Transport of jack mackerel (*Trachurus japonicus*) larvae inferred from the numerical experiment in the East China Sea

Heeyong KIM[1†], Shingo KIMURA[1] and Takashige SUGIMOTO[2]

An advection and diffusion model for particle tracking in three dimensions and the deployments of satellite-tracked drifters were conducted to examine the role of the Kuroshio front on the transport process of jack mackerel larvae in the East China Sea (ECS) in early spring. Larvae of jack mackerel transported from the shelf area remained largely in the ECS, and survival rate for them was estimated to be very high through the experiments adopting mortality dependent on temperature and salinity. It was also verified that the Kuroshio front played a significant role as a boundary in the transport processes of jack mackerel larvae. Furthermore, trajectories of satellite-tracked drifters released in the Kuroshio frontal region and over the shelf area supported that transport processes are significantly different according to the releasing locations which was suggested by the advection-diffusion model. It was also revealed that passive larvae from the Kuroshio frontal region showed a low survival and a cyclonic flow due to frontal disturbances southwest of Kyushu acts as a main mechanism in transporting them into the waters off western Kyushu (WWK), where has a good feeding condition. Therefore, it is probably important the passive larval transport from the Kuroshio frontal region into the WWK for the good survival.

Key words: jack mackerel, larval transport, East China Sea, particle-tracking experiment, satellite-tracked drifter

Introduction

The continental shelf of the East China Sea (ECS) is one of the biggest spawning grounds of pelagic fishes, such as common mackerel, jack mackerel and common squid migrating along the Japanese Islands. In particular, jack mackerel is known to spawn at the frontal region upstream of the Kuroshio in the ECS (Asami, 1974; Sassa and Konishi, 2002), and its stock in the ECS is divided into three populations as indicated in Fig. 1 (Hotta and Mako, 1970). Among them, the middle ECS population has shown the largest catches around Japan (Seikai Regional Fisheries Research Laboratory, 1986).

According to a previous study for movements of jack mackerel larvae in the ECS and the waters off western Kyushu (WWK) (Kozasa, 1971a), spawning ground was located in the middle ECS in February to April, and then shifted to the eastern ECS along the continental shelf margin in May. Hattori (1964) also estimated that a spawning ground was located in the Satsunan Region (the waters off southern Kyushu) and its spawning season was February. Sampling research by the Japan Fisheries Agency in 2001 showed that a main spawning ground of jack mackerel is probably generated at the ocean area northeast of Taiwan (Sassa and Konishi, 2002).

In the ECS and the WWK, larvae of jack mackerel select small copepods from 0.5 to 1.0 mm in body length as main diet, and the copepod was found abundantly in the WWK, five times larger than that around the region of the Yellow Sea Cold Water (Kozasa, 1974). This result suggests that the WWK has a good feeding condition for early survival of jack mackerel larvae.

For pelagic fishes spawning in the frontal region, hydrographic characteristics of the front could be important environmental conditions in egg and larval stages (McGurk, 1987; Frank *et al*., 1993; Stabeno *et al*., 1996; Nakata, 1996; Townsend and Pettigrew, 1996) because flow variability due to frontal disturbances affects the distribution of passively transported larvae.

Most of studies related to transport of jack mackerel larvae in the ECS have been based on biological sampling data as mentioned above. However, since the biological sampling data cannot reveal whole moving area of jack mackerel larvae temporally and spatially, there are many difficulties to understand the transport process of jack mackerel larvae. Numerical experiments of fish larval transport adopting flow conditions are therefore necessary to understand the survival strategy of jack mackerel larvae in the ocean area.

The objective of this paper is to examine the relative importance of the Kuroshio front on the transport process of jack mackerel larvae which have a main spawning

Received February 25, 2005; Accepted July 14, 2006.

[1] Ocean Research Institute, University of Tokyo, 1–15–1 Minamidai, Nakano, Tokyo, 164–8639, Japan
[2] Ocean Research Institute, School of Marine Science and Technology, Tokai University, 3–20–1 Shimizu Orido, Shizuoka, 424–8610, Japan
[†] kimhy@ori.u-tokyo.ac.jp

