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Behavior of the Warm Ocean Water at the South Coast of Kyushu

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Abstract : The warm ocean water filaments are emanated periodically in winter from the meandering Kuroshio Current at the East China Sea. They bring the intermittent warm ocean water intrusion into the Kagoshima Bay well known as 'Kyucho' phenomenon. From the satellite SST images, the warm water intrusion is also observed at the Fukiage Seashore. In addition to the warm water intrusions, the cold-water mass at the Osumi Strait is observed. In this study, the numerical analysis is performed to understand these phenomena. A density current is calculated by a multi-leveled finite difference method (FDM). Then, particle trajectories are calculated by the Lagrangian particle tracking method by using the previous current result. Particles are dealt with as passive tracers to be a model of plankton and hyponeuston (i.e. larva, eggs or seeds) of an open sea. Calculated results of the warm water mass show similar features of the SST images, i.e. the warm water intrusions into the bay and the cold-water mass generation. The warm water intrusion occurs when it reaches the mouth of the bay or the edge of the coast. The cold-water mass is concerned with a horizontal vortex shed from the edge of the cape. The cold-water mass is produced in a stagnation region by a horizontal vortex rather than upwelling from the deep ocean. The particle trajectories have a tendency to pile up in the bay and a stagnation region behind of the peninsula. These results supply the fundamental knowledge that contributes to biological problems at the south of Kyushu in winter adequately.

Keywords : Kuroshio Current, Warm water intrusion, Cold-water mass, Satellite image, Numerical simulation, Particle trajectory.

1. Introduction

The Kuroshio Current meanders at the south of Kyushu as shown in Fig. 1. Figure 2 shows the bottom topography of this area consisting of deep and shallow basins such as the Kagoshima bay and the Fukiage Seashore. The Osumi Strait has comparatively flat topography. The Kuroshio Current flows from the Tokara Islands to the Pacific Ocean through the south of Yakushima Island. The warm ocean water filaments are emanated periodically in this region.

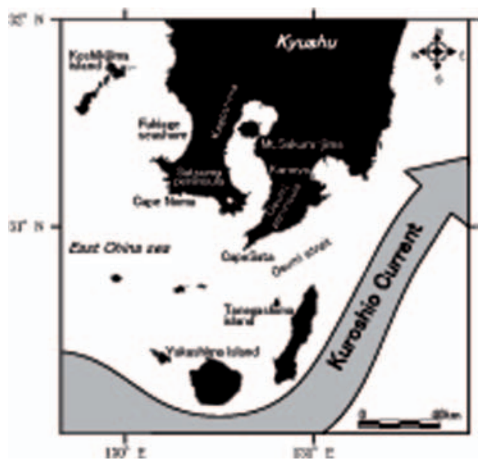


Fig. 1. Sketch of Kuroshio Current.

The Kyushu southern coast has some characteristic geographic features. The Kagoshima Bay is located in the southern end of Kyushu. It is long in the south-north direction with the length of about 75 km. There is a shill with the depth of about 100 m at its mouth opened to the south. The Fukiage Seashore is 44 km long and it is shallow up to far from the shoreline. In winter, the warm ocean water coming periodically into the south end of Kyushu. It causes the warm water intrusion into the Kagoshima Bay called 'Kyucho' phenomena (Nagata et al., 1982). The intermittent ocean water intrusion is observed by the current meter settled at the mouth of the bay (Sakurai, 1983; Ohtani et al., 1998) and the buoy robots at the fishing farms (Ohtani et al., 1998). In addition to the Kagoshima Bay, the satellite observations reveal the warm water intrusion into the Fukiage Seashore in the southwest of Kyushu (Kikukawa et al., 2004). The numerical analysis carried out to investigate these phenomena (Kohno et al., 2004; Hosotani and Kikukawa, 2005; Hosotani (under review)). They concluded that the warm water intrusions mainly is caused by a density flow.

As the water mass exchange in the Kagoshima Bay takes place mainly in winter (Takahashi, 1981; Kikukawa et al., 1997), the warm ocean water intrusion into the bay is important to take into consideration to the coastal environment. The warm water intrusion brings not only physical influences but also ecological influences to the coastal environment. The main ecosystem factors around the Kyushu that arrive from the open sea consist of plankton and hyponeuston (For example; larvae of crown-of-thorns starfish or coral, Nomura's jellyfish, vegetable seeds, and so on). Concerning behavior of hyponeuston of coral, a numerical particle tracking simulation is carried out in order to investigate coastal ecosystem in the Okinawa Islands (Nadaoka, 2002; Isobe, et al., 2005).

