Short Note

Larval transport of the amphidromous goby *Sicyopterus japonicus* by the Kuroshio Current

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Abstract — Oceanic larval transport of an amphidromous goby, *Sicyopterus japonicus*, was simulated using a Lagrangian modeling approach to validate the hypothesis that the Kuroshio Current could transport their larvae from Taiwan to northern Japan, which is the geographic range of this species. Simulated particles released at a 50 m depth from the off southernmost part of Taiwan reached Japan from southern Kyushu to northern Japan after 180 days. In contrast, many particles released at 120 m were trapped in eddies in the northwestern part of the subtropical gyre for 90 to 120 days and never reached the southern Japanese coast. These simulations showed that transport at a 50 m depth would enable many larvae to distribute over their entire species range after being transported away from Taiwan. The otolith growth increments of 30 larvae from Wakayama in April to August 2007 showed their oceanic larval duration ranged from 185 to 270 days, suggesting they have sufficient time as larvae for their transport from Taiwan to northern Japan. These results supported the hypothesis of larval transport described above and suggested a possibility that the Kuroshio would play an important role to maintain the apparent lack of population structure of *S. japonicus* from Taiwan to northern Japan.

Key words: *Sicyopterus japonicus*, transport, larval duration, Kuroshio, geographic distribution, larva, otolith, oceanic migration, diadromy, Lagrangian modeling

Introduction

Amphidromy is a type of diadromy that includes migrations between freshwater and the sea, which is exhibited by some taxa of fishes (McDowall, 1988). *Sicyopterus japonicus* (Teleostei: Gobiidae: Sicydiinae) is distributed along the strong Kuroshio Current from Taiwan to Fukushima in the northern part of Japan (Akihito et al. 2000, Iguchi et al. 2005) (Fig. 1). This species is known to be an amphidromous goby that spawns in freshwater and their newly hatched larvae migrate downstream to the sea where they have an oceanic larval life before migrating back to the rivers to grow and reproduce (Dôtu and Mito 1955, Iida et al. 2009). They have a unique ecology of "rock climbing" using their sucker-like pelvic fin and mouth (Fukui 1979), but their life history has been almost unknown.

There is no report of river resident or landlocked types of *S. japonicus* (Iida et al. 2009), while other amphidromous fishes such as gobies *Rhinogobius* spp., ayu *Plecoglossus altivelis*, and galaxids *Galaxias* spp. have landlocked population or river residents in the same genus that do not migrate to the sea (Iida et al. 2009). In addition, newly hatched larvae of *S. japonicus* do not develop in freshwater despite that they hatch in freshwater (Iida et al. 2010a). Those reports indicate that all larvae of this species can not stay in the freshwater habitat and have to migrate down to the sea and stay in the ocean during their larval life.

Preliminary study of oceanic larval duration (OLD, here equivalent to age at recruitment) by otolith analysis of *S.*
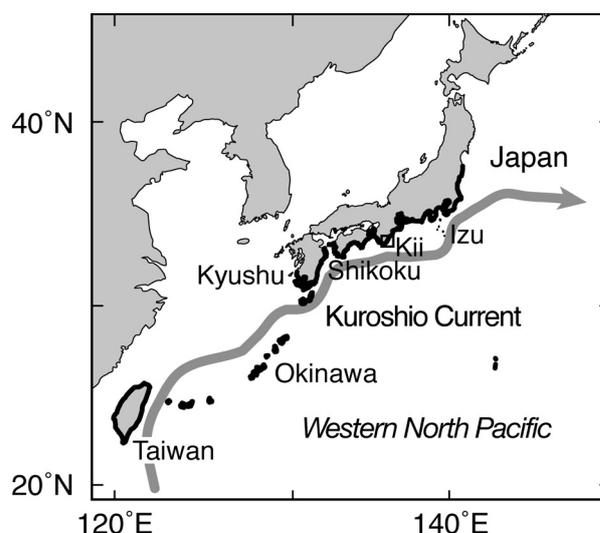
Fig. 1. Geographic distribution of *Sicyopterus japonicus* (thick black lines). Box indicates sampling site on the Kii Peninsula (the Ota River, Wakayama) and the grey line shows the Kuroshio Current.

japonicus showed that they have long OLD of 173–253 days in Wakayama, Japan (Iida et al. 2008), although these aging data were obtained on a limited number of specimens collected on a single day of recruitment and did not cover the whole recruitment season from spring to summer. The OLD of *S. japonicus* has also been reported from Taiwan, which showed durations of 130 to 198 days (Shen and Tzeng 2008). It is obvious that their oceanic larval life is obligatory and their long OLD would enable them to disperse widely. In addition, their geographic distribution extends exactly along the Kuroshio Current from southern Taiwan to northern Japan, so the Kuroshio may have some influence on the geographic range of the species. Further, no population structure has been observed in studies covering the species range (Ju 2001, Watanabe et al. 2006). These reports lead us to a hypothesis that the Kuroshio Current would be able to transport *S. japonicus* larvae from Taiwan to northern Japan.