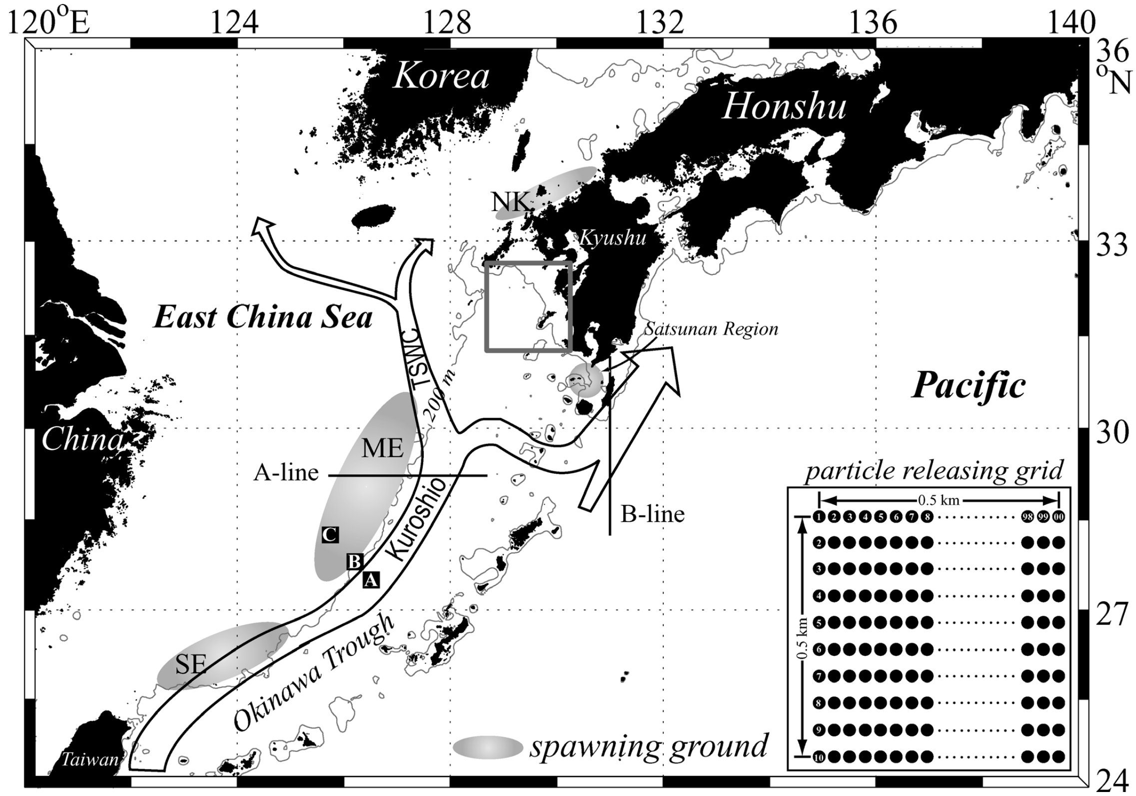

Figure 1. Location of the spawning grounds of jack mackerel and schematic of the current system in the East China Sea after Nitani (1972). SE, ME and NK indicate the spawning grounds of the southern East China Sea population, the middle East China Sea population and the northern Kyushu population, respectively. A-line is a hydrographic observational line along 29.25°N conducted by R/V Kaiyo-Maru of the Japan Fisheries Agency February 2001. B-line along 131°E is a line dividing the East China Sea and the Pacific Ocean. Solid rectangles with alphabet indicate released sites of particles, and releasing grid points of particles at each site are indicated in a rectangle at the lower-left of the map. A gray rectangle area indicates the waters off western Kyushu. Gray line indicates the isobath of 200 m depth.

ground in the ECS, inclusive of the transport to the WWK where the feeding condition for jack mackerel larvae is good. Thereby we conduct a particle-tracking model for the passively transported larvae using results of the 3-D ocean circulation model reproducing well the Kuroshio in the ECS. Results of the numerical particle-tracking experiments are discussed with trajectories of satellite-tracked drifting buoys.

Model Description and Data

Modeled ocean current and hydrographic data

The modeled ocean circulation and hydrographic data (Fig. 2) are provided by the Ocean Circulation and Climate Advanced Model (OCCAM) developed at the Southampton Oceanography Centre in the United Kingdom (Webb *et al*., 1998; Saunders *et al*., 1999). The OCCAM, a primitive equation numerical model of the global ocean, is based on the Bryan-Cox-Semtner ocean model. The model has global coverage with a spatial resolution of 0.25° in longitude and latitude, vertically separated by 36 levels with range in thickness from 20 m near the surface to 255 m at a depth of 5500 m and its topography are based on the DBDB5 (Digital Bathymetric Database-5 minute resolution) data set. Wind stress, which was interpolated from an annual cycle of 12 monthly fields calculated by Siefridt and Barnier (1993) from the years 1986 to 1988 inclusive, is applied on a 1.125 degree grid at the surface, and the surface temperature and salinity values are relaxed towards monthly climatological values. The model was initialized with climatological conditions and integrated for 14 model years and an annual average flow-field was constructed from the model-years integration (Kimura *et al*., 1999). The annual average flow-field was used to calculate larvae trajectories using a particle-tracking method. Upper 5 level layers with each 20 m depth in the model results, water temperature, salinity and flow-field were used for our calculation.

In the present study, because water temperature and salinity are important factors in calculating larvae mortal-