This study focuses on the warm water mass around the Kyushu southern coast generated at the East China Sea. The satellite images of a phenomenon of the warm water mass at the south coast of Kyushu are shown in the next section. Then, a numerical simulation is performed to study a density current and particle trajectories.

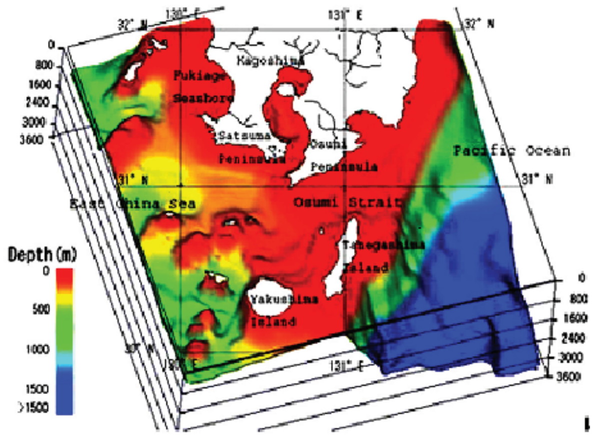


Fig. 2. Bottom topography of the Southern Kyushu.

2. Satellite Images

In this study, NOAA/AVHRR data received at Kagoshima University are used to observe the Sea Surface Temperature (Referred as SST, hereafter) around the south coast of Kyushu. However, the resolution (IFOV: instantaneous field of view) of NOAA data is 1.1km, which is not enough to investigate the detailed structure of the coasts. Thus the images are once enlarged using the linear interpolation (Kikukawa et al., 2004), so that the apparent resolution becomes 550 m.

Figure 3 shows the time series of the warm water mass around the south coast of Kyushu that is separated from the Kuroshio Current and then passing through the Osumi Strait on the 21st March to the 1st April in 2001. Figure 4 illustrates the behavior of the warm water, approaching to the Yakushima Island and then separated from the main Kurishio current. This event takes place periodically (Nagata et al., 1982). Therefore, it is different from the behavior of the warm water in the Bungo strait (Akiyama, 1994) or the Suruga Bay (Katsumata, 2003). The warm water mass plays dominant roles when it touches the mouth of the Kagoshima Bay or the edge of the Cape Noma, the warm water intrudes along the east side or the seashore.

The warm water intrusion into the Kagoshima Bay looks clear and its speed is estimated to be about 20 cm/s, which is comparable in the buoy robots observation that shows about 10 cm/s (Ohtani et al., 1998). In the Fukiage Seashore, estimating the speed of intrusion is difficult since the warm water mass spreads widely. On the other hand, the cold-water mass generation at the south of Osumi Peninsula is observed. The cold-water mass grows up at the coast of the Cape Sata when the warm water mass passes through the Osumi Strait. The AVHRR images showed that the temperature of the cold-water mass was the same as the SST before the warm water mass passes. Therefore, it is suggested the cold-water mass is produced by stagnated horizontal flow structures instead of upwelling flows from the deep ocean water, which is well known as a general cold-water mass.

Figure 5 summarizes the behavior by the satellite images. They are summarized as follows; (1) After the warm water mass touched with the south coast of Kyushu, the warm water intrusion occurs along the east side coasts of the Kagoshima Bay and the Fukiage Seashore. (2) The Cold-water mass is generated when the warm water mass passes through the Osumi Strait.

