

Simulating larval dispersal processes of white croaker in Ariake Sea using a coupled particle tracking and hydrodynamic model

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A hydrodynamic model was coupled to a particle tracking model to examine physical factors that influence transport of the white croaker larvae in the Ariake Sea, Kyushu, Japan. The idealized particles that mimic the larvae of white croaker are tracked under various physical and biological conditions. Freshet reduces the possibility of particles that reach the nursery ground around the head of the bay by 7 % on average. Spring tide has a positive impact on the feeding migration of particles. Selective tidal stream transport (STST) mechanism dramatically changed particle trajectories. Particles tend to reach the shallower nursery ground easier during ebb or low tide rather than high or flood tide, depending on whether the STST is considered during the particle tracking experiment. In particular, the ratio of the number of particles that reach the nursery ground increases by approximately 24 % from flood tide to low tide. When the sinking velocities of particles, ranging from 10^{-5} to 10^{-3} m/s, are considered during the particle tracking experiment, majority of the particles stayed in the releasing area.

Key Words : Numerical Simulation, Feeding Migration, Selective Tidal Stream Transport, Larvae of White Croaker, Tracer Experiment, Ariake Sea

1. Introduction

The Ariake Sea is located in the western side of Kyushu Island, Japan. The sea is a tidally-forced, semi-enclosed estuary encompassed by wide-spreading intertidal areas comprising mudflats and salt marshes, where flooding and draining are predominant. Its total area is about 1,700 km² and its length is about 100 km along the gulf axis. On average, its width is 16 km and water depth is about 20 m. It is known for macro tidal range (it is greater than 6 m at the head of the sea in the spring tides), high-speed tidal current and the widest tidal-flat area with the surface area of about 188km² that account for 40% of the total flat area in Japan. Owing to the characters above, the Ariake Sea plays an important role in the aquaculture of Japan and is a highly productive estuary for its rich fishery products and *Porphyra yezoensis* (one of the most popular seaweeds in Japan) cultivation¹⁾. Based on salinity level, the sea is often divided into three regions, which are the inner part, the central part and the gulf mouth.²⁾ The salinity,

nutrients and chlorophyll a levels in these three regions are quite different. According to observations³⁾, the salinity concentration is lowest in the inner part and highest in the lower part. In contrast, nutrients and phytoplankton concentrations in the inner part are much higher than those in the other regions. Summarized by yagi et al.⁴⁾, the upper estuaries of the Sea own highly turbid brackish waters with high tidal velocities, and they act as nursery grounds for various species of fish in Ariake Sea.

However, due to the reasons such as reduction of the lagoons, increasing sand mining, decreasing tide range and reclamation of Isahaya Bay, fishery environments of Ariake Sea were worsening since 1980s. Moreover, it is analyzed that most of these declining fish stocks have a common life history as they spawn in the central part of the Sea and migrate to the lagoon and estuaries located in the inner part of the sea acting as nursery ground. Thus, it is critical to study the cause of egg depletion during the feeding migration process.

Take account of that the white croaker is the dominance species in the inner part of Ariake Sea both

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in the total weight and the total quantity, otherwise the fish catch declining of this fish stock is very strictness. In this study we choose the larvae of white croaker to be the object.

Since larvae are unable to swim against estuarine currents, upstream movement must be accomplished through various adaptations that oppose the net downstream flux of waters.^{7, 8)} Fish larvae must therefore adopt alternative strategies for successful ingress into the estuarine nursery grounds. One of the behavioral mechanisms leading to this movement by larvae is selective tidal stream transport (STST), in which larvae are in the upper water column during rising tides and in the lower water column during falling tides. Especially if tidal current velocity is greater than optimum swimming speed,^{9, 10)} STST permits organisms to migrate long distances with energetic costs much lower than for active migration. The direction of transport is determined by the tidal phase during which the organism migrates up into the water column; ebb tide transport (ETT) is seaward, and flood tide transport (FTT) is landward. STST has been demonstrated by many fish species and crustaceans^{5, 10, 11, 12)}.

For the sake of preventing the decline of the fishery resources, it is important to investigate the main feeding migration processes of the white croaker in the natural environment. It is one of the fundamental problems that how the physical conditions such as current and tide influence the feeding migration. A series of numerical experiments that consist of the hydrodynamic simulations and particle tracking experiments were conducted for evaluating the effects of tidal currents, freshwater outflow of two upper estuaries, and the sinking velocities on successful transport.

2. Methods

2.1 Numerical Models

The Princeton Ocean Model¹³⁾ that is a three-dimensional hydrodynamic model was employed for simulating current field in the Ariake Sea. The hydrodynamic model used in this study reproduces very well the tidal currents¹⁴⁾ and results of the numerical experiment of the residual currents are discussed in Manda et al.¹⁵⁾ Moreover, it has been calculated that the spawning time of the white croaker is from May to August.^{16, 17)} and in this study we chose the period of July 2007 and 2008 to be research time.

Horizontal resolution of this model is 500 m and the water column is divided into 11 layers. The model is forced by the 4 principal tides on the open boundaries and freshwater outflow from the Chikugo and Yabe rivers. The

J-EGG500 (http://www.jodc.go.jp/data_set/jodc/jegg_intro.html) along with the J-BIRD (<http://www.jodc.go.jp/data/bathymetry/jbird.html>) bathymetry data are interpolated onto the model grid for specifying the bottom topography. The duration of each model run is two month, excluding the spin-up time.

With the current fields obtained by the hydrodynamic simulation, the particle tracking experiments were conducted. We made use of the widely used the Euler-Lagrange method¹⁸⁾ for the particle tracking.