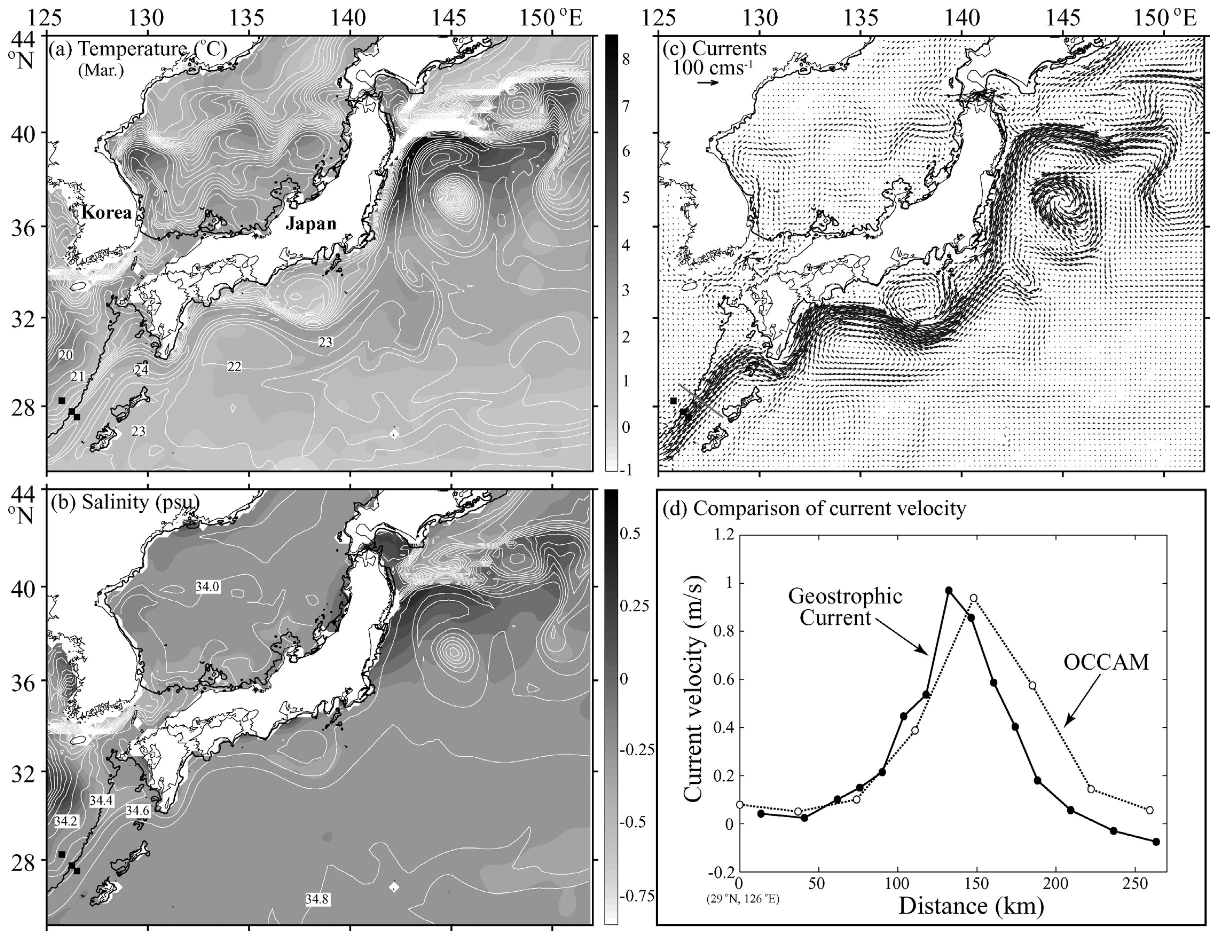

Figure 2. Horizontal distribution of (a) water temperature, (b) salinity, (c) current vectors derived from the Ocean Circulation and Climate Advanced Model (OCCAM), but the water temperature and salinity are superimposed on each horizontal distribution of the difference between that of OCCAM and a global climatology of GDEM, and (d) comparison of velocities of geostrophic current relative to the bottom calculated by 10-year hydrographic data at the PN-line (a thick line in (c)) of Japan Meteorological Agency from 1991 to 2000 with the modeled current at 20 m depth. Solid rectangles indicate the release sites of particles. Black line in each panel indicates the isobath of 200 m depth.

ity, the modeled temperature and salinity were compared with a global climatology of water temperature and salinity with a single horizontal grid resolution of 1/4° of General Digital Environmental Model (GDEM) which was developed by the Naval Oceanographic Office (Fig. 2a, b). Differences of the water temperature and salinity between two data sets were small around the Kuroshio region which was the main distribution region of jack mackerel larvae but were large east of Japan. Also, as compared the current velocities along a section across the Kuroshio in the OCCAM (Fig. 2c) with geostrophic current velocities relative to the bottom calculated by using long-term (1991–2000) hydrographic data at the PN-line shown as a thick line in Fig. 2c, There was very good agreement in the absolute velocity between two data sets around the Kuroshio region but a small difference in the position of the Kuroshio axis was shown (Fig. 2d). Furthermore, the speeds both of satellite-tracked drifters and of passive larvae in the ECS were almost same when indicated how the drifters and the passive larvae took to flow from the release site of to the Tokara Strait although mentioned in results. It therefore suggests the model data are appropriate to apply to the advection-diffusion model for the passive larvae in the ECS.

Particle-tracking experiments

We consider two cases for calculating the transport of the larvae. Case 1 of them is a transport experiment by advection and diffusion. Three release locations were selected as follows, Location A (126.50°E, 27.50°N: the Kuroshio region), B (126.25°E, 27.75°N, the Kuroshio frontal region), C (125.75°E, 28.25°N, over the continental shelf) in cross-stream direction to understand the influence of the Kuroshio front considering the meridional difference of spawning locations as show in Fig. 1 (solid circles with an alphabet).

Advection into an unfavorable environment was suggested to be the main cause of larval mortality (Morse, 1989). Houde (1989) concluded that expected mortality rates of marine fish larvae would be attributed to temperature. Thus, Case 2 is the same as case 1 but taking physical environmental factors for larval survival into consideration, assuming that eggs and larvae die instantaneously when ambient environmental conditions are out of range of the optimum water temperature and salinity.

The jack mackerel spawns at water temperature 16–24°C (Yamada *et al*. 1986) and eggs hatch out 40 hours later after fertilization in 20–22°C (Ochiai *et al*. 1982). Larvae and juveniles were usually collected at salinity 34.2–34.7 psu, and water temperature 16–26°C and 17–25°C, respectively (Hattori, 1964; Sassa and Konishi, 2002). Juvenile of jack mackerel complete the development of all fins and start to have a high swimming ability from when it being total length 30 mm (about 43 days after hatching) (Ochiai *et al*., 1982). In case 2, based on the above studies and the sampling results, early life stages were separated into three developmental stages, egg after spawning (0–2 days), larvae (3–29 days), and juvenile (30–41 days) according to Ochiai *et al*. (1982), and the optimum temperature ranges for the three development stages were determined as 16–24, 16–26 and 17–25°C, respectively.

The 1000 particles released in a 0.5×0.5 km horizontal grid at 30 m depth were tracked over a 41-day period (Fig. 3). The released depths were selected by the results of Olivar (1990) and Sassa and Konishi (2002). The flow fields with a 10-day interval were applied for the calculation of the particle tracking. Transport of passive larvae released on a site was simulated using a three-dimensional advection-diffusion scheme. The position [$Xp(t+\delta t)$] of a particle at a time step $t+\delta t$ is given by

$$Xp(t+\delta t)=[Xp(t)+u(t)*\delta t]+\delta l_{diff} \qquad (1)$$

$Xp(t)=(xp_t, yp_t, zp_t)$ represents the position of the particle at the previous time step t. $\delta t=1$ hour for the scheme, which thus requires interpolation between the 10-day mean velocity fields from OCCAM. The particle is advected with velocity u (xp, yp, zp, t), which weighted by the distances from each grid point for four velocities in a grid field was used for the advection calculation. δl_{diff} is a diffusion scheme added to the position of a particle by advection. For diffusion of particles, $5\times10^2\,m^2\,s^{-1}$ (Yanagi *et al*., 1998; Kimura *et al*., 1999) was adopted as the horizontal eddy diffusivity, and the diffusion calculation was conducted once every five advection calculations.