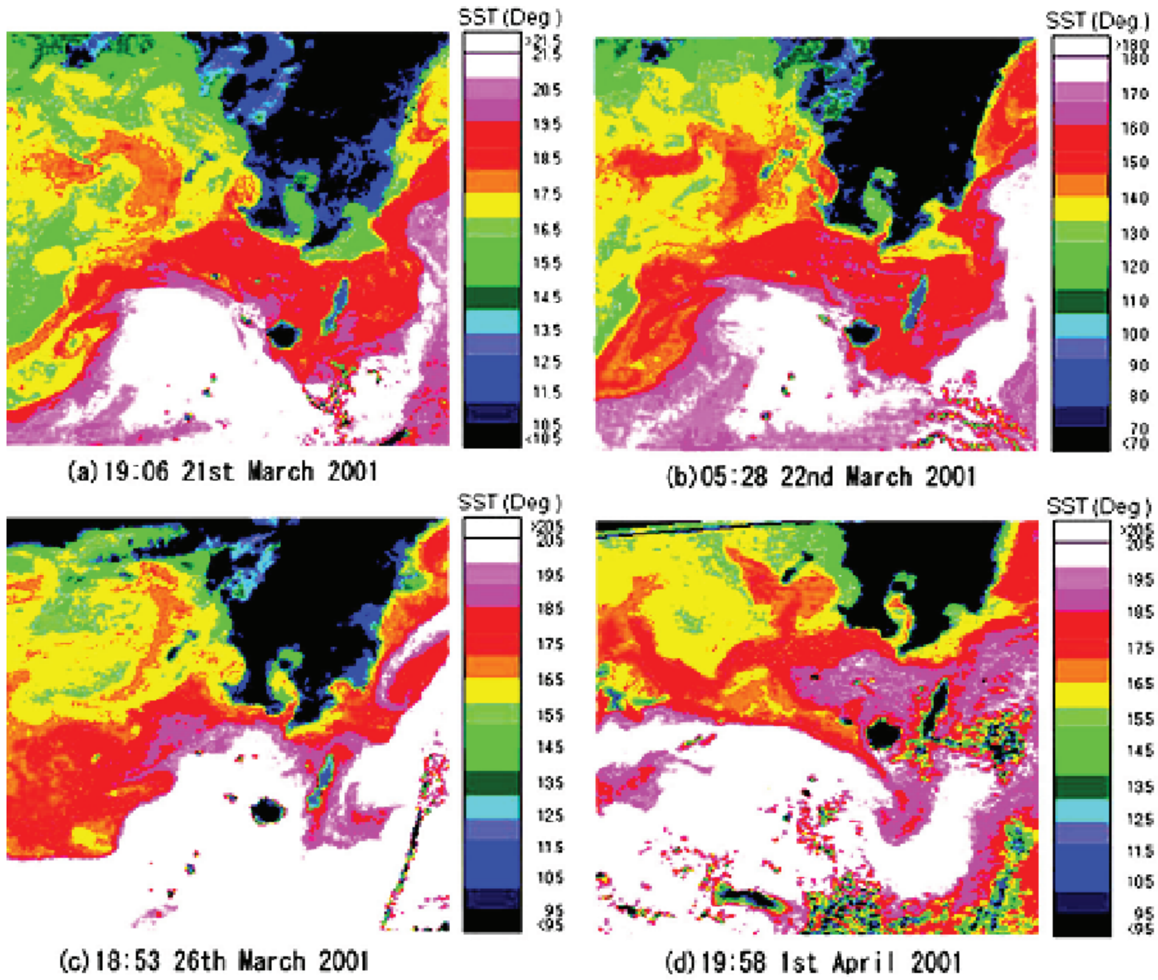


Fig. 3. The time progressed SST images of the NOAA/AVHRR data.

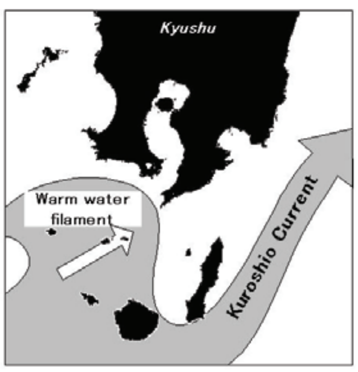
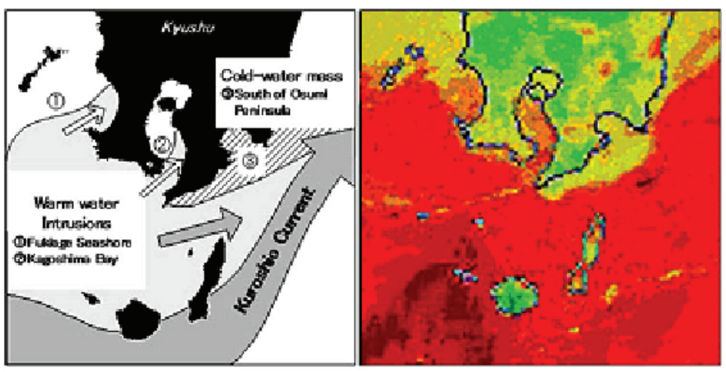


Fig. 4. Sketch of the warm water mass.



(a) Sketch (b) SST image

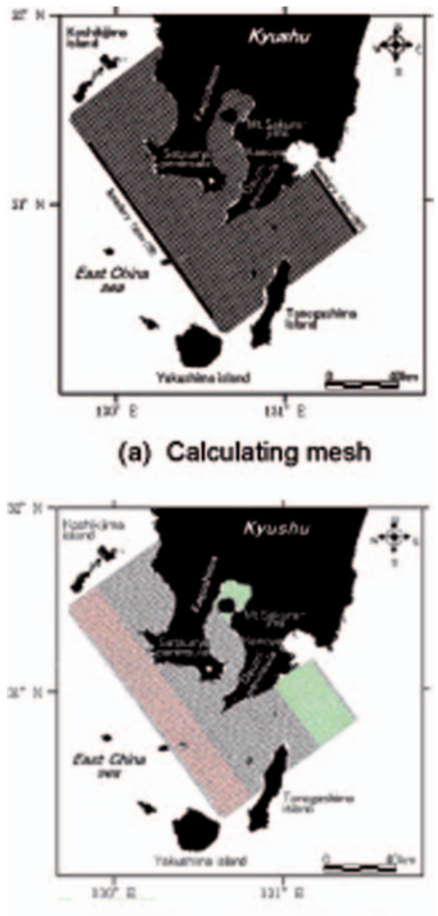
Fig. 5. Influences of the warm water mass.

