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Hydraulic Model Experiment on Circulation in Sagami Bay, Japan (IV) -Time-Varying States of Flow Pattern and Water Exchange in Baroclinic Rotating Model-

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Baroclinic hydraulic model experiments on the time-varying states of the flow pattern and water exchange in Sagami Bay were carried out based on quasi-steady state experiments on the flow pattern. For the model experiments, density changes as well as time changes in the volume transport of the upper layer were executed to investigate the flow response of the bay in the case of a sudden inflow of low density water and variable volume transport into the Sagami Bay.

The results of the model experiments showed that when the volume transport was increased frontal eddies or frontal wave streamers from the Kuroshio Through Flow were transferred to the inner part of the bay along with cyclonic circulation in the bay. In addition, density boundary currents appeared and flowed along the eastern boundary of the bay. As the upper layer density decreased, frontal eddies, frontal streamers and coastal boundary density currents occurred and proceeded along the eastern boundary of the bay at a high speed.

Key words : Sagami Bay, Kuroshio Through Flow, Hydraulic model, Two layer, Flow pattern, Water exchange, Frontal eddy, Frontal wave streamer, Density boundary current, "Kyucho" event

1. Introduction

Sagami Bay is an open-type bay on the southwest coast of the main island of Japan(Fig. 1). In the bay, there is a branch current from Kuroshio that flows along the southern coast of Japan. The entrance of the bay is divided into two channels by Oshima Island. Generally the branch current - the Kuroshio Through Flow - flows into the bay through the western channel and flows out through the eastern channel. Accordingly, the flow pattern and circulation structure of Sagami Bay are affected by fluctuations in the Kuroshio Through Flow. Fig. 2 shows a schematic view of the surface circulation during the winter season[1], and Fig. 3 details the current meters and drifting buoys observed in Sagami Bay during 1979 and 1982～1983.[2,3]

The average and fluctuating flow patterns in the Sagami Bay, caused by changes in the Kuroshio Through Flow, have been previously studied with a focus on the "Kyucho" event(a sudden rapid coastal boundary current). Kimura[4] reported that the "Kyucho" event involved a rapid rise in water temperature and defined it as a sudden intrusion of oceanic warm water into the Sagami Bay.

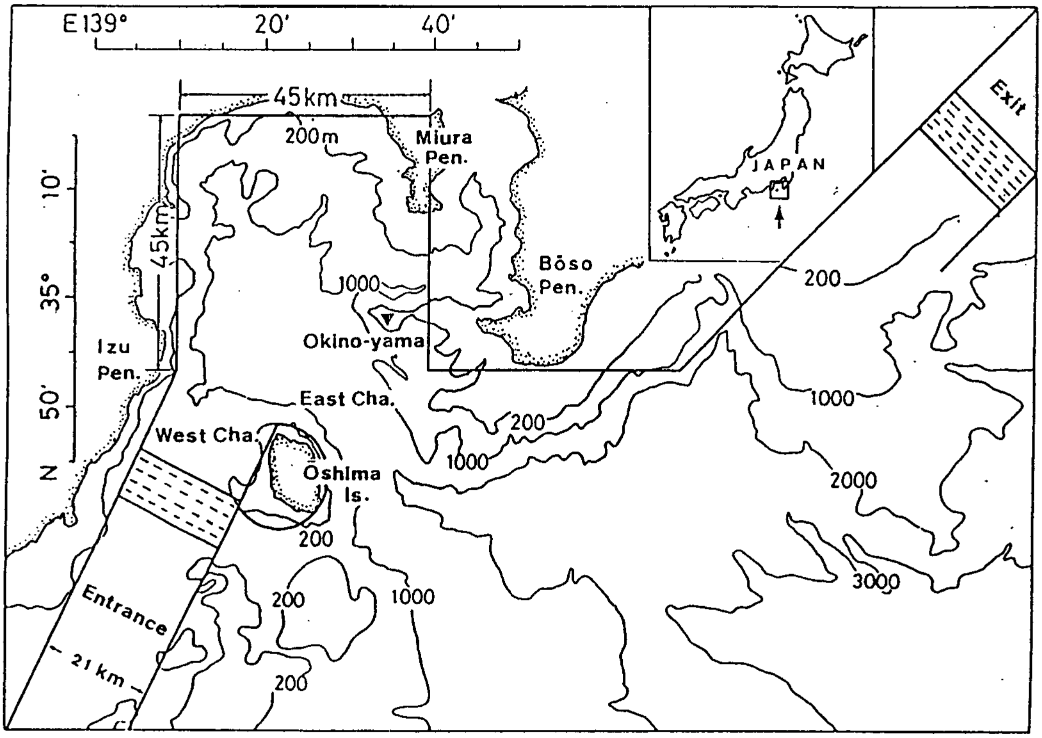


Fig. 1. Domain of the hydraulic model and the general configuration. Thin lines show bathymetry.

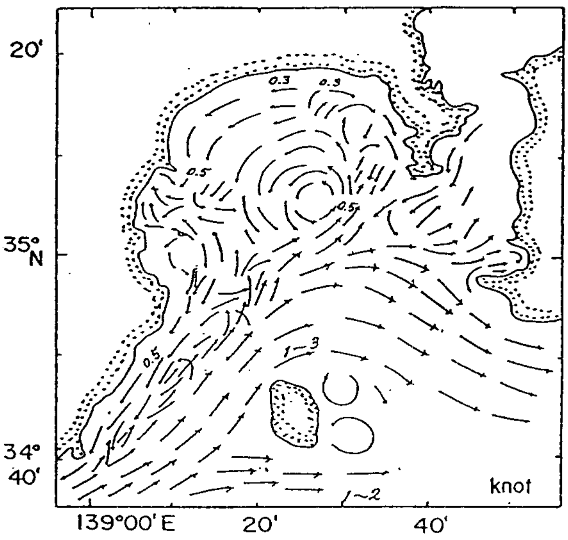


Fig. 2. A schematic view of the surface circulation during the winter season in Sagami Bay(after[1] Uda, 1937).

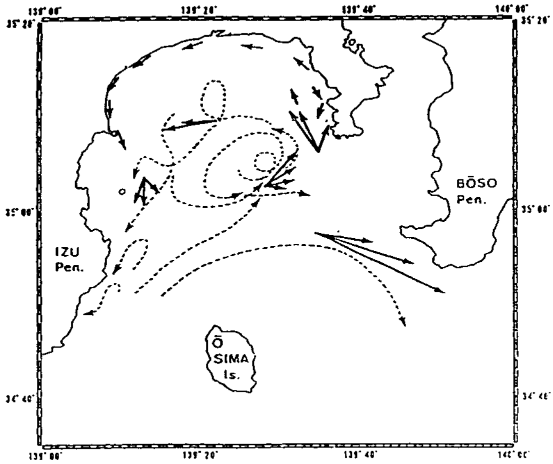


Fig. 3. Observational results of current meters and drifting buoys in Sagami Bay. Arrows of the solid line indicate current vectors during 1982~1983 and the dashed lines are paths of the driftingbuoys tracked during March 1979(after[2,3] Iwata and Matsuyama, 1989 : Nakata et al. 1989).

