward flow are generated. Here, it is important to note that in summer, vector plots on the 5th day do not show the inflow from the upper layer, but instead show it from the middle layer. This situation facilitates water mixing inside the bay differently than in winter. The mechanism of the inflow from the middle layer can be estimated from the water level contour plot of Fig. 7. Indeed, the water level inside the bay rises up by about 10 cm on the 5th day above the applied tidal amplitude (75 cm), and it is enough to induce a gravity flow. While high temperature conditions are given as the boundaries, the intrusion from the upper layer is maintained. When this condition has stopped, an upper outward flow is generated by the high water level found inside the bay (although only the stagnated flow is visible on this survey line, a local outward flow is recognized in Fig. 8). Therefore, the inflow from the middle layer is produced as a result of this outward flow. This tendency agrees with the observed phenomenon, which suggests that the flow rises with density instability when the water thermocline progresses in summer. Because the biochemical process is not considered in this model, the results may not fully describe the chl-a distribution. For this reason, the calculated chl-a patterns may be overestimated, especially inside the middle of the bay.

The calculated vertical chl-a distributions are shown in Fig. 9. As shown in this figure, according to the intrusion in the upper layer, lower concentration values are diffused in the high-concentration environment. The upper flow was overestimated, diffusion of the upper chl-a stopped and, instead, signs that low chl-a values of the medium layer were mixed as shown in the 5th day, when the inflow from the middle layer is generated. This result showed the same tendency with the satellite chl-a images, which manifested no clear diffusion, although the intrusion of low-concentration chl-a near Kanoya was clear.

Also, considering the driving force of the oceanic water intrusion again, it is influenced by the branching of the flow that depends on the rossby wave that is driven by the sea surface wind (in this case, the rosbby number may exceed 1) or the intermittently meandering Kuroshio Current that is reported in other coasts of Japan. These phenomena are difficult to demonstrate completely because they include many or too strong nonlinear terms.

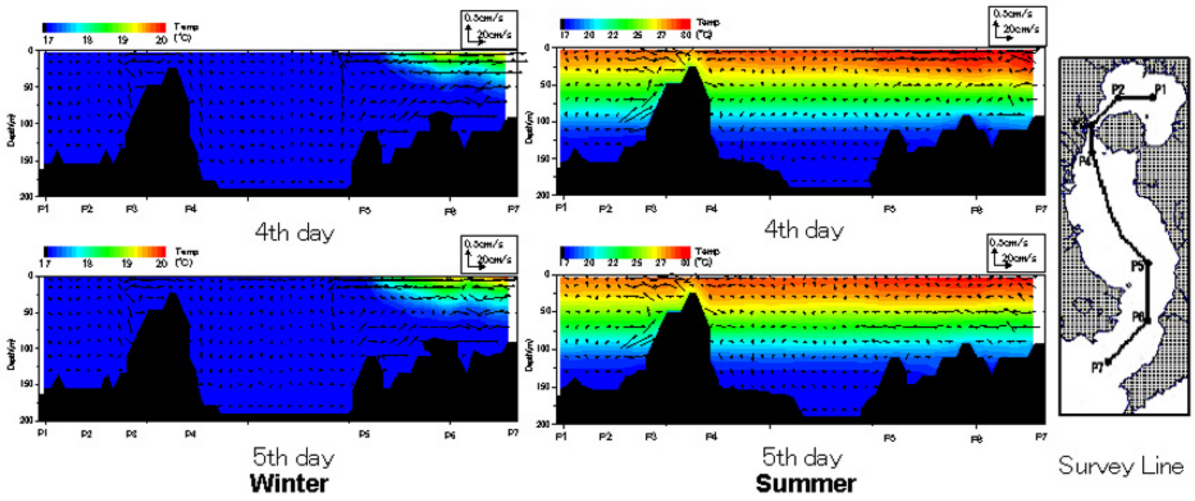


Fig. 8. Simulated vertical water temperature distributions and current velocity vector plots through the section set at the middle section shown in the right figure (P1-P7) in winter and summer. Note that the temperature field used was the average for one tide. On the other hand, vector plots are at high tide.

4. Conclusion

The oceanic water intrusion into Kagoshima Bay in the summer season with thermal stratification was difficult to analyze, although the existence and occurrence were already suggested before. This paper has visualized and described the phenomenon by using satellite chl-a images instead of using SST images. A numerical simulation was used with the assumption that it is the semi-geostrophic current influenced by Coriolis effect which gives the thick warm water condition. The basic mechanism is exactly the same as the warm water intrusion observed in winter. The intruding speed was the same as that in winter, but the process differs. Although the intrusion has inflow from the upper layer while the boundary temperature stays high, even after suspending the high temperature boundary condition at the mouth of the bay, an inflow from the middle layer and an outflow from the upper layer were shown.

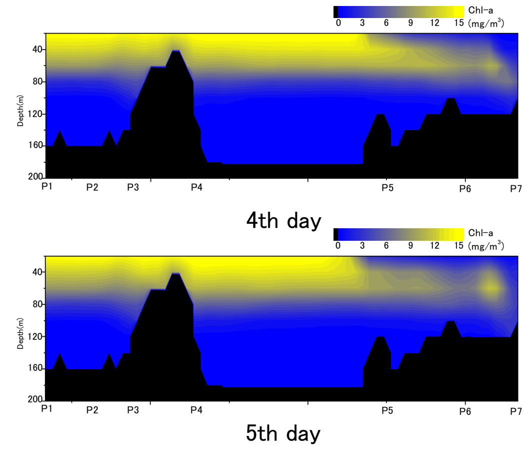


Fig. 9. Simulated Chl-a field at P1-P7 section.

The oceanic water intrusion into the closed Kagoshima Bay is a very important factor for the coastal environment. The result of this research suggests that oceanic water intrusion could be predicted by continuous monitoring of the water temperature conditions at the mouth of the bay, which will contribute to provide mitigating solutions in the protection of the coastal environment of Kagoshima Bay.

Acknowledgement

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Author Profile

Kazunori Hosotani:He received his MS. in Mechanical engineering from Tottori University (1999) and Ph.D. from The United Graduate School of Agricultural Sciences, Kagoshima University (2007). He is currently a part time technical staff at the Faculty of Fisheries, Kagoshima University. His research interests are environmental fluid dynamics.

Gathot Winarso: He worked in the Remote Sensing Center, Indonesian National Institute of Aeronautic and Space. He received his MS. in Fisheries Science from Kagoshima University. And now he is a Doctor al course student of Graduate School of Science and Technology, Nagasaki University. His research interests are satellite remote sensing and oceanography.