Table 1. Calculation parameters.

H-mesh size	Δ X,Y	2.0km (Fig. 7)
Level (10Layer)	ΔZ	1:0-10m 6:80-100m 2:10-20m 7:100-140m 3:20-40m 8:140-180m 4:40-60m 9:180-250m 5:60-80m 10:250-btm.
Horizontal viscosity ratio	ν_H	1.0×10^5cm²/s
Vertical viscosity ratio	ν_V	1.0×10^0cm²/s
Horizontal diffusion ratio	K_H	0cm²/s
Vertical diffusion ratio	K_V	1.0×10^0cm²/s
Coriolis parameter	f	8.0×10^{-5}s^{-1}

Table 2. Boundary conditions.

Water Temp.	IN	Initially uniformed at 17deg. and 21deg. given for five days to upper 6 Layer (0m-100m). Then uniformed to 17degree again.
	OUT	Uniformed to 17 degree.
Salinity	IN/OUT	Uniformed to 34‰
Elevation	IN	Uniformed as proportional. Satsuma Peninsula side given to 0cm and Osumi Peninsula side given to 10cm.
	OUT	Uniformed to 0cm.



(a) Calculating mesh

(b) Initial particles (3-color)

Fig. 6. Division of the south of Kyushu and initial particles.

3. Numerical Simulation

The numerical simulation is a possible approach to understand these phenomena. However, it is difficult to calculate unsteady phenomena in the south coast of Kyushu, because they are affected by various conditions such as wind, density, and large scaled structures and so on.

In this section, results of a simple ocean model are presented in order to investigate the influence of the warm water mass in winter that passes through the south coast of Kyushu. The given conditions are only water temperature and water elevation at the inlet and the outlet boundary. This model is based on a known theory that a density flow contributes to the warm water intrusion into the bay or the seashore. Kubokawa and Hanawa (1984) show a density current along an east side coast by a theoretical model with the shock wave solution of semi geotropic gravity waves in a shallow water equation. Kohno et al. (2004) reproduced the warm water intrusion into the Kagoshima Bay by the Finite Difference Method (Referred as FDM, hereafter) and Hosotani (under review) reproduced that the warm water mass generates an intruding density flow at the mouth or the edge of the cape. They concluded that it begins to intrude into the bay and the intrusion keeps along the east side of the coast looking at the coast at the right hand side according to the Coriolis effect when the warm water touches to the bay water. In this study, the 3-D FDM (multi-leveled) model is applied to calculate a density current. The basic assumptions of this method are 1) Hydrostatic approximation for the vertical momentum equation, 2) Boussinesq approximation and 3) f-plane approximation. The boundary conditions are based on a simple assumption that the Kuroshio warm filament brings the warm water mass close to the coasts as described in section 2. The boundary temperature and the boundary surface elevation express it.

In this study, the Lagrangian particle-tracking model is also calculated particle trajectories. In the numerical model, particles are dealt with as passive tracers that are regarded as plankton and hyponeuston that drifts on a sea surface from an open sea. This model is based on an assumption that they follow with the calculated surface current flow. However, almost all kinds of plankton don't act as passive tracer in fact. Therefore, it requires a notice that a meaning of this calculation. This model focused on plankton that is regarded as the imitated kinds.

The division of the Kagoshima Bay by the square meshed elements and the initial Lagrangian particles are shown in Fig. 6. The calculation parameters and open boundary conditions are given in Table1 and Table2 respectively. The boundary conditions are determined with references to the field observation. Initially, the water temperature is set as 17 degrees. The water temperature of the warm water mass is set as 21 degrees at the inlet boundary. The thickness of the warm water mass condition is referred to the report at the east side of Kyushu (Akiyama, 1994), because the appropriate observation report couldn't come to hand. Consequently, the depth of a warm water filament is set as 100 m. The water surface elevation is based on the field observation (Ichikawa et al., 1982), which shows it has a 10 cm height between Odomari (near the Cape Sata) and Nishinoomote (middle of the Tanegashima island). Although the height difference of this area is always changed, this condition is an appropriate value which is observed when the warm water mass passes through the Osumi Strait. In the model, the west side of the inlet boundary grids is higher than the outlet boundary grids that are set to 0 cm. In the inlet boundary, an inclination is given in the east-west direction. This inclination is made that the west side sets higher than the east side. The western end sets 10 cm and the eastern end sets 0 cm.