2.2 Implementation of STST

Selective Tidal Stream Transport (STST) was implemented as follows. The semi-major axis of the M_2 tidal ellipse maximum tidal current velocity in each grid cell of the hydrodynamic model was computed using the harmonic analysis. The velocity vectors of the maximum flood current, which are spatial dependent but time-invariant, were obtained from the semi-major axes. The angle between the maximum flood current vector and the instantaneous current velocity vector in each model grid cell computed at every time step. While the angle is a sharp angle, the particles were set to move upward and float near sea surface. On the contrary, while the angle is obtuse, the particles move downward and float near the bottom.

The accurate angle of alternate flow up and sink down ought to be 90 degree. Due to the direction of the maximum vector during flood period is spatially variable and the frequently alternate flow up and sink down at the moments during slack tide will make troubles on the model running, we decided that particles float up only when the angle was smaller than 85 degrees and sink down only when the angle was greater than 95 degrees. If the angle falls in between 85 degrees and 95 degrees, particles was set to act as passive tracers. At present, the information of the parameters about the velocity in STST haven't received, toward the float up and sink down in this time experiment, we let the particles instantaneously move to the 10% and 90% depth at the places of those times.

2.3 Experiment Setting

Table 1. shows the description of 28 experiments conducted in this study. Runs 1 and 2 were designed for evaluating the influence of freshet. Runs 3 ~ 6 were carried out to investigate the effect of the tides. Since the smaller changes in freshwater outflow are better for investigating the effect of tide, the flow field with small changes of estuary flow rate in year 2008 was used.

Among which Run 3 and Run 4 were contrast tests in order to clarify the difference between influences of spring tide and neap tide. All types of tide in Run 5 and Run 6

Table 1 Conditions of the particle tracing experiments (ST: spring tide; MT: moderate tide; NFR: normal flow rate ; AF : after freshet)

Name of experiment	Date of releasing	Type of Tide	Estuaries' Condition	Tidal Phase while releasing	STST	Days of apply STST after releasing	sinking rate (m/s)
Run 1-1	6/7/2007	Neap	freshet	low tide	—	—	—
Run 1-2	6/7/2007	Neap	freshet	low tide	+	1	—
Run 1-3	6/7/2007	Neap	freshet	low tide	+	3	—
Run 1-4	6/7/2007	Neap	freshet	low tide	+	5	—
Run 2-1	20/7/2007	Neap	AF	low tide	—	—	—
Run 2-2	20/7/2007	Neap	AF	low tide	+	1	—
Run 2-3	20/7/2007	Neap	AF	low tide	+	3	—
Run 2-4	20/7/2007	Neap	AF	low tide	+	5	—
Run 3-1	11/7/2008	Neap	NFR	low tide	—	—	—
Run 3-2	11/7/2008	Neap	NFR	low tide	+	1	—
Run 3-3	11/7/2008	Neap	NFR	low tide	+	3	—
Run 3-4	11/7/2008	Neap	NFR	low tide	+	5	—
Run 4-1	18/7/2008	ST	NFR	low tide	—	—	—
Run 4-2	18/7/2008	ST	NFR	low tide	+	1	—
Run 4-3	18/7/2008	ST	NFR	low tide	+	3	—
Run 4-4	18/7/2008	ST	NFR	low tide	+	5	—
Run 5-1	5/7/2008	MT	NFR	flood tide	—	—	—
Run 5-2	5/7/2008	MT	NFR	high tide	—	—	—
Run 5-3	5/7/2008	MT	NFR	flood tide	—	—	—
Run 5-4	5/7/2008	MT	NFR	low tide	—	—	—
Run 6-1	5/7/2008	MT	NFR	flood tide	+	1	—
Run 6-2	5/7/2008	MT	NFR	high tide	+	1	—
Run 6-3	5/7/2008	MT	NFR	ebb tide	+	1	—
Run 6-4	5/7/2008	MT	NFR	low tide	+	1	—
Run 7-1	18/7/2008	ST	NFR	low tide	—	—	10^{-3}
Run 7-2	18/7/2008	ST	NFR	low tide	—	—	10^{-4}
Run 7-3	18/7/2008	ST	NFR	low tide	—	—	10^{-5}

are all the same. But the experiments in Run 6 totally implement of STST in the second day of model-running but meanwhile the ones in Run 5 entirely hadn't implement of which. The differences between four kinds of tide phases at releasing also can be seen both in Run 5 and Run 6.

Towards Run 7, the main difference from Run 4 is that particles separately have their own sinking velocities. In order to discover clearly the effect of the sinking velocity, there is no adding of STST mechanism throughout the Run 7. Because of the larval swimming ability in horizontal direction is very weakness compare with the vertical velocity, in this study only the vertical velocity of larvae being argued. Due to lack of the sinking velocities of the

larvae, hypothetical velocities were being set in this study. Run 7-1 was 10^{-3} m/s, Run 7-2 was 10^{-4} m/s and Run 7-3 was 10^{-5} m/s.

According to the biological samplings, the white croaker larvae were majority founded in the bottom layer of their spawning ground located in the inner part of Ariake Sea with a depth of water from 40 m to 60 m (Atsuko Yamaguchi unpublished data). However, the actual depth cannot be determined by our sampling method. We use two different vertical layers which were 2 m and 5m from bottom in order to see the overall results of the particle tracking do not depend on the depths of the particles at initial conditions. The particles were tracked for 6 days.