Also Uda[5] pointed out that the occurrence of the "Kyucho" event resulted from the approach of the Kuroshio current near Sagami Bay, and that it was related to a sudden rapid inflow of oceanic water caused by a low atmospheric pressure or an inflow of a reinforced tidal current in a spring tide. These results suggest that the changes in the flow pattern in Sagami Bay caused by fluctuations in the Kuroshio Through Flow are closely related to short term fluctuations in oceanographic conditions or the "Kyucho" event.

From temperature and current data on the coastal area of the bay, Iwata[6,7,8] showed that there are two distinct characteristic features related to the "Kyucho" event. One is accompanied by a temperature increase, the other is not. From their observations of Sagami Bay, Matsuyama and Iwata[9] presented that the "Kyucho" event was a phenomenon correlated with a front or intrusion of oceanic warm water. With reference to the formation structure of the "Kyucho" event in Sagami Bay, Yamagata[10] attempted to explain it as a shock wave caused by a coastal boundary density current and confirmed it with field data. Kubokawa[11] presented a theory that the "Kyucho" event appears as a result of the intrusion of a density current and is preserved by the conservation of its potential vorticity. Since some "Kyucho" events did not include a temperature rise, it is also necessary to suggest a barotropic element, for example a density current, besides a baroclinic one in order to explain the formation structure of the "Kyucho" event more exactly.

The purpose of the hydraulic model experiments in this paper are to clarify the time changes in the flow pattern and water exchange process in Sagami Bay caused by fluctuations in the low density water of the Kuroshio Through Flow. Accordingly, baroclinic two layer model experiments were executed. In these model experiments, wide ranges of parameters relating to the inflow and density difference were utilized. The time-varying states of the flow pattern and water exchange were fully reproduced by changing the inflow and density difference in relation to time.

2. Models and Experimental Arrangement

2.1. Basic equations and similitude

In order to simulate the Kuroshio Through Flow, it was assumed that the density (ρ) of the upper layer corresponding to the Kuroshio Through Flow was as low as $\Delta\rho$, that the lower layer density and velocity in each layer was uniform, and that mixing at the interface between the upper and lower layers was minor. Thereafter the equation of motion for the upper layer can be expressed by

$$\partial V/\partial t + V \cdot \nabla V + f\, k \times V = -g'\, \nabla h + K_h\, \nabla^2 V + K_z\, \partial^2 V/\partial Z^2 \qquad (1)$$

where V is the horizontal velocity vector with v as the northward component, t is time, $\nabla = i\ \partial/\partial x + j\ \partial/\partial y$, $\nabla^2 = \partial^2/\partial x^2 + \partial^2/\partial y^2$, f is the Coriolis parameter, k is the unit vector in the vertical direction, $g'=(\Delta\rho/\rho)g$, h is the upper layer thickness, and K_h and K_z are the horizontal and vertical eddy viscosities, respectively. Equation (1) for the prototype can be scaled with L as the typical horizontal length scale(45km), f^1 as the typical time scale, V_0 as the characteristic speed of the current in the Oshima Western Channel, and H as the characteristic value of the upper layer thickness(200m). Then equation (1) becomes

$$\partial V^*/\partial t^* + Ro \cdot V^* \cdot \nabla^* V^* + k \times V^* = (Ro/Fr_i^2) \cdot \nabla^* h^* + Ek_h \cdot \nabla^{*2} V^* + Ek_z \cdot \partial^2 V^*/\partial Z^{*2} \quad (2)$$

where asterisks denote non-dimensional variables, and

Table 1. Scale ratios of the model and parameter values for the prototype and model.

Property		Scale ratio	Prototype	Model
Horizontal length	L	Lr $=3.0\times10^{5}$	45km	15cm
Vertical length	H	Hr $=3.6\times10^{`}$	1000m	28cm
Time	T	Tr $=5.0\times10^{3}$	1.5×10^{5}sec	30sec
Volume transport	Q	Qr $=6.5\times10^{10}$	$2.0\times10^{12}cm^3/s$	$30cm^3/s$
Velocity	V	Vr $=6.0\times10^{1}$	60cm/s	1.0cm/s
Kinematic Viscosity	K_h	Khr $=1.8\times10^{7}$	$1.8\times10^{5}cm^2/s$	$0.01cm^2/s$
	K_z	Kzr $=2.6\times10^{3}$	$2.6\times10^{1}cm^2/s$	$0.01cm^2/s$

non-dimensional parameters Ro, Fr_i, Ek_h and Ek_z indicate the Rossby number($V_0/fL\sim10^{-1}$), internal Froud number($V_0/(g'H)^{1/2}\sim10^{-1}$), horizontal Ekman number($K_h/fL^2\sim10^{-4}$) and vertical Ekman number ($K_z/fH^2\sim10^{-4}$), respectively. Using the values $K_h\sim1.8\times10^5$ cm^2/s and $K_z\sim2.6\times10$ cm^2/s, the values of the non-dimensional parameters in equation (2) become $Ro\sim10^{-1}$, $Fr_i\sim10^{-1}$, $Ro/Fr_i\sim1$, $Ek_h\sim10^{-4}$, $Ek_z\sim10^{-4}$ as shown in table 1.

If the four parameters Ro, Fr_i, Ek_h and Ek_z are made equal for the prototype and the model, the flow patterns as a solution of equation (2) become equivalent in the prototype and the model. The similitude conditions in the model are

$$[\ V_0/fL\ ]_p = [\ V_0/2\Omega L\ ]_m \quad (3)$$
$$[\ V_0/(g'H)^{1/2}\ ]_p = [\ V_0/(g'H)^{1/2}\ ]_m \quad (4)$$
$$[\ K_h/fL^2\ ]_p = [\ v/2\Omega L^2\ ]_m \quad (5)$$
$$[\ K_z/fH^2\ ]_p = [\ v/2\Omega H^2\ ]_m \quad (6)$$

where the suffix p and m denote the prototype and the model, Ω the angular velocity of the model(turntable), and v the molecular viscosity, respectively. Denoting the ratios $Vr=(V_0)_p/(V_0)_m$, $Lr=(L)_p/(L)_m$, $Hr=(H)_p/(H)_m$ and $Tr=2\Omega/f$, they become $Vr=Lr/Tr$, $Vr^2=Hr$, $Lr=TrHr^{1/2}$, $K_hr=Lr^2/Tr$ and $K_zr=Hr^2/Tr$ from equation (3),(4),(5) and (6). As the Rossby number and internal Rossby number(Ro^*) are greater than Ek_h or Ek_z in the two-layer model, it is assumed that the conditions of the model ratios caused by Ro or Ro^* are principle. A depth of 5.5 cm was selected for the mean upper layer water depth of the model.

2.2. Experimental facilities and procedure

The general geometry of Sagami Bay and the domain of the hydraulic model are shown in Fig. 1. Figs. 4(a) and (b) show a side view of the model used in the model experiments, its outside arrangement, and measurement system, respectively.[12)] The model basin had a 35 cm height, 120 cm width, and 80 cm length. The upper layer water which had a depth of 5.5 cm in the model flowed from an approaching channel(source) to an exit channel(sink) by use of electro-magnetic pumps and floater-type flow meters. In particular, the approaching channel was designed in order that only the upper layer water could flow in. Fig.5 shows a lengthwise sectional view of the entrance channel in the model. Turbulence from the source and sink was reduced by screens, iron nets, and sponges.