4. Results

4.1 The Warm Water Intrusions into the Kagoshima Bay and the Fukiage Seashore

Figure 7 shows the surface and vertical temperature distributions, which are calculated at the 5th day. The same phenomena from the SST images are shown in the calculated results. The warm water mass intrudes into the Kagoshima Bay and the Fukiage Seashore along the east coast after the warm water mass touched with the south coast.

In the Kagoshima Bay, the warm water mass continues to intrude into the bay along the east side coast up to the 6th day and when it arrives to the south coast of Sakurajima, it begins to rotate anticlockwise. Intruding speeds near the leading head of the warm water mass and around its middle has obtained the same result as about 20 cm/s estimated by the buoy robot (Ohtani et al., 1998) and the NOAA images (Kohno et al., 2004). The vertical temperature distribution shows its thickness of the warm water layer is up to about 50 m. On the other hand, in a low layer, it turns out that internal water is flowing out for mass conservation theory. The vector plots at the 2nd day for the 1st and the 5th-layer are shown in Fig. 8. These results show the same tendency as observation which show an upper layer flows to inside and lower layer flows to outside (Sakurai et al., 1983; Hosotani and Kikukawa, 2005). The warm water intrusion is also calculated in the Fukiage Seashore. As shown in Fig. 7, it is also similar to the satellite SST images (Fig. 3).

The intrusion occurs when the warm water mass touches with the Cape Noma at the edge of the Satsuma Peninsula. It also intrudes along the east side of the seashore. However, this shape spreads widely by the shallow offshore and its speed is slower than the case of the Kagoshima Bay. These intrusions are also shown in Fig. 9 that shows the isothermal surface distributions of 20 degrees. The warm water intrusion into the Kagoshima Bay keeps the same thickness along the east side. On the other hand, in the Fukiage Seashore, the warm water intrusion distributes widely and it is shallower than that in the Kagoshima Bay. Each intrusion depends on the same mechanism. It concludes that geographical features and mass conservation balance affect these phenomena.

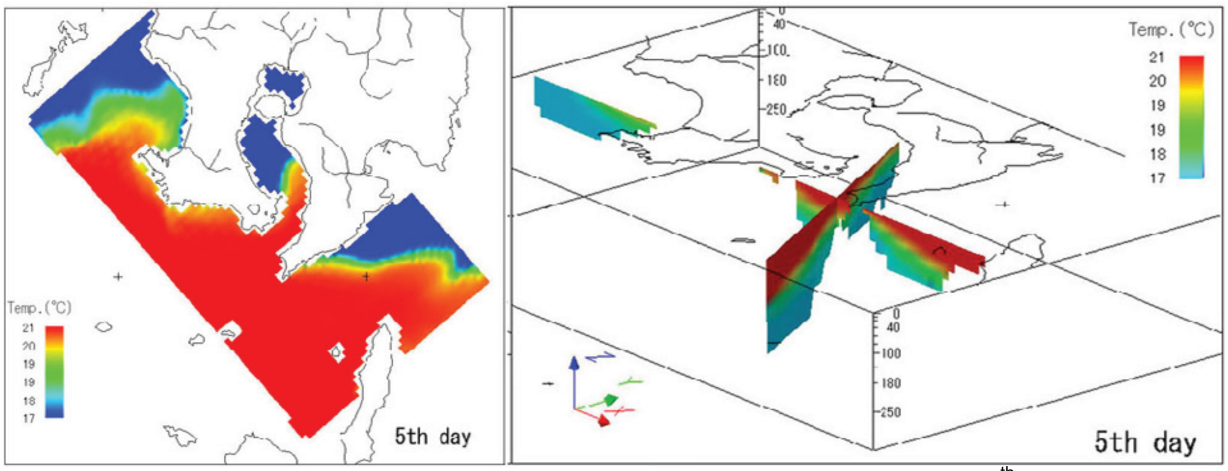
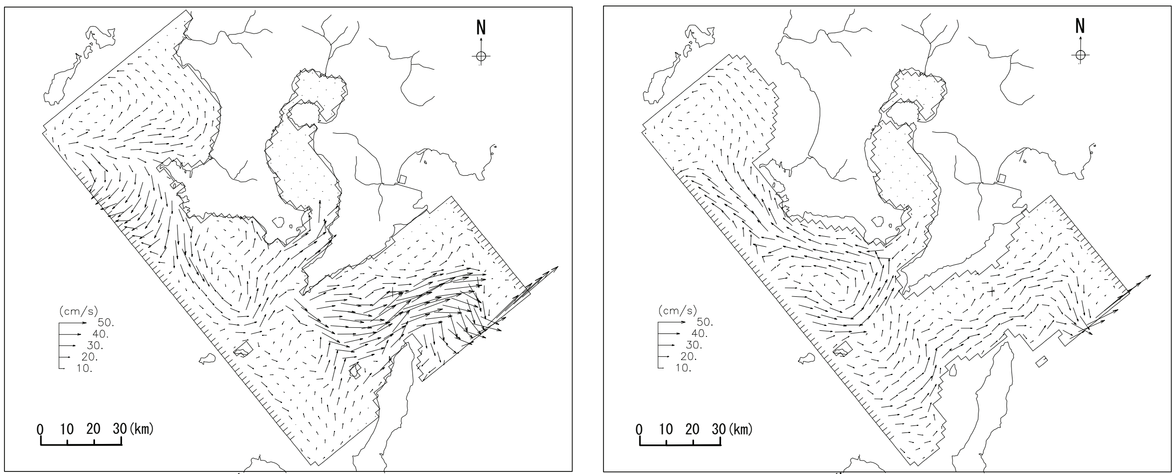