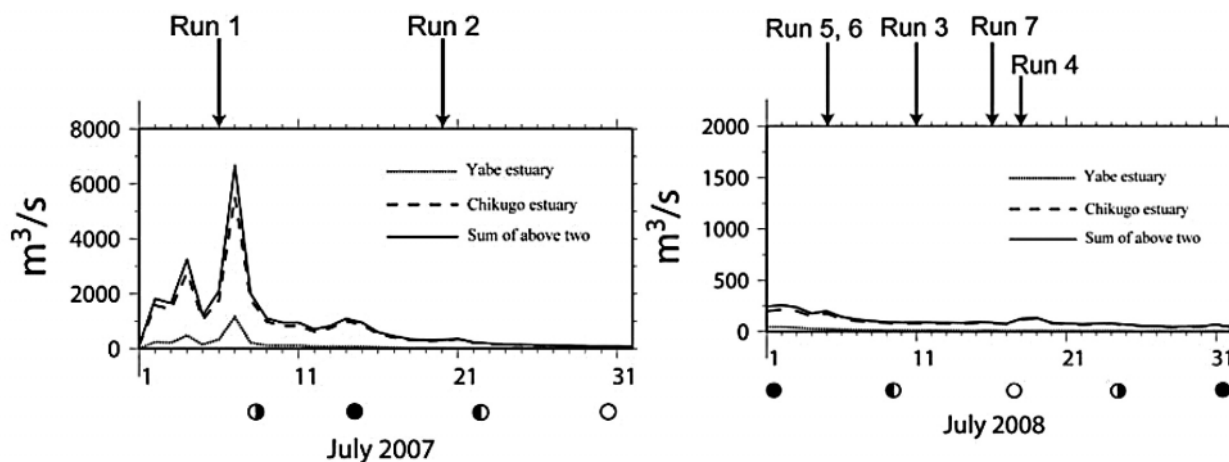


Fig. 1 Rates of freshwater outflow during July 2007 (left) and July 2008 (right). The dashed and dotted lines indicate the flow rate of Chikugo and Yabe Rivers, respectively. The solid lines indicate the sum of the above two. The arrows show the dates when the particles are released at the beginning of experiments. Phases of the moon are given below abscissas.

3. Results

Fig.1 shows the estuarine flows, phases of moon and particles-releasing dates of each experiment in July 2007 and 2008. The estuarine flows were downloaded by Water Information System, Ministry of Land, Infrastructure and Transport, Japan (<http://www1.river.go.jp/>). Temporal variation of freshwater outflow in 2008 is quite different from that in 2007 due to the different rainfall in northern Kyushu

Island, Japan. Since the rainfall during summer varies very much in Japan, the long-term (i.e., climatologically) mean of rainfall is quite different from that in a single year such as 2007 and 2008.

Figs.2. to 8 shows the distributions of the particles at the beginning and end of each experiment as well as their initial distributions.

Approximately 9% and 3% of particles reach the nursery ground in Run 1-1 and Run 2-1 without STST, respectively. Beyond these two experiments, the other ones also without STST indicate particles barely reached the nursing ground. In contrast, the experiments with the STST, about 80% of particles reached the nursery ground. There is not a large difference between Run 1 that the particles are released during freshet and Run 2 that the particles are released after freshet in July 2007. In both cases, STST started on the first day of the experiment. The maximum percentage reaches approximately 73% on average. If the day when STST starts is delayed, the ratio declines significantly. When the STST starts on the third day of the experiment, the ratio reaches 31.3% in Run 1-3 and 35.8% in Run 2-3. When the STST starts on the fifth day of the experiment, the percentage declines to 16.2% during freshet and 6.6% after freshet respectively.