Using the observation results of the current in the Oshima Western Channel recorded by Taira and Teramoto(1986), time changes in the volume transport were determined in the model experiments according to three cases, small(0.4～0.9 sv), middle(1.4～1.8 sv) and large(2.7～3.2 sv). The changes in the volume transport(flow rate) for 6.6～8.5 cc/s (0.4～0.5 sv in the prototype) were executed almost immediately during one rotation of the turn table(1.7 days in the prototype) for each flow rate case. Fig. 6 shows the time changes in

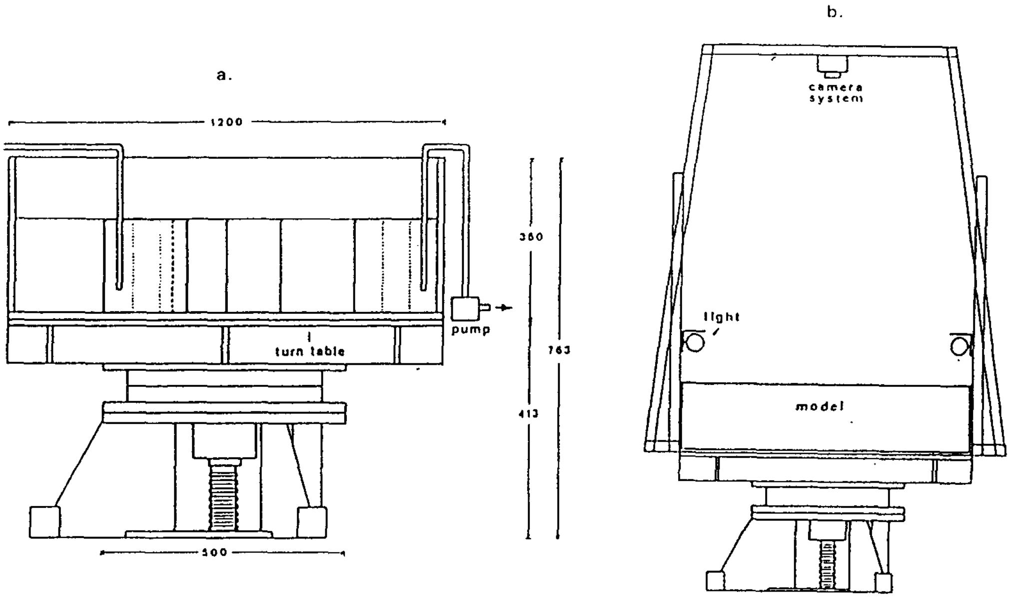


Fig. 4. (a) Schematic views of the turntable, the tank and (b) the measurement system in the model experiment. All dimensions are given in millimeters.

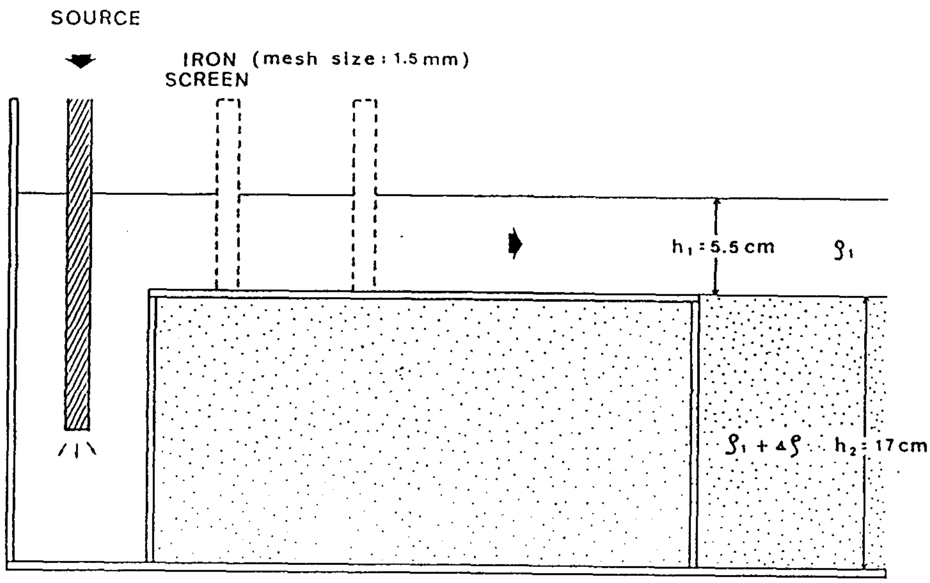


Fig. 5. A length sectional view of the entrance channel in the model experiment.

the flow rate in the model(the upper layer water) experiments. The experimental cases and parameter ranges for the time changes for the flow rate in the model are listed in Table 2.

Table 2. Cases and parameter ranges for the time variance in the model experiments.

Factors		Values given in the model		
Revolution rate	Ω (rpm)		2	
Volume transport	Q (cc/s)	5.5~14.0	20.8~27.0	42.0~48.6
Volume transport change	ΔQ (cc/s)	8.5	6.2	6.6

In Sagami Bay, the density difference between the Kuroshio Through Flow in the upper layer and the subarctic intermediate water in the lower layer was about 1.5×10^{-3} as a yearly mean and fluctuated from 1.7×10^{-3} to 5.0×10^{-3} [13]. Accordingly, in order to produce a density increase of about 5.0×10^{-4} in the upper layer from the mean density difference $\Delta\rho = 1.5\times10^{-3}$, the water temperature of the upper inflow water increased by 2℃ during 5 minutes(17 days in the prototype). The temperature increase was executed using a heater with a thermostat in the approaching channel(Fig. 5). Fig. 7 shows the time changes for the water temperature in the upper layer of the model.

The minute process of the flow change caused by time changes in the flow rate was determined by use of photography and video tapes. To determine flow change, aluminum flakes were placed on the surface and photographed with a video camera. The amount of the water exchange between the inner bay water and the Kuroshio Through Flow water was estimated by calculating the surface areas of each section of water which were then visualized by tracing the motion pictures onto video tapes.

3. Results

3.1. Response of flow pattern to time changes in increased flow rates

The flow rate was changed within a small flow rate range(5.5 cc/s~14.0 cc/s). The straight lines in Fig. 8(a)~(h) indicate the stream lines at the northern edge of the Kuroshio Through Flow

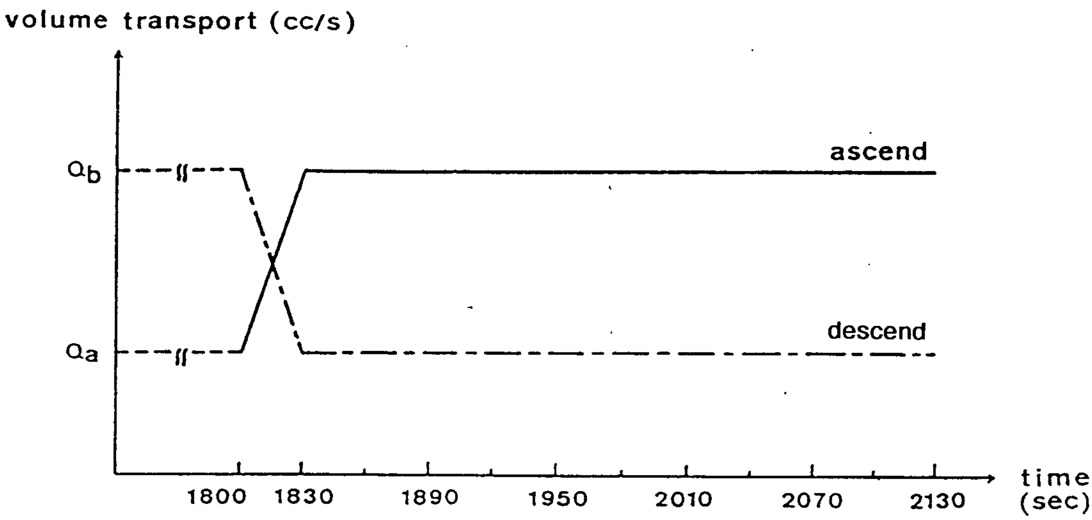


Fig. 6. Time changes of volume transport for the flow of the upper layer in the model experiment.