Fig. 7. Calculated surface and vertical temperature distributions at the 5th day.



(a) The 1st layer (0 m-10 m) (b) The 5th layer (60 m-80 m)

Fig. 8. Calculated vector plots.

4.2 The Cold-Water Mass in the Osumi Strait

The formation of the cold-water mass in the Osumi Strait is confirmed as shown in Fig. 7. The cold-water mass grows at the Cape Sata along the Osumi Peninsula. It is surmised in the previous section that the cold-water mass generated by a stagnated flow rather than upwelling flow of deeper water. The calculated results of the vector plots (Fig. 8) show horizontal vortex structure shed from the Cape Sata. Moreover, the temperature distributions across the thickness (Fig. 7) suggests that is a horizontal structure rather than a vertical one.

This cold-water mass is possible to be generated by the geographical effect. The Osumi Strait has flat and shallow topography. The warm water mass tends to flow to the Tanegashima Island side due to the Coriolis effect. That is the cold-water mass which should tend to stagnate behind of the Osumi Peninsula. In addition, at the mouth of the Kagoshima Bay, the topography shows a deep basin. The flow structure of a deep layer shows an anticlockwise circulation (Fig. 8), so that the warm water mass tends to form two layers flow without mixing. Therefore, it cannot concentrate into the strait easily. The warm water mass passing through the Osumi Strait has a tendency to flow to the Tanegashima Island according to the Coriolis effect. In addition, a sharp edge of the Cape Sata should contribute to form a two dimensional vortex flow like that shed from a bluff body in a laminar flow. The calculated cold-water mass consists in each power balance and geographic condition. In this numerical model, the boundary conditions are set up based on field observations. Since the elevation of east side of the inlet boundary is 10 cm higher than the west side and the outflow boundary, this current received external force directed to northeast. Moreover, the warm density current also tends to flow clockwise by the Coriolis effect, so that the warm water mass tends to flow to the

Tanegashima Island side. The topographical feature of the Cape Sata is impartation to the cold-water mass generation as mentioned above. The Cape Sata behaves as a bluff body to shed vortices. It also forms a stagnation region behind of the Osumi Peninsula. These characteristics are shown by the isothermal surface distributions (Fig. 9). The warm water mass keeps the same thickness at the inlet of the Osumi Strait and it is controlled by the shallow and flat topography. This topography also serves the passing current as a laminar flow. It helps to form the stagnation region. The shallow bottom prevents the deep cold water from going up well and flowing into the strait. For these reasons, the warm water mass generates a horizontal vortex from the edge of the Osumi Peninsula as the cold-water mass along the Tanegashima Island as shown by the isothermal distributions in Fig. 9.

4.3 Visualization by the Lagrangian Particles

This section is devoted to visualization of calculated the Lagrangian particles, which behave as passive tracers on a surface. In this model, the red particles initially located at the south area (Fig. 6) are regarded as plankton and hyponeuston in the warm water mass from the East China Sea. Figure 10 shows the trajectories of the Lagrangian particles up to the 6th day.

The red particles spread to the south coast of Kyushu and intrude into the Kagoshima Bay and the Fukiage Seashore. In the Fukiage Seashore, the red particles show anticlockwise rotation. In the Kagoshima Bay, they tend to gather to the center of the bay and pile up at the east side of the bay. The black particles initially located in the Kagoshima Bay tend to gather mixing with the red particles in the middle of the bay. These particles are not left outside. The green particles initially located at the north side of the bay are stayed without almost changing. These intrusions of the Lagrangian particles are similar to the density current as shown in section 4.1. It suggests that plankton and hyponeuston particles from an open sea to each bay under the warm water temperature condition.