Figs.4. and 5 indicate the results during the spring and

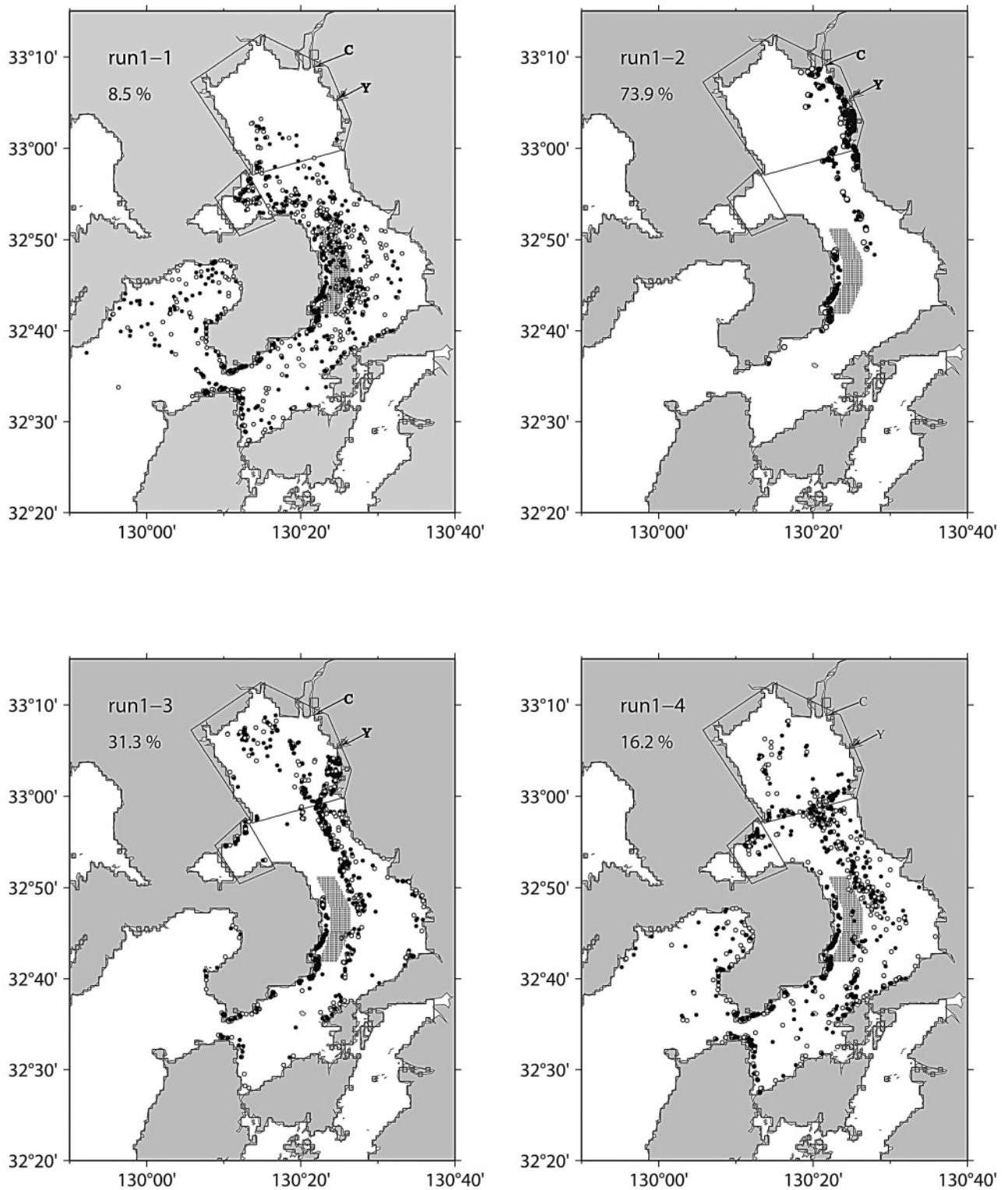


Fig. 2 Distributions of the particles at the beginning each experiments (small dots). Also shown are the distributions of the particles that released at 2 m (filled circles) and 5 m (open circles) above the bottom. The domains surrounded by the polygons are the expected nursing grounds of larvae. The figure showed in the upper left in each panel indicates the percentage of the particles that reaches the nursery ground. The arrows in top right indicate the locations of the rivers. The letters C and Y indicate mouths of Chikugo and Yabe Rivers, respectively.

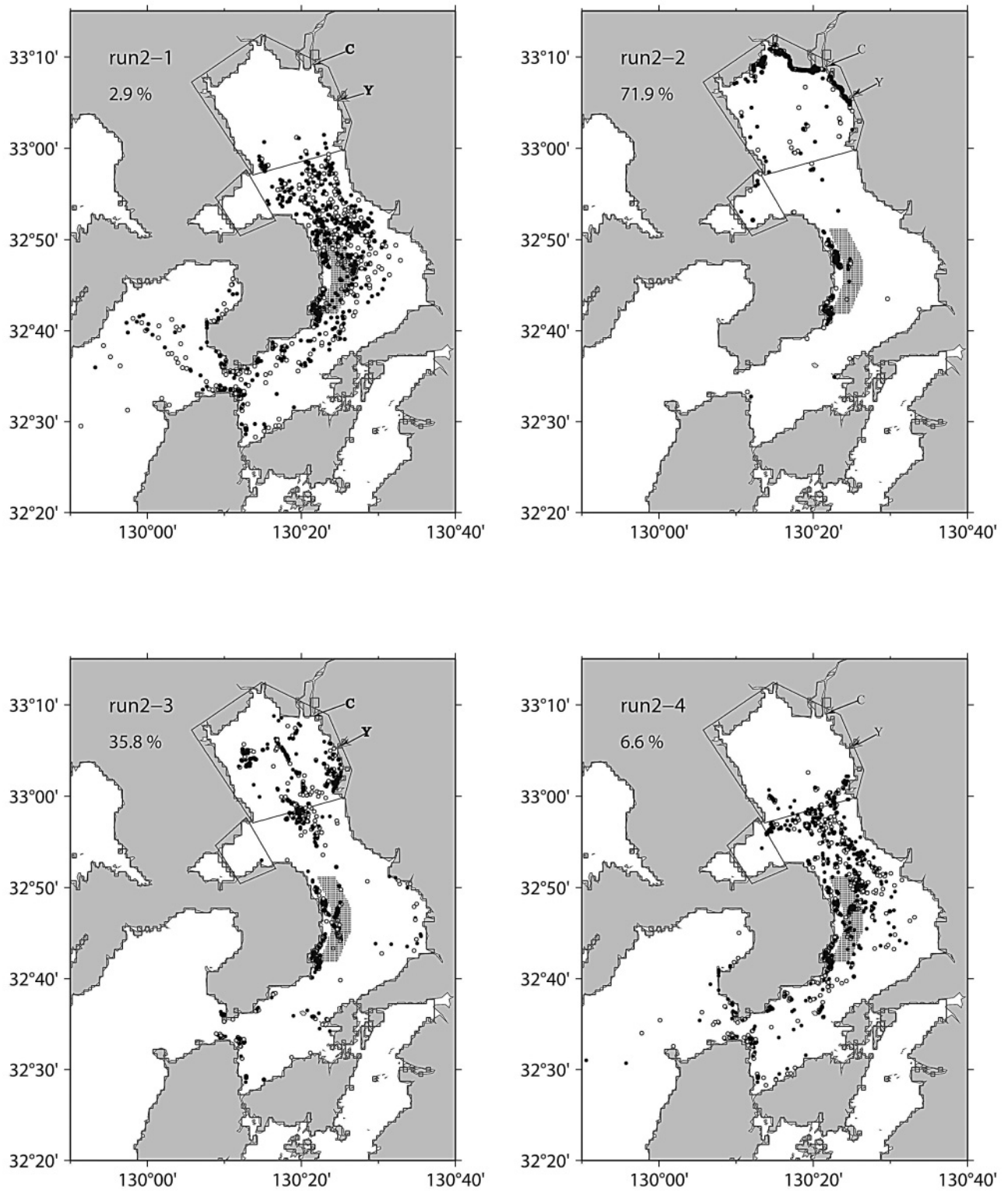


Fig. 3 Same as Fig.2 except for the Run names.