(fronts between the Kuroshio Through Flow and cyclonic circulation in the bay). Each figure in Fig. 8(a)~(h) shows time changes in the circulation in the bay at 30 second(about 1.7 days in the prototype) intervals after the flow rate was increased from 5.5 cc/s to 14.0 cc/s. 30 seconds later(Fig. 8(a)), the amplitude of the frontal waves at the northern edge of the Kuroshio Through Flow became large and made its appearance in the form of a frontal eddy or frontal wave streamer (dashed and dotted lines). The frontal wave streamers from the Through flow were transferred to the inner part of the bay along with the cyclonic circulation. In addition, it was found that a density boundary current flowed into the bay along the eastern boundary 60 seconds later(Fig. 8(b)), this density boundary current then turned around the bay counterclockwise along the eastern boundary

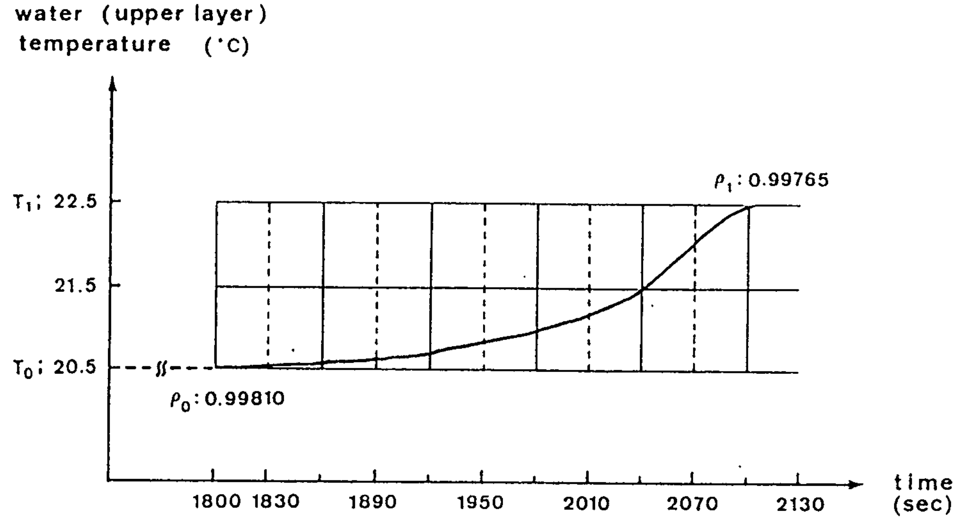


Fig. 7. Time changes of water temperature(℃) for the upper layer in the model experiment. T0 and t1 indicate the water temperature of the initial stage and the changed after 5 minutes.

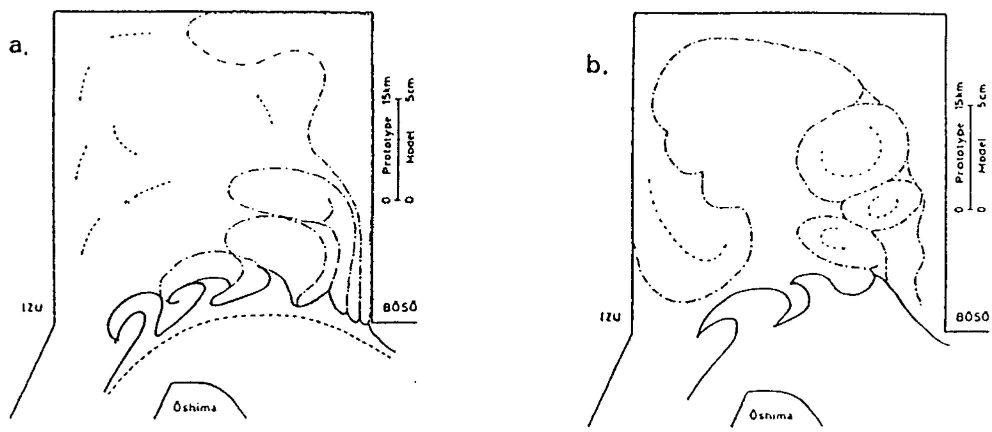


Fig. 8. Time changes of the current path on the flow rate change(Q=5.5 cc/s~14.0 cc/s) in the model The dashed lines on Fig. 6a. indicates the current path for the steady state of flow rate Q=5.5cc/s. The dash-and-dotted lines indicate the schematic views of frontal streamers to run out from the Kuroshio Through Flow.