On the other hand, in the Osumi Strait, particles mainly flow. At the south coast of the Osumi Peninsula, where the cold-water mass is formed as a horizontal vortex, the black particles has a tendency to pile up and be washed up on the coast. Moreover, the green particles, which initially located the north side, tend to spread to southwest along the coast by the vortex.

These results shown by red particles that have a tendency to intrude and pile up into the bay or at the coast, contribute physical consideration of coastal ecosystems in winter.

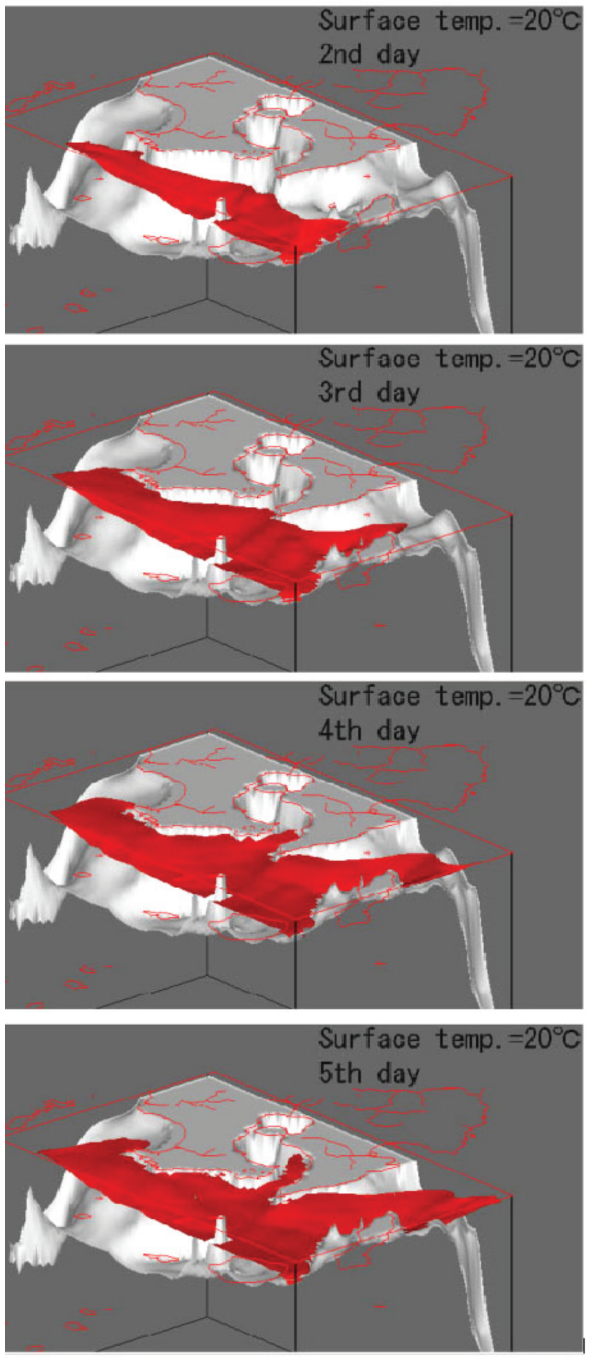


Fig. 9. Calculated isothermal surface of 20 ºC.