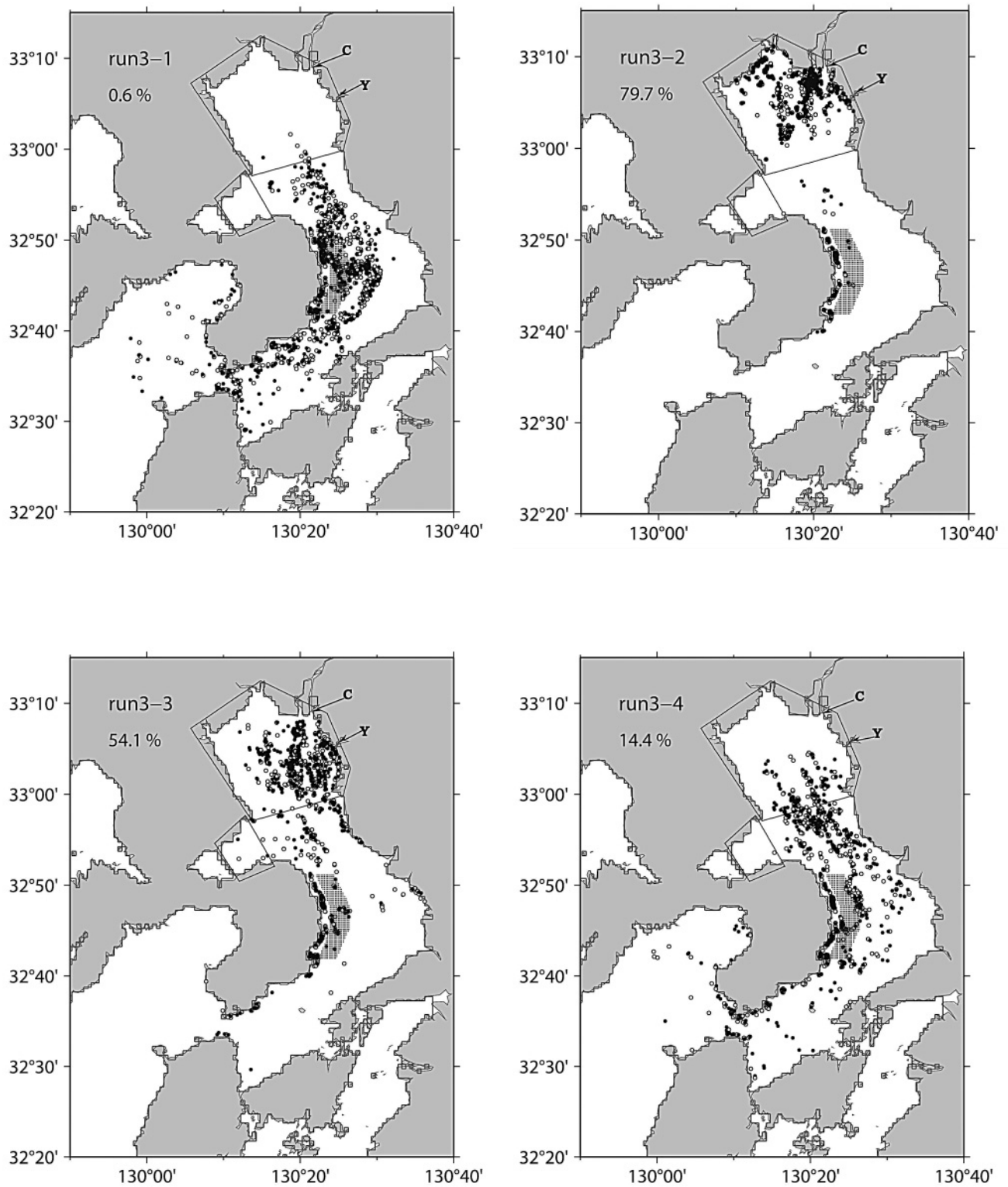


Fig. 4 Same as Fig.2 except for the Run names.