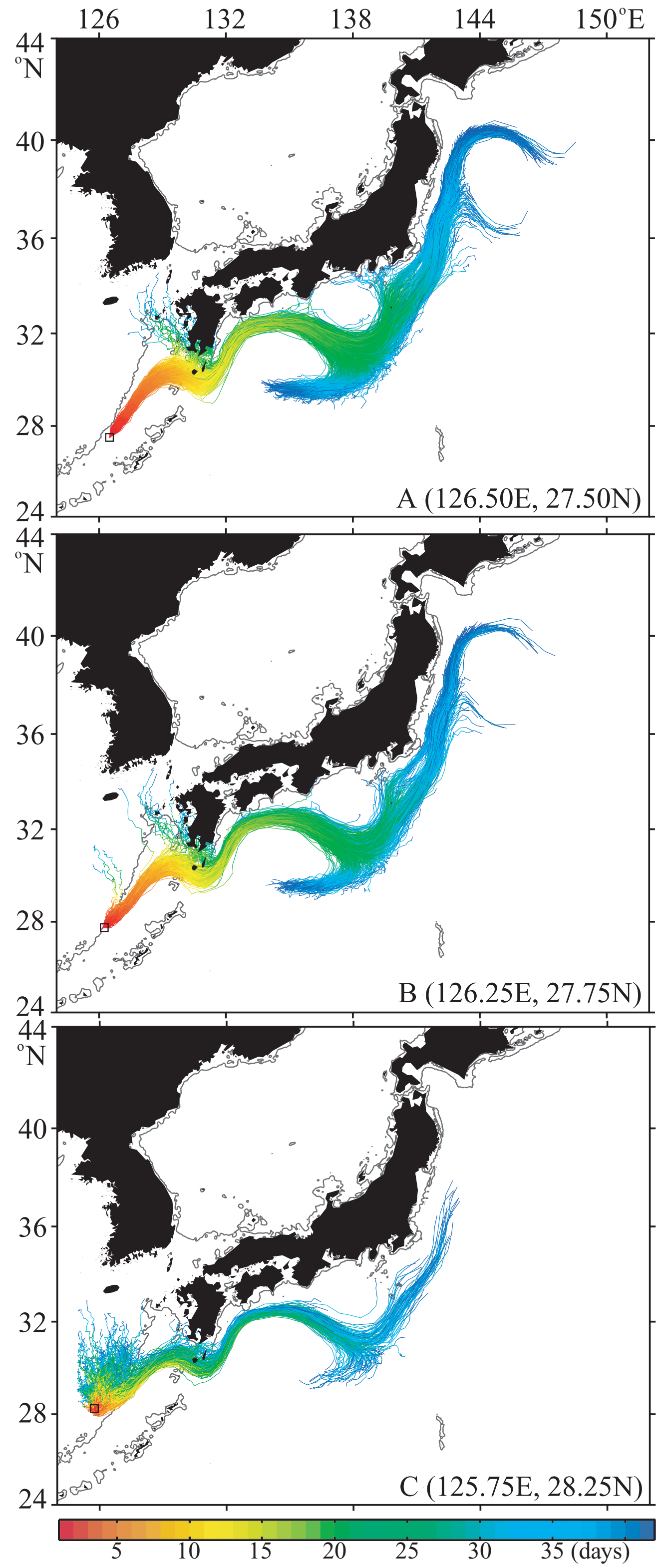

Figure 3. Temporal changes of particle trajectories calculated by advection and diffusion model (Case 1). The rectangles indicate each release site at (a) the mainstream of the Kuroshio, (b) the Kuroshio frontal region, and (c) the shelf area, respectively. Gray line in each panel indicates the isobath of 200 m depth.

Satellite-tracked drifters

To estimate the transport path of jack mackerel larvae in the ECS during spawning season of jack mackerel, satellite-tracked drifters were released in the continental shelf and the Kuroshio frontal regions northwest of Okinawa Islands 15–17 February 2001 by R/V Kaiyo-Maru of the Japan Fisheries Agency with hydrographic observations (A-line in Fig. 1). A window-shade type drogue of 2 m width and 5 m length was attached to each surface buoy, and the depths of the drogues were 15 and 75 m. Another three drifters were also deployed in the northern Okinawa Trough southwest of Kyushu in 11–15 May 2002 by R/V Hakuho-Maru of the Ocean Research Institute, University of Tokyo.

Results

Passive larval transport calculated using advection and diffusion (Case 1) is shown in Fig. 3. Most particles released at the mainstream of the Kuroshio (Location A) and the Kuroshio frontal region (Location B) are entrained into the Kuroshio and then flowed to the Pacific Ocean after 10 days. They are also moved into the WWK from the

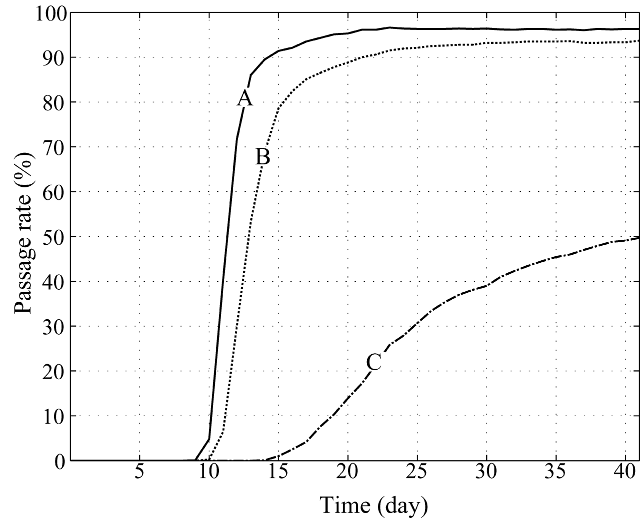

Figure 4. Passage rate (%) crossing over B-line (Case 1). Solid (A), dotted (B), and dashed-dotted (C) lines indicate the passage rate of particles released from (a) the mainstream of the Kuroshio, (b) the Kuroshio frontal region, and (c) the shelf area, respectively.