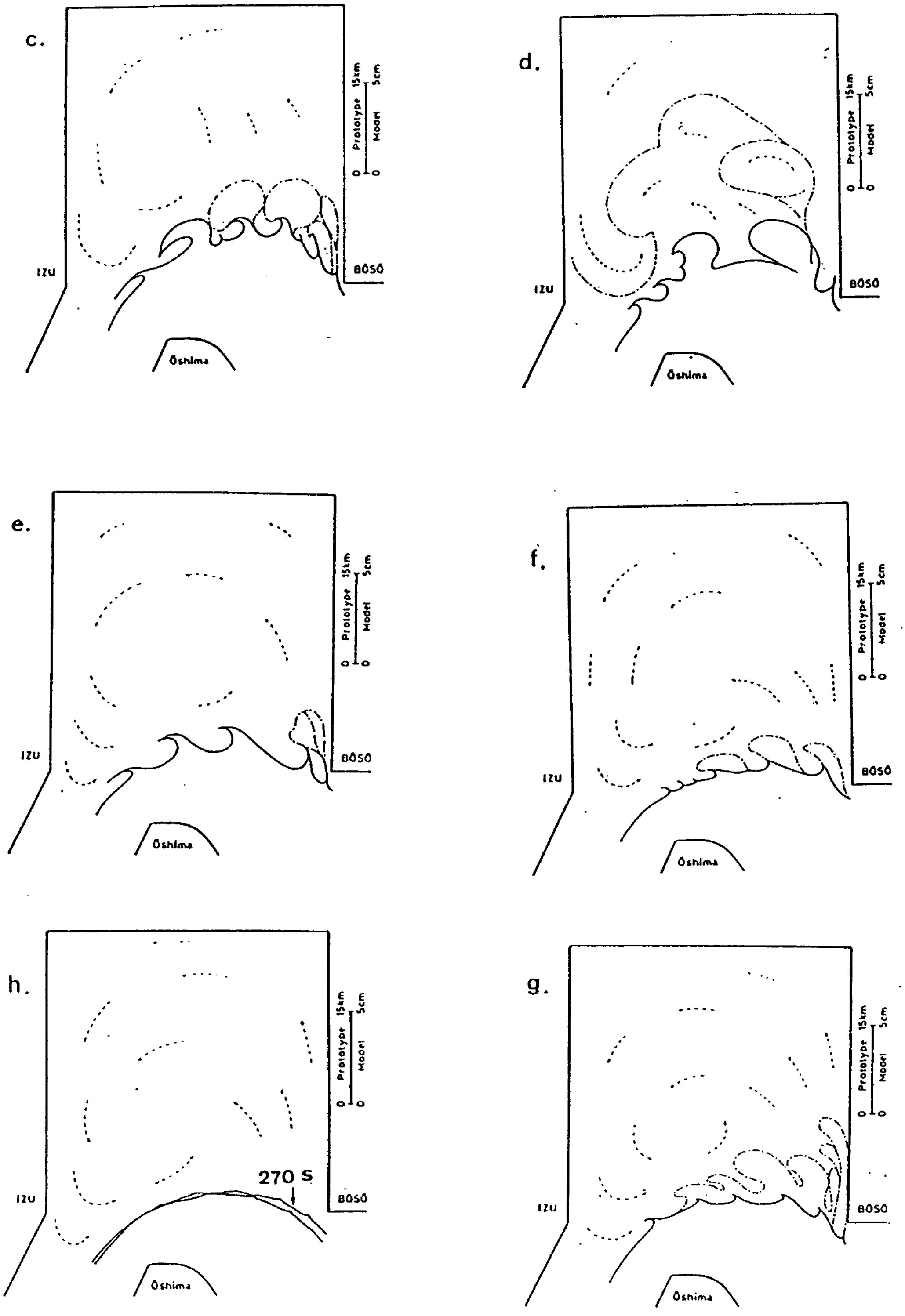


Fig. 8.

and finally arrived at the frontal region near the entrance of the bay. Cyclonic eddies from the edge of the density boundary current were formed and gradually spread in all directions.

90 seconds later(Fig. 8(c)), after the cyclonic eddies from the density boundary current had spread to some extent, the density boundary current became weak. However, as the density boundary current was formed, the cyclonic circulation in the bay became strong. Some small frontal wave streamers bounded out at the northern boundary of the Kuroshio Through Flow were reformed and then another density boundary current began to move up north along the eastern boundary. The flow pattern of Fig. 8(d)(120 seconds later) is similar with Fig. 8(b), yet the width and speed of the density boundary current along the boundary in Fig. 8(d) are wider and slower, respectively, than those in Fig. 8(b). Thereafter, 150 seconds (Fig. 8(e)) to 270 seconds later(Fig. 8(h)), the density boundary current slowly weakened, however, the cyclonic circulation in the bay became stronger and stronger. After 270 seconds(Fig. 8(h)), there was no further change in the flow pattern and a quasi-steady state was reached at the increased flow rate of 14.0cc/s.

3.2. Response of flow pattern to time changes in decreased flow rate

The flow rate was changed from 14.0 cc/s to 5.5 cc/s. Figs. 9(a)~(f) show time changes in the circulation in the bay at 30 second intervals after the flow rate was decreased. As in the case of the increased flow rate, the straight lines and dash and dotted lines in Fig. 9(a)~(f) indicate the stream lines at the northern edge of the Kuroshio Through Flow and frontal wave streamers, respectively.

For the first 30 seconds after the flow rate decreased, frontal eddies and frontal wave streamers bounded out from the northern boundary of the Kuroshio Through Flow in the eastern part of the bay(Fig. 9(a)). These frontal eddies and streamers then moved west and were transferred to the middle of the bay by the cyclonic circulation.

On the inner side of the bay, a weak anticyclonic circulation was formed, and 60 seconds later (Fig. 9(b)), the frontal wave streamers from the eastern part of the bay arrived at the western boundary. Consequently, a cyclonic circulation was formed in the south of the bay and an anticyclonic circulation in the north. As the cyclonic circulation in the south extended towards the entrance of the approaching channel, the inner bay water approached the frontal area of the Kuroshio Through Flow which had been brought down to Oshima Island. 90 seconds later(Fig. 9(c)), the frontal wave streamers from the eastern boundary weakened. The cyclonic circulation moved southward and the anticyclonic circulation in the inner part of the bay disappeared, thus the flow in the bay became a weak cyclonic circulation. After 120 seconds(Fig. 9(d)), the northern boundary of the Kuroshio Through Flow which had been brought down near the north shore of Oshima Island returned north due to the decrease in the flow rate. At this point, the inner bay water which had been extended north of Oshima Island was trapped in the Kuroshio Through Flow, transferred to the east, and finally discharged through the Oshima Eastern Channel.

Figs. 9(e) and (f) show the stream lines at the northern boundary of the Kuroshio Through Flow and schematic views of the flow patterns 150 seconds later and 180~270 seconds later, respectively. After 180 seconds(Fig. 9(f)), changes in the path of the Kuroshio Through Flow stopped. After 270 seconds, there was no further change in the path of the Kuroshio Through Flow and a quasi-steady state was reached with the decreased