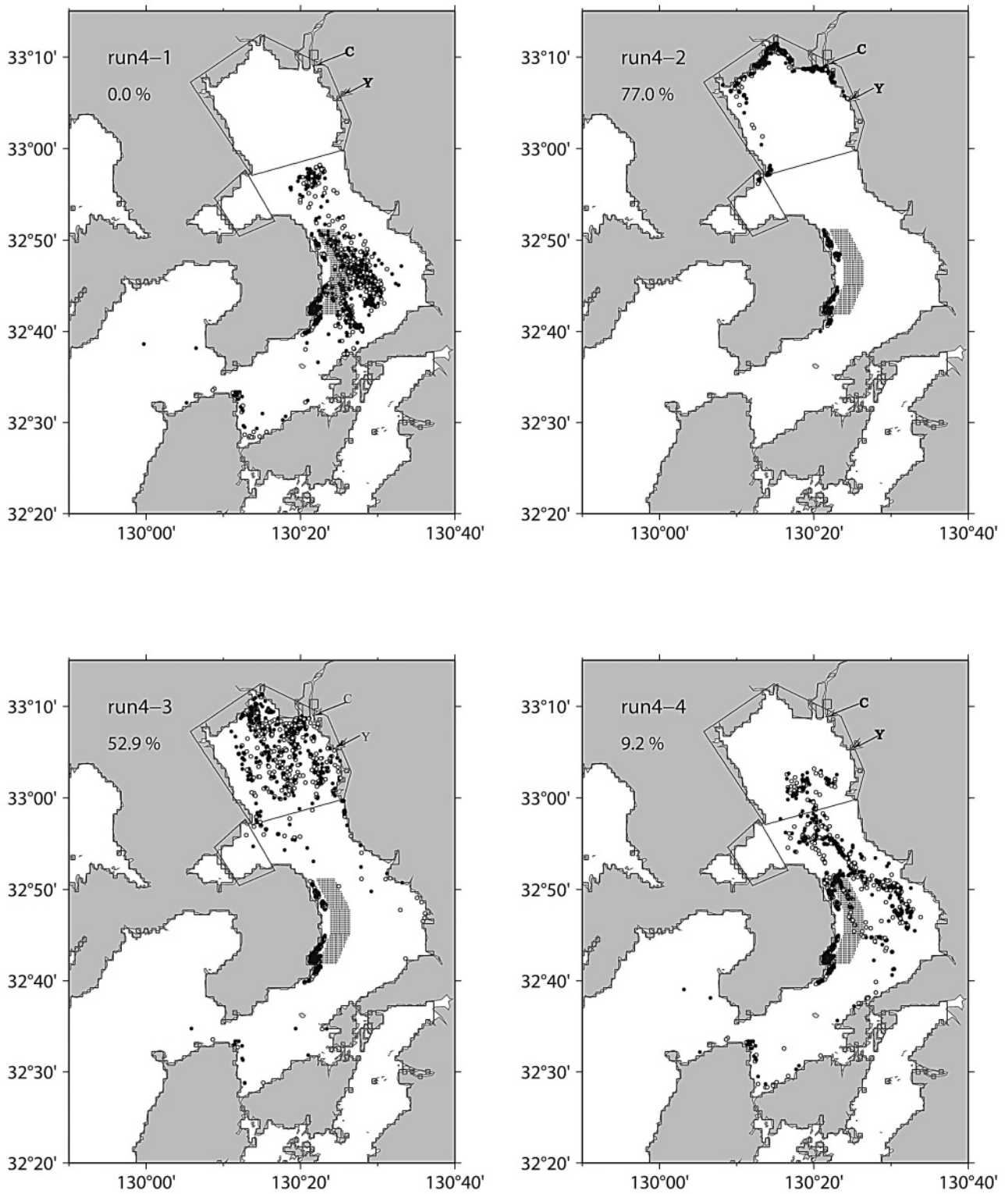


Fig. 5 Same as Fig.2 except for the Run names.

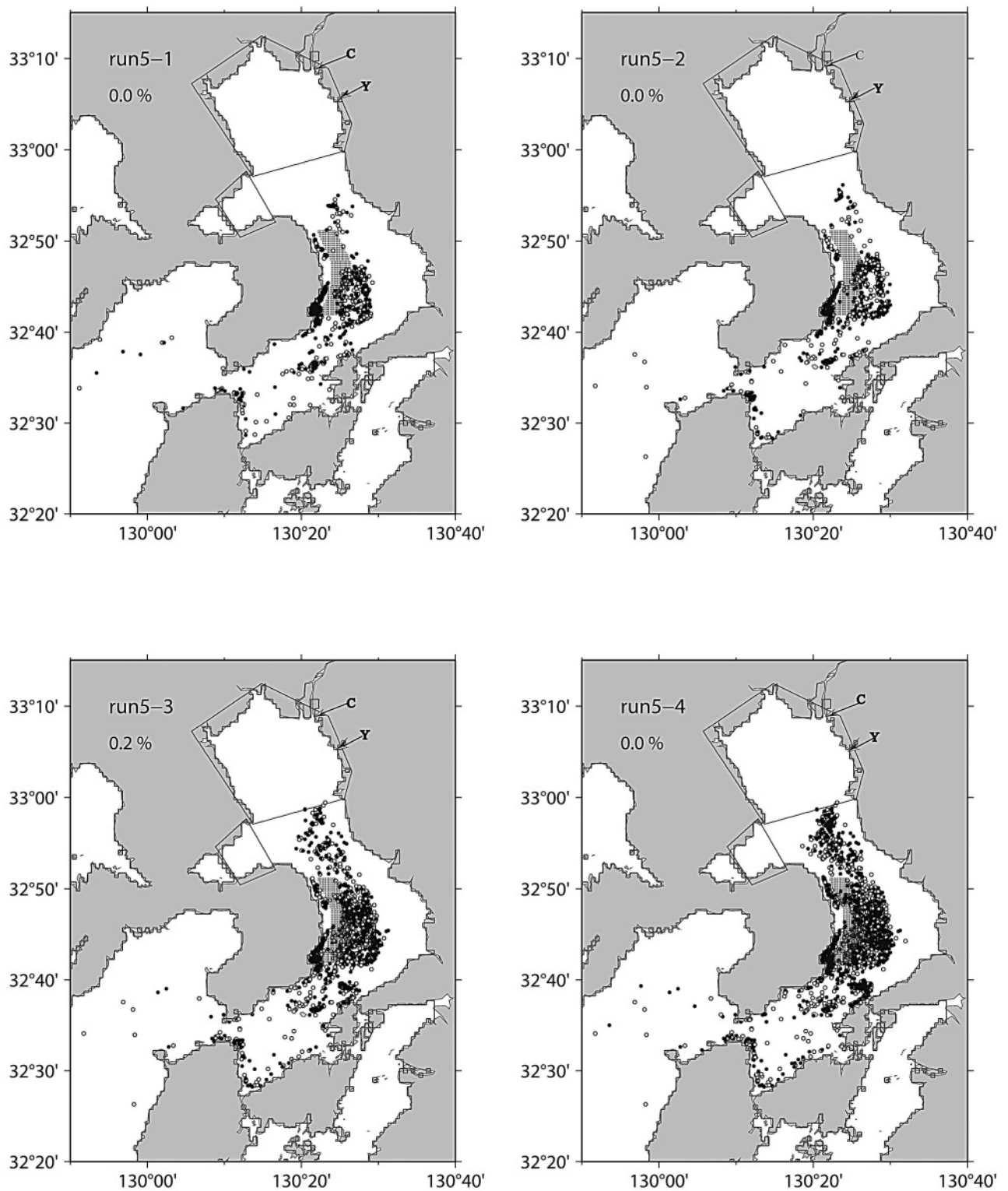


Fig. 6 Same as Fig.2 except for the Run names.