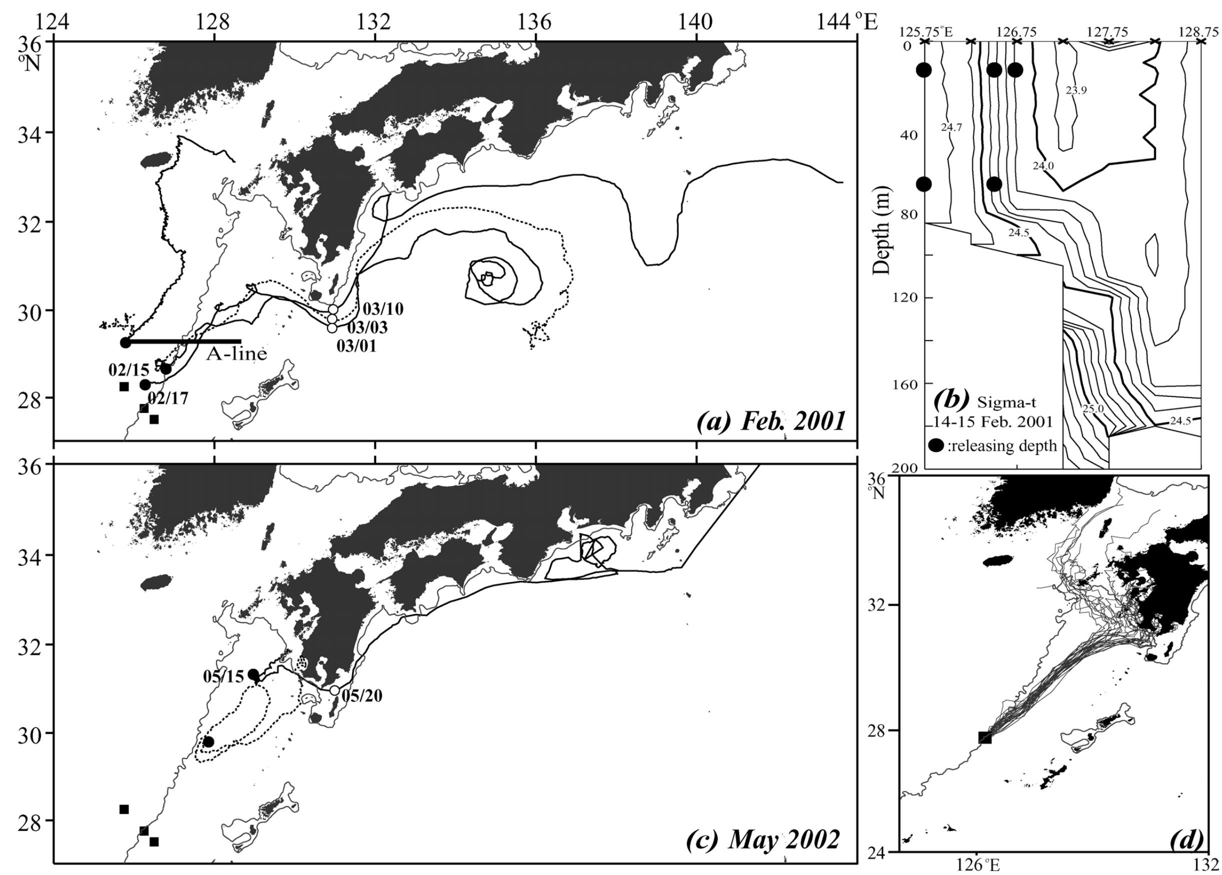

Figure 5. (a) Trajectories of satellite-tracked drifters released in the mid-ECS 15–17 February 2001, (b) vertical profile of sigma-t at A-line, (c) the trajectories of drifters released in the northern Okinawa Trough west of Kyushu 11–15 May 2002, and (d) trajectories of passive larvae flowed into the WWK from the Kuroshio frontal region. mm/dd indicates a date of release and of passing the Tokara Strait. Solid circles indicate the release locations and depths of buoy's drogue. Solid and dotted lines in the buoy trajectories indicate the trajectories released at 15 m and 75 m depth, respectively.

Kuroshio region and then flowed to the Tsushima/Korea Strait. Furthermore, a few of them released at the Kuroshio frontal region are flowed to the shelf area although the transport is small. Most of passive larvae from the shelf area remain within the area and show the smallest transport into the WWK and the Pacific Ocean. Figure 4 shows passage rates of the particles transported to the Pacific Ocean through the B-line in Fig. 1. Over than 90% and 75% of the particles released at the Kuroshio mainstream and the Kuroshio frontal region were moved to the Pacific Ocean until 15 days, respectively, and most of them were finally transported to the Pacific Ocean during the period of experiment. Particles from the shelf area remained about 50% in the ECS until the end of experiment period. Differences of the transported particles to the Pacific Ocean according to releasing sites suggest that there is a distinct difference of transport process due to a boundary situated between the frontal region and the shelf area. Four drifters deployed in the middle ECS in 15–16 February 2001 support the model results (Fig. 5a). Over the continental shelf, a drifter went forward the Tsushima/Korea Strait, and other three at the Kuroshio frontal region and the mainstream of it flowed into the Pacific Ocean in two weeks regardless of the deployment depths. Vertically uniformed density structure surface 80 m depth in the Kuroshio frontal region is also recognized in Fig. 5b and it means that current structure has weak baroclinic condition. Flow periods of the drifters to the Tokara Strait corresponded with that of the passive larvae in the experiment. Also, the trajectories in May (Fig. 5c) showed the formation of anti-cyclonic flow southwest of Kyushu, which worked as an important factor for the larval transport in the ocean area as shown in Fig. 5d.

Because the WWK has a good feeding condition for jack mackerel larvae as mentioned in section 1, transport into the WWK is considered to be profitable for survival of jack mackerel larvae. Although passive larvae from all sites were flowed into the WWK as shown in Fig. 3, the amounts change largely in time depending on releasing sites (Fig. 6). Particles from the Kuroshio frontal region show the largest inflow into the WWK during the larval stage of jack mackerel compared with those from other sites. On the other hand those from the shelf area show the lowest inflow into this region.

Figure 7 shows survival rate of the passive larvae calculated by temperature-salinity dependent mortality during the experiment period. All passive larvae show similar survival curves but have definite survival differences according to the releasing sites. The passive larvae from the Kuroshio mainstream (A) and the shelf area (C) show an abrupt decrease in larval stage and in the metamorphosis period, respectively. Through our experiment, the mortality of the larvae from around the Kursohio region was caused by both water temperature and salinity, but that of the larvae from the shelf area was dependant mainly to water temperature as shown in Fig. 8.