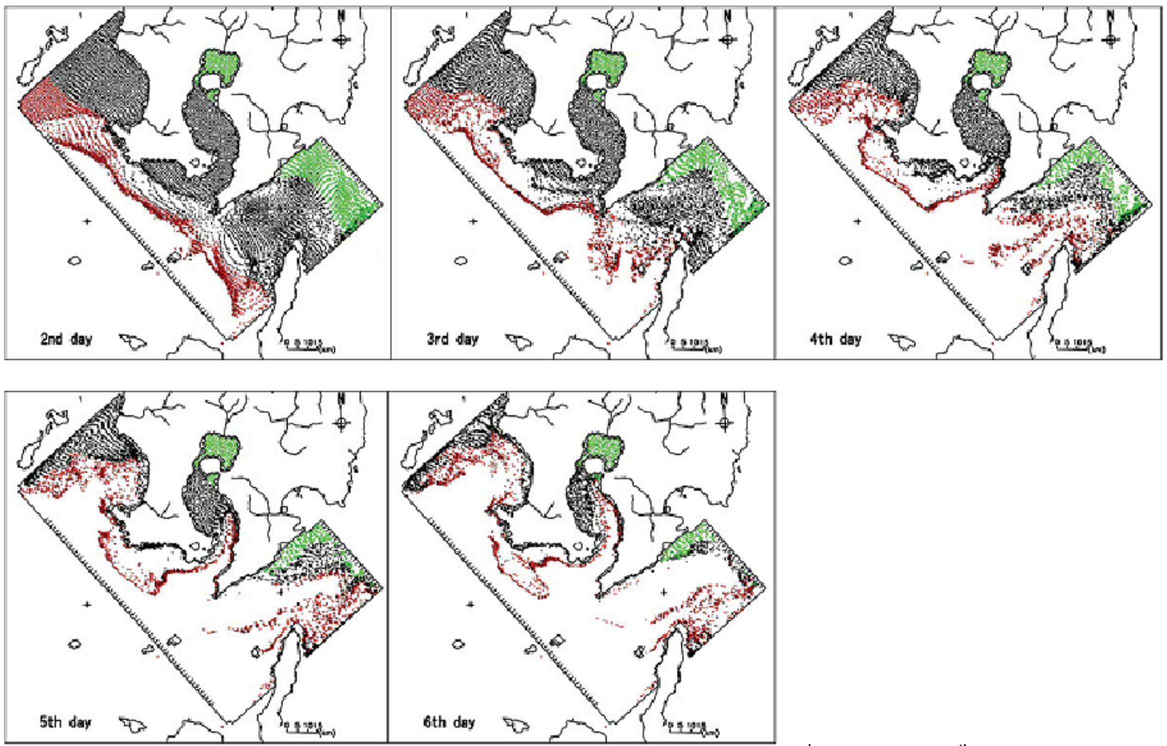


Fig. 10. Locations of the Lagrangian particles from the 2nd day to the 6th day.

5 Conclusion

The warm water filaments are frequently generated from the Kuroshio Current in winter. In this paper, the SST images show their behaviors at the south coast of Kyushu such as the warm water intrusions into the Kagoshima Bay and the Fukiage Seashore. In addition to the intrusions, the warm water mass generates the cold-water mass which looks like a stagnation region of a horizontal vortex shed from the Cape Sata. These phenomena would be expected to give physical and ecological influences to the coastal environment such as a water exchange in the bay or the coastal ecosystem. In this study, a 10-leveled FDM model and the Lagrangian particle-tracking model were performed in order to understand mechanisms. So these models carried out under simple conditions that are based on the observations.

As the calculation result, it was found that a density current of the warm water mass contributes to the phenomenon. The warm water mass begins to intrude along the east side of the coast when it arrives and touches with to the mouth or the edge of the bay. The warm water intrusions into the Kagoshima Bay and the Fukiage Seashore have the same tendency as the SST images. These intrusions are controlled by geographical conditions. The isothermal surface distributions of 20 degrees (Fig. 9) also show the characteristics of the warm water mass. In the Kagoshima Bay it keeps a same thickness during intruding. On the other hand, the intrusion of the Fukiage Seashore is shallow and wide influenced by a shallow basin.

In addition to the warm water intrusions, the satellite SST images show the cold-water mass that generates at the south coast of the Osumi Peninsula. As the calculated result, it is caused by a horizontal vortex shed from the Cape Sata. It is possible that this the cold-water mass forms as a horizontal structure rather than upwelling. It has received some influences on a topographical features and the warm water mass generates a density current that is affected by the Coriolis effect. It helps to make a stagnation region of vortices. The vector plots as shown in Fig. 8, in the lower layer, show an anticlockwise circulation that is not observed in the upper layer including the warm water mass. The shallow and flat Osumi Strait is also contributed to suppress upwelling of the deep cold water.

The Lagrangian particle-tracking model is also used to visualize a density current. The result provides a basis to understand physical processes of the coastal ecology in winter, such as influences of plankton and hyponeuston (For example; coral, Nomura's jellyfish, and crown-of-thorns starfish, a larva, or seed of plant). These passive tracers that don't deal with ecological behavior pose a number of challenges for investigation to the specific kinds of plankton. But to get back to the point, results that Lagrangian particles tend to intrude into the bay and they also tend to gathering and piling up at the coast. It is suggested that the biological particles may drift on the shore without being accompanied by an environmental rapid temperature change. Although this study does not deal with the influence of the ecological behavior, this result would be useful to study the ecosystem.

Recent years, it is predicted that the Kuroshio Current would be faster by higher temperature because of the global warming (Sakamoto et al., 2005). In this paper, a local small environment as the warm water filament that is caused in the Kuroshio meandering region is focused. It should be noted that it would become a key to know the signs of change of the large-scale environment. Therefore, more quantitative investigations are required for the future work. In the next paper, the dominant and coherent structure in local area will be analyzed quantitatively.

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