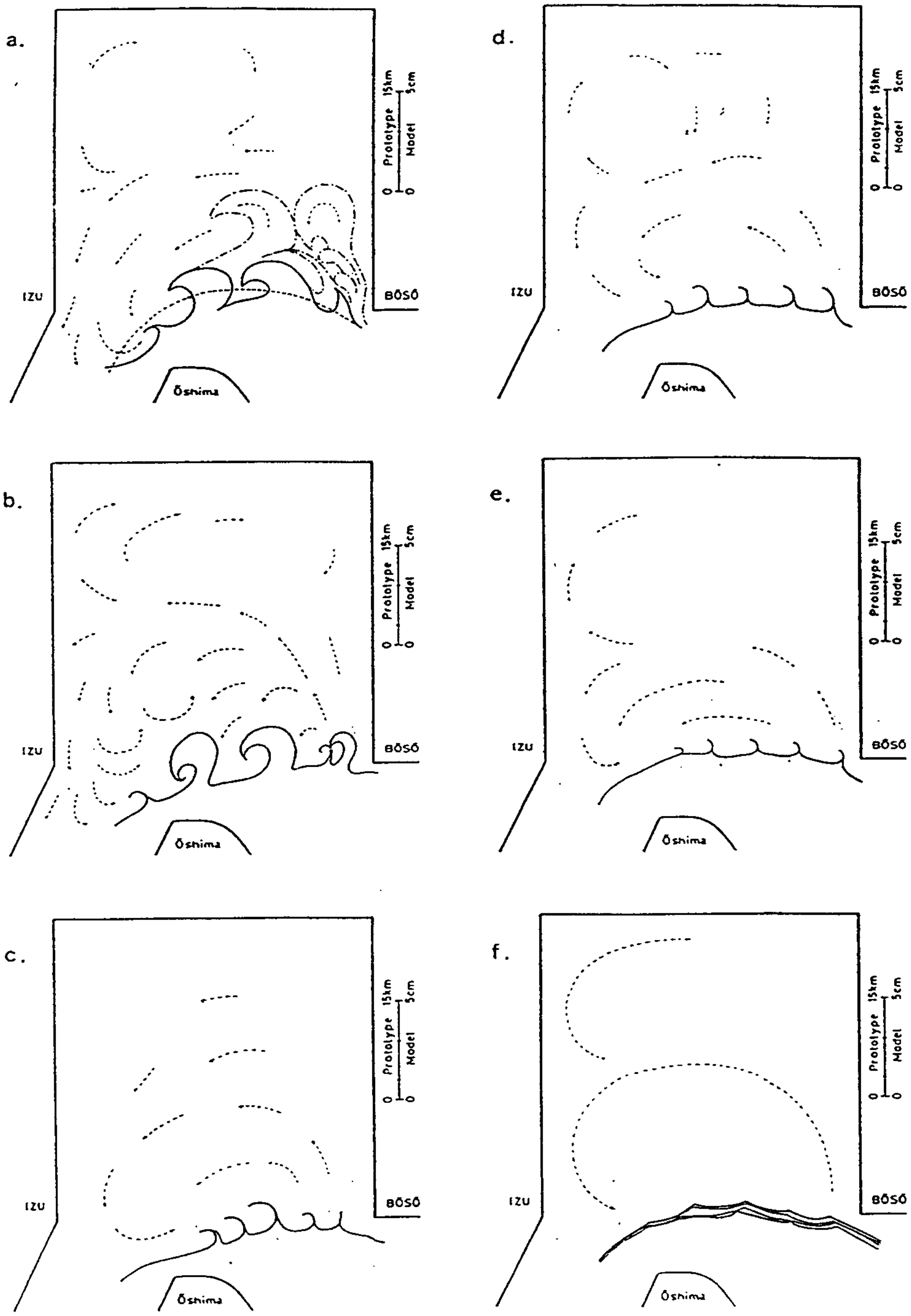


Fig. 9. Time changes of the current path on the flow rate change(Q=14.0 cc/s~5.5 cc/s) in the model. The dashed lines on Fig. 7 a. indicates the current path for the steady state of flow rate Q=14.0 cc/s. The dash-and-dotted lines indicate the schematic views of frontal streamers to run out from the Kuroshio Through Flow.

flow rate of 5.5 cc/s.

3.3. Response of flow pattern to the inflow of low density water

After a quasi-steady state of flow was established with a density in the upper layer that was 1.5×10^{-3} lighter than the lower layer, the response process of the flow was investigated when the upper layer density was reduced by heating the inflow of the upper layer as shown in Fig. 7. Figs. 10(a)~(j) show schematic views of changes in the flow patterns at 30 second intervals. When an inflow of buoyancy was introduced at the entrance of the approaching channel by heating the upper layer water, frontal waves developed at the northern boundary of the Kuroshio Through Flow and fell out into the bay in the form of a frontal eddy or frontal wave streamer, shown as the dash and dotted lines in the figures. These frontal wave streamers were moved to the eastern part of the bay due to the cyclonic circulation in the bay. Then a density boundary current along the eastern boundary of the bay moved up north. Fig.

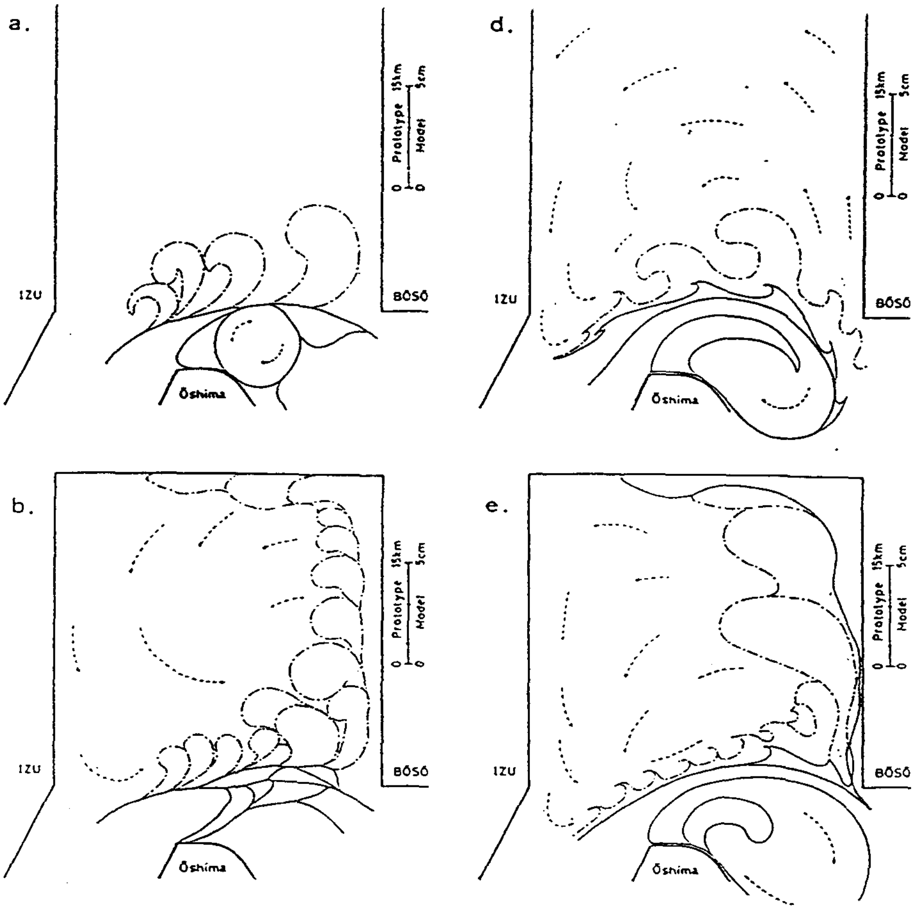


Fig. 10. Time changes of the current path on the change of the density difference($\Delta\rho$=0.0015~0.002) in the model. The dash-and-dotted lines indicate the schematic views of frontal streamers to run out from the Kuroshio Through Flow.