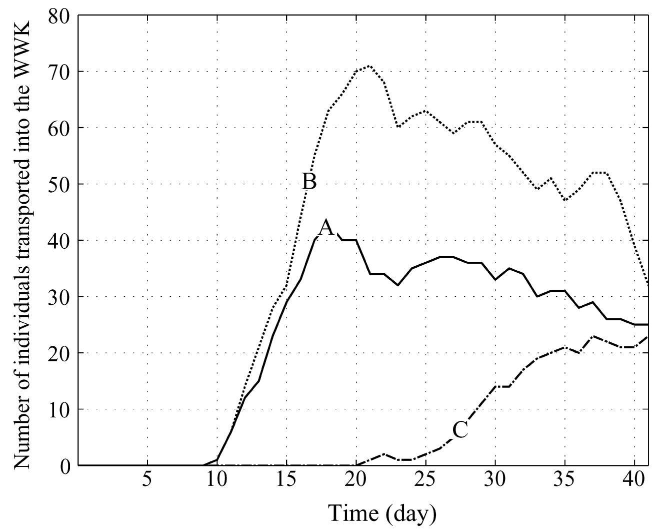

Figure 6. Number of particles transported into the waters off western Kyushu (gray rectangle area in Fig. 1) during experiment period (Case 1). Solid (A), dotted (B), and dashed-dotted (C) lines indicate numbers of particles released from (a) the mainstream of the Kuroshio, (b) the Kuroshio frontal region, and (c) the shelf area, respectively.

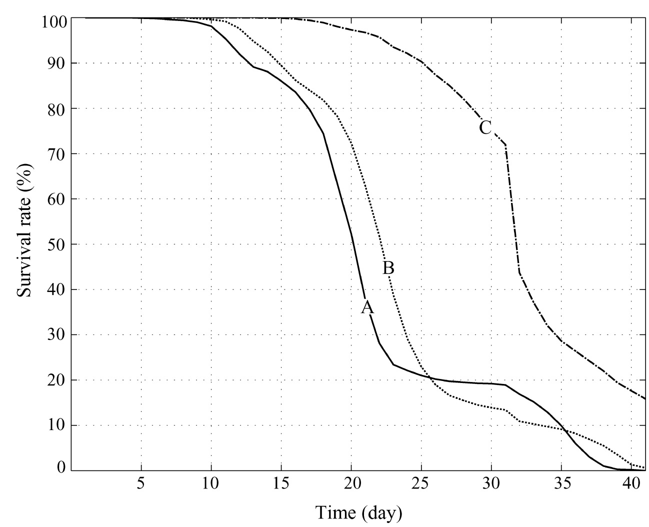

Figure 7. Survival rate (%) during experiment period calculated by advection and diffusion model considering the optimum temperature-salinity dependent mortality according to developmental stages of jack mackerel (Case 2). Solid (A), dotted (B), and dashed-dotted (C) lines indicate the survival rate of particles released at (a) the mainstream of the Kuroshio, (b) the Kuroshio frontal region, (c) the shelf area, respectively.

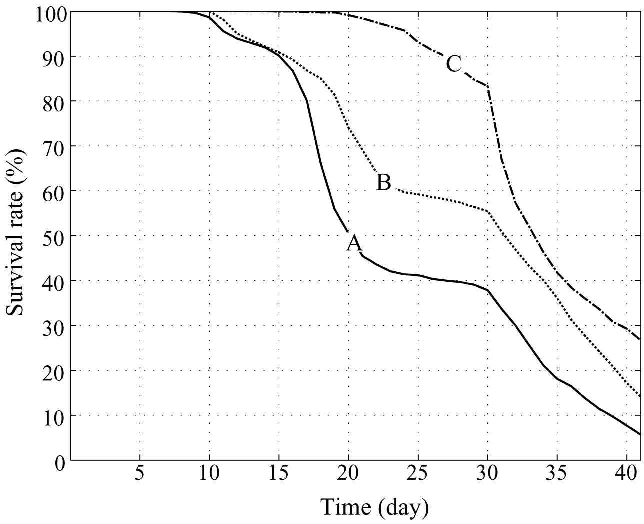

Figure 8. Survival rate (%) during experiment period calculated by advection and diffusion model considering only the optimum temperature dependent mortality according to developmental stages of jack mackerel (Case 2). Solid (A), dotted (B), and dashed-dotted (C) lines indicate the survival rate of particles released at (a) the mainstream of the Kuroshio, (b) the Kuroshio frontal region, (c) the shelf area, respectively.

Discussion and conclusion

The model results presented here clarified influences of current on the distribution of jack mackerel in early life stages in the ECS, mainly from a spawning ground pointed by Sassa and Konishi (2002). Most of passive larvae at three sites were entrained into the Kuroshio and then transported to the Pacific Ocean off southern Japan showing a disparity in the number. The larval transport dependent on the releasing sites indicate that flow differences with tens-km spatial scale by the location of the Kuroshio front cause distinguished difference of the transport processes related to survival of jack mackerel larvae. The trajectories of satellite-tracked drifters showed a similar pattern to modeled larval transport in flow path and flow speed around the Kuroshio frontal region. This correspondence supports our idea in larval transport of jack mackerel.

Mitani and Shojima (1966) calculated a natural mortality coefficient of jack mackerel with a high level of 0.994 using the known fishing effort and total mortality coefficient in the ECS. However, it includes all mortalities besides the fishing mortality. Katsuragawa and Ekau (2000) tried to estimate the mortality in the early life of rough scad (*Trachurus lathami*) and obtained 17.2% as a daily mortality rate. Rough scad has similar ecological environments to jack mackerel, that is to say, their larval food item is mainly copepod species and they are affected by warm currents such as the Gulf Stream and the Brazil Current. In our model, we obtained daily mortality rate, 2.5%, 2.48%, and 2.10% for the passive larvae from the Kuroshio mainstream, the Kuroshio frontal region and the shelf area, respectively. Compared to the mortality of rough scad, our mortalities were underestimated for jack mackerel larvae by applying only temperature-salinity dependent mortality. It was also why the present experiments did not reflect sufficiently an initial mortality in egg stage of young jack mackerel and the predation.