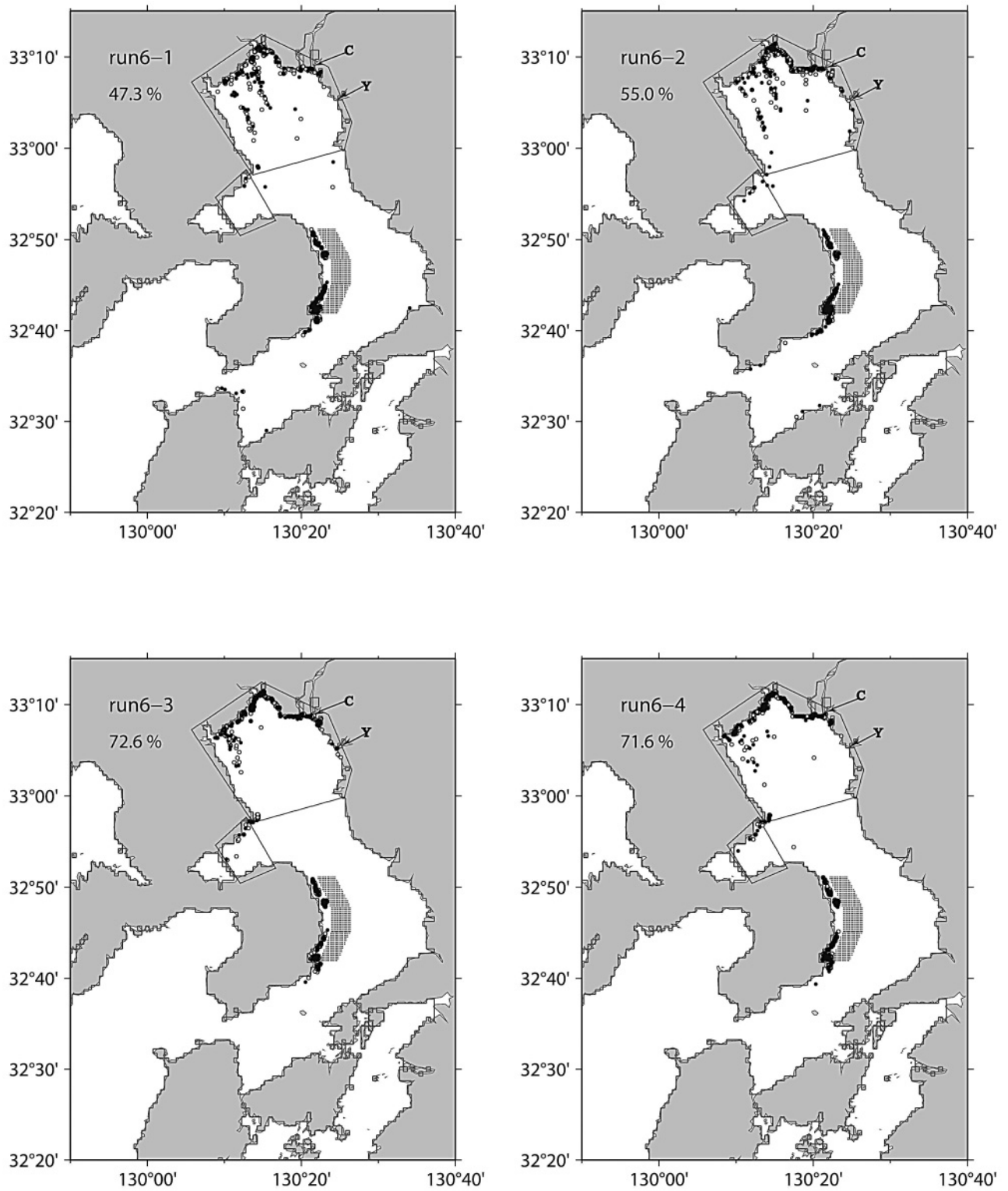


Fig. 7 Same as Fig.2 except for the Run names.