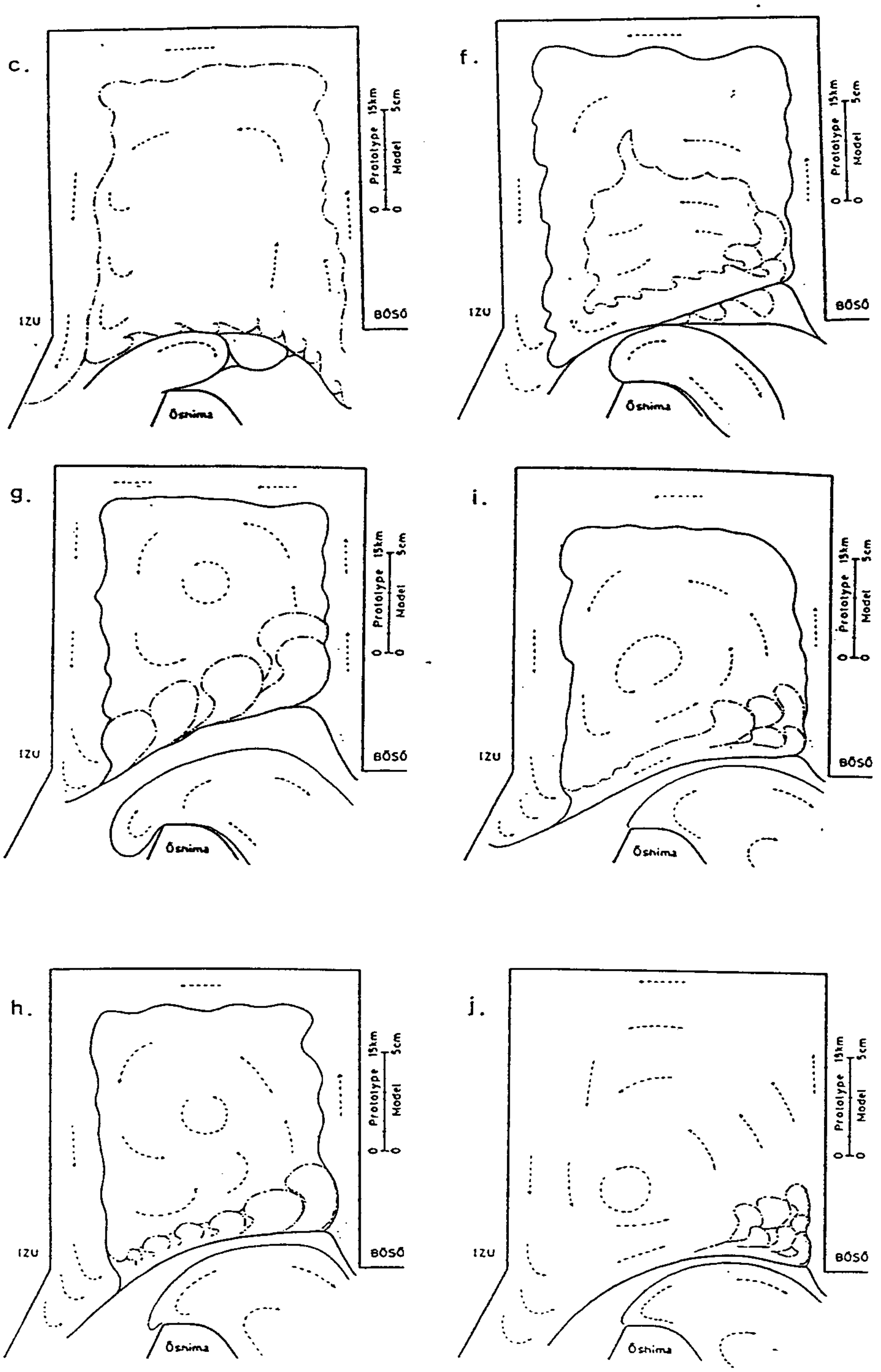


Fig. 10.

10(c) shows a density boundary current along the boundary of the bay and another density boundary current being formed along the northern shore of Oshima Island. Thereafter, the density boundary current caused by the lower density water flowed out through the Oshima Eastern Channel according to the process illustrated in Figs. 10(d)~(f).

In this process, an anticyclonic warm eddy was formed northeast of Oshima Island (Fig. 10(d)). The anticyclonic warm eddy became larger with time and extended to the end of the southern boundary of the bay(Fig. 10(e)). At this point, the frontal wave streamers from the lower density water plus considerable quantities of the lower density water flowed into the bay along its eastern boundary. Fig. 10(f) shows the flow pattern after the lower density water along the eastern boundary reaches the western boundary of the bay. As the bounds of the anticyclonic warm eddy extended from the northeast of Oshima Island to the eastern boundary of the bay, a branched density boundary current from the lower density water(anticyclonic warm eddy) was formed along the eastern boundary of the bay. The anticyclonic warm eddy became smaller as the density boundary current prevailed (Fig. 10(f)).

Fig. 10(g) shows that the frontal waves at the northern boundary of the Kuroshio Through Flow became large due to the disturbance caused by the density boundary current after going around the bay. It also shows that more lower density water flowed into the bay at its eastern boundary. Thereafter, the inflow of frontal eddies and lower density water gradually weakened due to a decreased density difference between the density boundary current and surrounding water through mixing and diffusion (Fig. 10(h)~(j)). The lower density water then took a route formed by the newly controlled density difference between the upper and lower layers.

4. Discussion

Fig. 11 presents schematic views of the water exchange between the Kuroshio Through Flow water and cyclonic circulation water of the bay, and time changes in the flow pattern caused by flow rate changes in Sagami Bay. In the case of the baroclinic mode, it was observed that the changes in the flow pattern were caused by frontal waves that were formed on the front between the Kuroshio Through Flow and cyclonic circulation in the bay. When the flow rate was increased(the upper Fig. 11), the Kuroshio Through Flow water entered into the bay in the form of frontal eddies or frontal wave streamers along the eastern boundary of the bay(No.①~② process in the upper Fig. 11). At this point, the cyclonic circulation in the inner bay was strengthened and the Kuroshio Through Flow path gradually ascended northward as the flow rate increased (No. ③ process in the upper Fig. 11). When the flow rate was decreased(the lower Fig. 11), the frontal eddies and frontal wave streamers from the Kuroshio Through Flow entered from the western boundary of the bay(No.② process in the lower Fig. 11) and a weak anticyclonic circulation was formed in the inner part of the bay. The cyclonic circulation water extended to the western entrance of the bay southward and the flowed out through the Oshima Eastern Channel along with the Kuroshio Through Flow(No.③ process in the lower Fig. 11).

The water exchange was more efficient when the flow rate decreased than when it increased. The increased flow amounts from the Kuroshio Through Flow were used in strengthening the cyclonic circulation. In the case of an increased flow rate, the amount of flow discharged from the inner bay was small. Whereas, in the case of a decreased flow rate, the cyclonic circulation water