Transport from the northern area of the Kuroshio front allows jack mackerel larvae to remain largely in the ECS and indicates a high survival rate for them. Considering that the catches of jack mackerel in the ECS occupy about 60% of total landings in Japan, jack mackerel larvae transported to the shelf area and the WWK probably dominate its stock recruitment. In addition, since most of the larvae from the southern area of the Kuroshio front were flowed into the Pacific Ocean and their survival rates were also considerably lower, larval transport mechanism from the northern area of the Kuroshio front should be considered as one of the most probable mechanism for the sustenance of jack mackerel stock. It was also revealed through recent sampling researches that jack mackerel larvae distribute mainly around the northern area of the Kuroshio frontal region. It is also probably important the larvae from the Kuroshio frontal region to be transported into the WWK for the survival within the ECS.

Hewitt *et al*. (1985) made clear through field observations and laboratory experiments that starvation and predation were the main causes of mortality of larval jack mackerel (*Trachurus symmetricus*) off the west coast of America, although the effect of two factors differed from according to the larval growth. As mentioned above, the food condition in the ECS does not allow the starvation to be the main cause of mortality of young jack mackerel. Although the effect of the predation is an unknown quantity, environmental factors, particularly water temperature and salinity, may be fundamental factors to decide the early mortality of young jack mackerel in the ECS.

Hsueh *et al*. (1997) showed that cyclonic eddies were recognized in the mid-layer in the northern Okinawa Trough southwest of Kyushu based on ocean circulation model. Using ADCP (Acoustic Doppler Current Profiler) observations and satellite thermal images, Nakamura *et al*. (2003) also verified the generation of the cyclonic eddy in the northern Okinawa Trough. The cyclonic circulation shown by the drifters southwest of Kyushu plays a main mechanism in transporting jack mackerel larvae from the Kuroshio region into the WWK. Furthermore, total amount of copepods such as Paracalannus, Oithona, Oncaea and Corycaeus, which is the principal diet of jack mackerel larvae, is five times larger in the WWK than that in the shelf area of the ECS (Suzuki, 1965; Kozasa, 1971b; Kozasa, 1974). Thereby inflow of larvae as passively transported particles into the WWK experience good survival condition.

There were almost no larval transports to the Tsushima/Korea Strait although a few of passive larvae go forward the Tsushima/Korea Straits. According to Isobe (1999), that is why the Tsushima Warm Current has a seasonality showing the Taiwan-Tsushima Warm Current System except for the autumn, that is to say, most of volume transport of the Tsushima Warm Current comes directly from the Kuroshio region only in autumn, crossing the shelf edge of the ECS. Thus, our results taking up the transport mechanism of jack mackerel larvae in the early spring could not represent the transport into the Tsushima/Korea Straits.

In our computation of mortality, we assumed that passive larvae experienced environmental conditions in the ocean area transported by advection and diffusion. We realize that our experiments are insufficient to examine the survival of young jack mackerel. However, we believe that our approach of estimating the distribution and the survival of young jack mackerel by the current field in the ECS provides useful information for further understanding of stock fluctuation.

Acknowledgments

The authors would like to express our sincere thanks to Dr. Akihide Kasai of Graduate School of Agriculture, Kyoto University for giving useful comments in programming numerical experiments. In addition, we wish to extend sincere thanks to officers and crew of R/V Kaiyo-Maru of the Fisheries Agency of Japan, and R/V Hakuho-Maru of Ocean Research Institute, Univ. of Tokyo for their helpful assistances in the field observations.

References

Asami, T. (1974) Distribution of fish eggs and larvae in the southern Japan and its significance of source of the supply of fish stocks. Bull. Japan Soc. Fish. Oceanogr. **25**, 176–192. (in Japanese with English abstract)

Frank, K. T., J. E. Carscadden and W. C. Legget (1993) Causes of spatio-temporal variation in the patchiness of larval fish distributions: differential mortality of behaviour? Fish. Oceanogr., **2**, 114–123.

Hattori, S. (1964) Studies on fish larvae in the Kuroshio and adjacent waters. Bull. Tokai Reg. Fish. Res. Lab. **40**, 1–113. (in Japanese with English abstract)

Hotta, H. and H. Mako (1970) Studies on the structure of the population of jack mackerel, *Trachurus japonicus*, in the western seas of Japan-I. Analysis from the variation of catch and size composition. Bull. Seikai Reg. Fish. Res. Lab. **38**, 87–100. (in Japanese with English abstract)

Houde, E. D. (1989) Comparative growth, mortality, and energetics of marine fish larvae: temperature and implied latitude effects. Fish. Bull. U.S. **87**, 471–495.

Hsueh, Y., J. R. Schultz and W. R. Holland (1997) The Kuroshio flow-through in the East China Sea: A numerical model. Prog. Oceanog. **39**, 79–108.

Hewitt, R. P., G. H. Theilacker and N. C. H. Lo (1985) Causes of mortality in young jack mackerel. Mar. Ecol. Prog. Ser. **26**, 1–10.

Isobe, A. (1999) On the origin of the Tsushima Warm Current and its seasonality. Continental Shelf Res. **19**, 117–133.

Katsuragawa, M. and W. Ekau (2000) Distribution, growth and mortality of young rough scad, *Trachurus lathami*, in the south-eastern Brazilian Bight. J. Appl.Ichthyol. **19**, 21–28.

Kimura, S., K. Doos and A. C. Coward (1999) Numerical simulation to resolve the issue of downstream migration of the Japanese eel. Mar. Ecol. Prog. Ser. **186**, 303–306.

Kozasa, E. (1971a) An observation on the drift of larvae of jack mackerel in the East China Sea. Bull. Seikai Reg. Fish. Res. Lab. **39**, 1–14. (in Japanese with English abstract)

Kozasa, E. (1971b) Feeding of the larvae of jack mackerel, *Trachurus japonicus* -I. Bull. Seikai Reg. Fish. Res. Lab. **38**, 79–86 (in Japanese with English abstract).