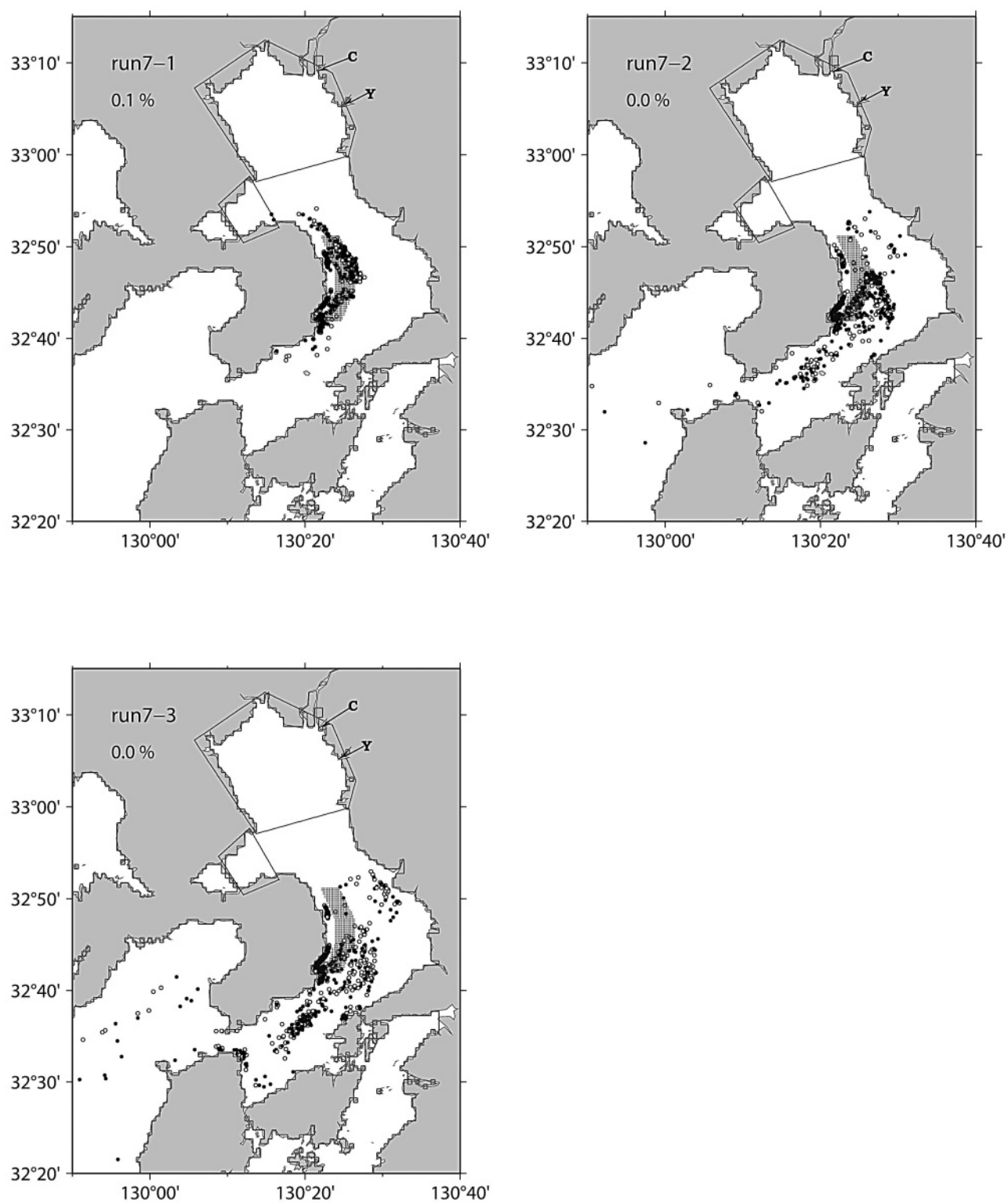


Fig. 8 Same as Fig.2 except for the Run names.

neap tides, respectively. During the neap tide, the particles reach the nursery ground once STST is incorporated, result shown 79.7% (first day), 54.1% (third day) and 14.4% (fifth day). Meanwhile, during the spring tide when STST was applied, result shown 77.0% (first day), 52.9% (the third day) and 9.2% (the fifth day).

The Fig.6. indicates clearly the results between different tidal phases appeared during the same time and when STST was not applied. Although each particle in each experiment has its own particular distribution, the common point is that the particles could barely reach the inner part of the Sea. And even have the tendency to diffuse into the gulf mouth.

Meanwhile, on Fig.7., STST was applied on the first day of each particle tracking experiment. The transport success rate changed greatly from 47.3% during flood tide of Run 6-1 to 72.6% during ebb tide of Run 6-3; from 55% during high tide of Run 6-2 to 71.6% during low tide of Run 6-4.

The experiment results for (Run 7-1, 7-2, 7-3) which have considered the sedimentation velocities were showed on Fig.8. Majority of the particles stayed in the released area when the sinking speed was high.

4. Discussion

Above all, through the results of all the 28 experiments in this study, it's quite easy to find out that the STST contribute enormously to the successful feeding migration of the larvae since larvae use low velocity regions such as the shore or the stream to reduce the chance of being transported to downstream. As indicated by many studies^{19,24)}, larval and juvenile fish use tidal systems as a retention mechanism.

In the contrast experiments of run 1, run 2 and run 3, run 4 all shows difference, in addition the front one has a more significant result. On the one hand, impact of bigger flow rate increases the success rate for larvae to reach the nursery ground obviously by way of comparing the results showed in Fig.2. and Fig.3. Moreover, even through the experiment of Run1-1 which without applying STST also got 8.5% particles arrived in the nursery ground.

Secondly, the tide lever of neap tide compared with spring tide has a moderately impact on the feeding migration of particles analysis on Runs 3 and 4. But cause the difference is really inconspicuous, and there also has a bit difference on the being time of the two groups of experiments which determine the difference of flow rate through these ones, so we couldn't give a categorical conclusion of which tide lever effort more.

From the results of Runs 6, particles tend to reach

upper nursery ground easily during ebb tide or low tide rather than high tide or flood tide. The success rate increased by 24.3% from flood tide level to low tide level during (Run 6) in which STST was applied.

When the sinking velocity of the particles is incorporated, most of the particles stay in the middle part of the bay and hardly reach the nursery ground. After compare the results of Run 7 to its contrast experiment named Run 4-1, it indicates that the adding of sinking velocity has a restrain effort on the feeding migration of the larvae as showed in Figs.5 and 8.

Considering these factors such as tidal currents, freshwater outflow of two upper estuaries, phases of the moon as well as hypothetical sinking velocity of larvae in the above study; the process about feeding migration of larval white croaker using numerical simulation method has been revealed in preliminary stage. But the actual hydrodynamic circulation in Ariake Sea contains much more complicated factors as one of it be known as residual tidal current which is aperiodicity. The other factors are water temperature and salinity which has a direct effect on piscine propagate, sea circulation, material transport, etc.

Except the hydrodynamic factors, species-specific variations such as ontogenetic stages, fat content, and abundance ratio during their feeding migration also need to be concerned. In future, we need to gather more quantitative data by a field campaign and/or a laboratory experiment such as sinking velocity of the larval white croaker.

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* In Japanese with English summary

有明海における卵稚仔輸送過程の数値モデル

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海洋数値シミュレーションモデルと粒子追跡モデルを用いて、物理的要因が有明海の仔魚輸送に及ぼす影響について調べた。モデルにおいて仔魚は仮想的流体粒子として表現される。河川水の出水は生育場へ輸送される粒子数を7%減少させる。大潮時に潮流流速が増すことによって、生育場へ輸送される粒子数は増加する。稚魚の鉛直移動の効果 (Selective tidal stream transport) によって、粒子の輸送過程は大幅に変化する。干潮時や下げ潮時に投入された粒子は、より生育場へ到達しやすくなる傾向がある。 10^{-5} から 10^{-3} m/sの範囲で粒子の沈降速度を加味した場合、粒子は放流地点付近にとどまる傾向が強くなる。

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