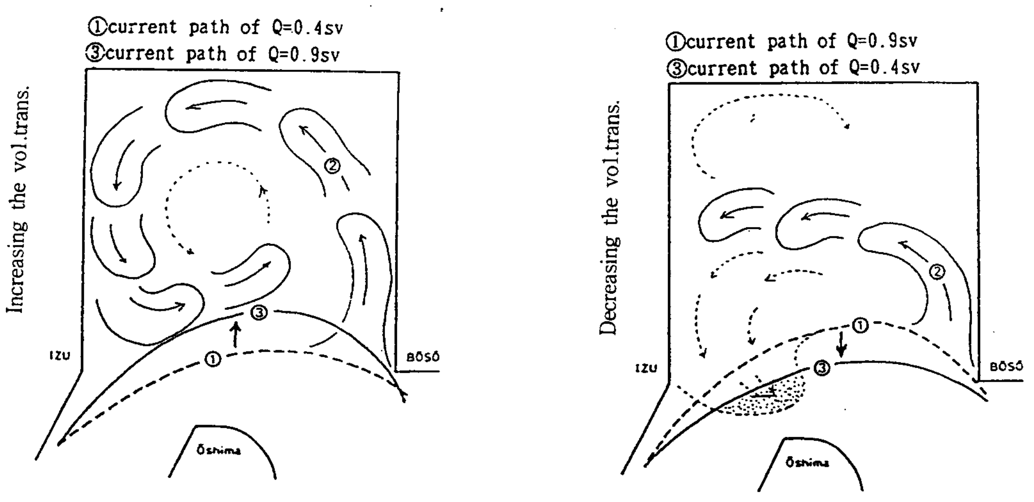
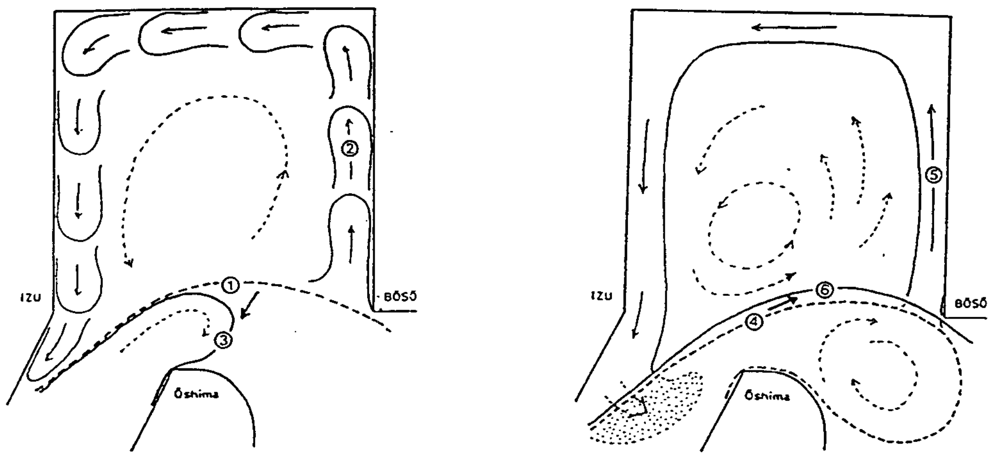


Fig. 11. Schematic views of the water exchanges with time changes of the volume transport of Kuroshio Through Flow in Sagami Bay.



① Current path of $\Delta\rho$=0.0015
③ A gyre is initiated from the inflow of the lower density water
④ Agyre continues to grow.
⑤ Generation of a coastal boundary density current
⑥ Current path of $\Delta\rho$=0.0020

Fig. 12. Schematic views of the water exchanges with time changes of the density difference of Kuroshio Through Flow in Sagami Bay.

extended to the western part of the bay and was discharged out of the bay through the Oshima Eastern Channel. The amount of discharged cyclonic circulation water was determined by a combination of the southward extension of the cyclonic circulation and northward penetration length of the Kuroshio Through Flow.

Schematic views of the time change processes in the flow pattern caused by lowering the upper layer density are shown in Fig. 12. Initially, an

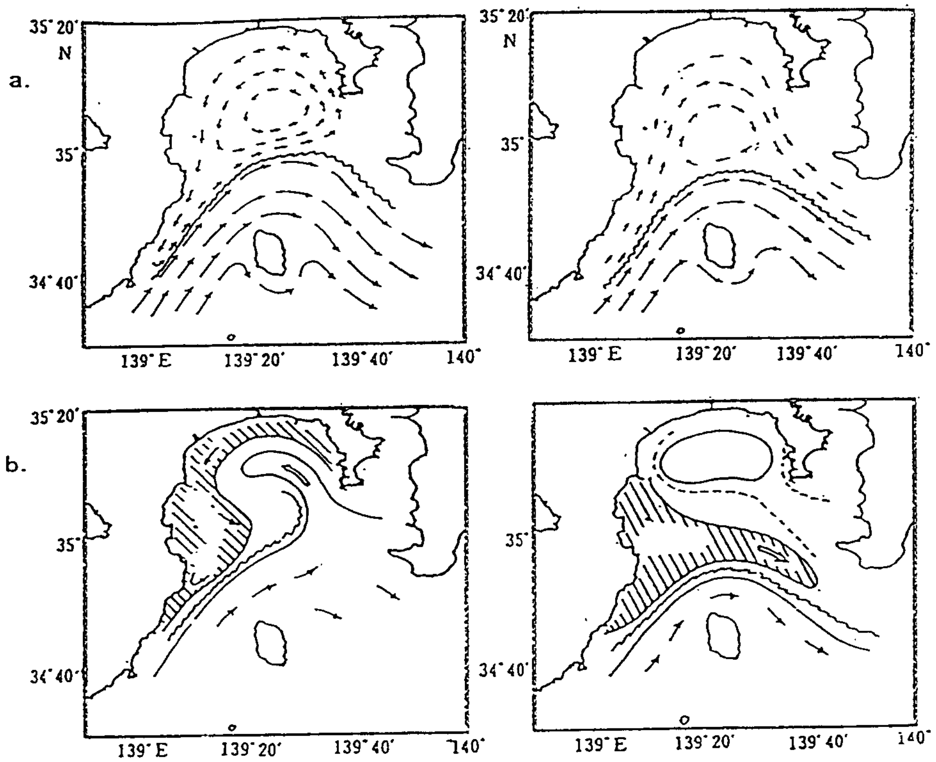


Fig. 13. Schematic views on (a) the surface circulations and (b) the water exchange process in Sagami Bay(after[14] Nakata and Hasunuma, 1987).

anticyclonic warm eddy was formed along the northern boundary of Oshima Island as the low density water(2℃ higher than the bay water) flowed in through the approaching channel(No.③ process in Fig. 12). The radius of the eddy became larger until it reached the northeast shore of Oshima Island(No.④ process in Fig. 12) and the warm waters(low density waters) intruded into the bay along the eastern boundary as a coastal boundary density current(No.⑤ process in Fig. 12). The coastal boundary density current progressed with a speed of more than 0.5 cm/s which is much faster than frontal eddies or frontal wave streamers. In addition, since its temperature is about 2℃ higher than the surrounding water, it is similar with the "Kyucho" event which is often observed on the coast of Sagami Bay. Gradually, the coastal boundary density current died out as a result of mixing(water exchange with the inner bay water) and diffusion due to the density difference with the cyclonic circulation water(No.⑥ process in Fig. 12). However, as the volume transport of the Kuroshio Through Flow became larger, the response time of the change in the flow pattern became shorter.

As a result of a numerical source-sink flow model experiment, Awaji et al.[15] showed that the volume transport of the Kuroshio warm water transported from the Kuroshio region to the continental shelf region on the southern coast of Japan was about $6\times10^{12}m^3$ multiplied by the on-and-off shore of the Kuroshio path, which corresponds to 20% of the coastal water in the continental shelf region. They also suggested that the on-and-off shore of the Kuroshio path plays an important role in water exchange between the continental shelf and Kuroshio regions. Even though the main focus of their numerical experiments was not Sagami Bay, their results on water exchange coincide with the hydraulic model experiments presented in this paper. The results on the flow pattern response and water exchange process in this paper also match the results of Nakata and Hasunuma[14] in relation to the limits of the schematic views showing the changes in surface circulation and water exchange process caused by fluctuations in the Kuroshio Through Flow in Sagami Bay. Fig. 13 shows schematic views of the surface circulations and water exchange process obtained from field observations of drift buoys in Sagami Bay.[14] From these results, it can be postulated that the water exchange process between the Kuroshio Through Flow and inner bay water in Sagami Bay is strongly related to the movement of a front that fluctuates north and south as the volume transports from the Kuroshio Through Flow are changed.

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