Kozasa, E. (1974) Feeding of the larvae of jack mackerel, *Trachurus japonicus*, II. Selectivity of food. Bull. Seikai Reg. Fish. Res. Lab. **43**, 15–21 (in Japanese with English abstract).

McGurk, M. D. (1987) The spatial patchiness of Pacific herring larvae. Env. Biol. Fish. **20**, 81–89.

Mitani, F. and E. Shojima (1966) Studies on the resources of the jack mackerel, *Trachurus japonicus* (THMMINCK ET SCHLEGEL), in the East China Sea-III, -Natural and fishing mortality coefficients. Bull. Japan Soc. Scientific Fish. **32**, 57–63. (in Japanese with English abstract)

Morse, W. W. (1989) Catchability, growth, and mortality of larval fishes. Fish. Bull. U.S. **87**, 417–446.

Nakamura, H., H. Ichikawa, A. Nishina and H.-J. Lie (2003) Kuroshio path meander between the continental slope and the Tokara Strait in the East China Sea. J. Geophys. Res. 108(C11); 3360, doi:10.1029/2002JC001450.

Nakata, H. (1996) Coastal fronts and eddies: their implications for egg and larval transport and survival process. In: Survival strategies in early life stages of marine resources. Watanabe Y., Yamashita Y., Oozeki Y. (eds.) AA Balkema Publishers, Brookfield, VT, 227–244.

Nitani, H. (1972): Beginning of the Kuroshio. In Kuroshio, its physical aspects, H. Stommel and K. Yoshida (eds.), University of Tokyo Press, Tokyo, 129–163.

Ochiai, A., K. Mutsutani and S. Umeda (1982) Development of eggs, larvae and juveniles of jack mackerel, *Trachurus japonicus*. Japanese J. of Ichtyology **29**, 86–92. (in Japanese with English abstract)

Olivar, M. P. (1990) Spatial patterns of ichthyoplankton distribution in relation to hydrographic features in the Northern Benguela region. Mar. Biol. **106**, 39–48.

Sassa, C. and Y. Konishi (2002) Distribution and transport of jack mackerel larvae and juveniles in the East China Sea. Kaiyo Monthly. **31**, 92–98. (in Japanese)

Saunders, P. M., A. C. Coward and B. A. de Cuevas (1999) Circulation of the Pacific Ocean seen in a global ocean model: Ocean Circulation and Climate Advanced Modelling project (OCCAM). J. Geophys. Res. **104(C8)**, 18281–18299.

Seikai Regional Fisheries Research Laboratory (1986) Fishes of

the East China Sea and the Yellow Sea. 1986, 170–173 (in Japanese).
Siefridt, L. and B. Barnier (1993) Banque de Donnees AVISO Vent/flux: Climatologie des Analyses de Surface du CEP-MMT. Report No. 91 1430 025, 43.
Stabeno, P. J., J. D. Schumacher, K. M. Bailey, R. D. Brodeur and E. D. Cokelet (1996) Observed patches of walleye Pollock eggs and larvae in Shelikof Strait, Alaska: their characteristics, formation and persistence. Fish. Oceanogr. **5(suppl. 1)**, 81–91.
Suzuki, T. (1965) Ecological studies on the jack mackerel, *Trachurus japonicus* (TEMMINCK et SCHLEGEL)—I. On the feeding habits. Bull. Jap. Sea Reg. Fish. Res. Lab. **14**, 19–29 (In Japanese with English abstract).
Townsend, D. W. and N. R. Pettigrew (1996) The role of frontal currents in larval fish transport on Georges Bank. Deep-Sea Res. II Top. Stud. Oceangr. **43**, 1773–1792
Webb, D. J., B. A. de Cuevas and A. C. Coward (1998) The first main run of the OCCAM global ocean model, internal report of James Rennel Div., Southampton Oceanogr. Cent., Southampton, England, U.K. 50.
Yamada, U., M. Tagawa, S. Kishida and K. Honjo (1986) *Trachurus japonicus*. In Fishes of the East China Sea and the Yellow Sea. Okamura O. (ed.) Nihon Shiko Print. Co. Ltd., Japan, 170–171.
Yanagi, T., T. Shimizu and H.-J. Lie (1998) Detailed structure of the Kuroshio frontal eddy along the shelf edge of the East China Sea. Continental Shelf Res. **18**, 1039–1056.

東シナ海における数値実験によるマアジ(*Trachurus japonicus*)仔魚の輸送

金　熙容[1†]，木村伸吾[1]，杉本隆成[2]

東シナ海におけるマアジ仔魚の輸送過程に対する黒潮前線の影響を調べるため，三次元の移流・拡散モデルを用いた粒子追跡実験と衛星追跡ブイ実験を行った．陸棚域から輸送されたマアジ仔魚は東シナ海に多く残り，適水温や適塩分帯による死亡を与えた実験によって最も生残率が高いことが示された．そして，東シナ海において黒潮前線はマアジ仔魚の生残と輸送メカニズムの境界線として重要な役割を果たしていることが認められた．さらに，黒潮前線や陸棚域に投入した衛星ブイの追跡経路は移流・拡散モデルで得られた投入地点による輸送過程の違いを明らかにした．一方，低い生残率を示した黒潮前線域の仔魚が，餌環境が良い九州西方への輸送には九州南西沖で前線擾乱によって形成される反時計回りの循環流が重要なメカニズムであることが示唆された．従って，東シナ海において黒潮前線域の仔魚の生残には九州西方に輸送されることが重要であると考えられる．さらに，適水温・適塩分による死亡実験により，黒潮前線より数十km離れた陸棚域がマアジの仔魚の生残に有利な輸送プロセスを持たせることが示唆された．

[1] 東京大学海洋研究所，〒164–8639　東京都中野区南台1–15–1
[2] 東海大学海洋研究所，〒424–8610　静岡県静岡市清水折戸3–20–1
[†] kimhy@ori.u-tokyo.ac.jp