To test this hypothesis, numerical simulations were performed using particle tracking Lagrangian modeling, and OLD was estimated using larvae that were collected throughout their recruitment season from April to August in Wakayama, Japan. Combining these results, we estimated the effect of the Kuroshio Current on the geographic distribution of *S. japonicus*.

Materials and Methods

Circulation model and particle tracking

The Lagrangian study of *S. japonicus* larval transport was made based on a high-resolution circulation field model developed by the Frontier Research System for Global Change, of the Japan Agency for Marine-Earth Science and Technology (http://www.jamstec.go.jp/esc/research/AtmOcn/ofes/index.ja.html). The high resolution ocean model for the earth simulator (OFES) is based on the Modular Ocean Model (MOM3), and the model domain covers a near-global region extending from 75°S to 75°N, but excluding the Arctic Ocean, with horizontal grid spacing of 0.1°. There are 54 vertical levels, with the distance among levels varying from 5 m at the surface to 330 m at the maximum depth of 6065 m. Detailed descriptions of the basic settings of the model are given by Masumoto et al. (2004) and Sasaki et al. (2008).

Southern Taiwan is the southern limit of the species range for *S. japonicus* (Biodiversity Research Museum, Academia Sinica, Taiwan, GBIF Data Portal, www.gbif.net, 2009-12-15). A few specimens of larvae that appear to be *S. japonicus* were collected at a 50 m depth in the open ocean near the Izu Islands by layered sampling from July to October 2006, 2007 and 2008 (H. Maeda, personal communication). A few other specimens were collected by otter trawl sampling in the center of Tosa Bay, Japan in April, May, July and August from 1997 to 2007 and the deepest depth at the

sampling was at 120 m depth (Watanabe et al. submitted manuscript). Based on this information, we released 1000 particles from off southern Taiwan (22.5°N, 122°E) at 50 and 120 m depths. Since the mode of the estimated hatch date in Taiwan area is around late October (Shen and Tzeng 2008), and the OLD of the species was reported to be 173 to 253 days (Iida et al. 2008), particles were released at a model date of 1 November and were tracked for 180 days as passive tracers.

Velocity data from the OFES were applied to Lagrangian particle tracking in order to simulate the transport of larvae of *S. japonicus*. In this study, the vertical distribution was fixed at 50 and 120 m throughout the simulation. Particles were advected passively for 180 days, because *S. japonicus* larvae would not be able to swim well. Trajectories of 1000 passive particles were released forward using a 3D advection-diffusion scheme. The position $[Xp(t+\delta t)]$ of a particle at time-step $t+\delta t$ is given by $Xp(t+\delta t)=[Xp(t)+\mu(t)\delta t]+\delta l_{diff}$ and represents the position of the particle at the previous time-step $\delta t=1$ h for the scheme. The velocity u (xp, yp, zp), where $zp=50$ and 120 m depth, which was weighted by the distance from each grid point for four velocities in a grid field, was used to calculate the advection of particles. The term δl_{diff} is a diffusion parameter added to account for the change in the position of each particle by advection. For diffusion of particles, $1\times10^2\,\mathrm{m^2\,s^{-1}}$ was adopted as the horizontal eddy diffusivity.

Otolith analysis

Iida et al. (2008) previously reported that the mean OLD of *S. japonicus* was 208 days, but they only used specimens collected on a single day of recruitment. To obtain a representative OLD value for the whole recruitment season, we estimated OLD from specimens collected throughout their recruitment season from April to August in the present study. Newly recruited larvae of *Sicyopterus japonicus* (ca. 30 mm in total length) were collected by a set net (7.8 m wide×0.9 m high, with 1.5 mm mesh) in the estuary of the Ota River, Wakayama, Japan from April to August 2007. After collection, the specimens were frozen. Thirty specimens were randomly selected from among different collection periods and were used for otolith analysis. Sagittal otoliths were extracted from each specimen and mounted on glass slides with euparal (Chroma-Gesellschaft Schmid GmbH & Co.), and were examined at 50–500× under an optical microscope and photographed using a digital camera (Nikon, digital camera DXM1200F). As this species has daily periodicity in the deposition of otolith growth increments (Iida et al. 2010b), the OLD was estimated by counting the otolith increments from the core to the edge of the otoliths.
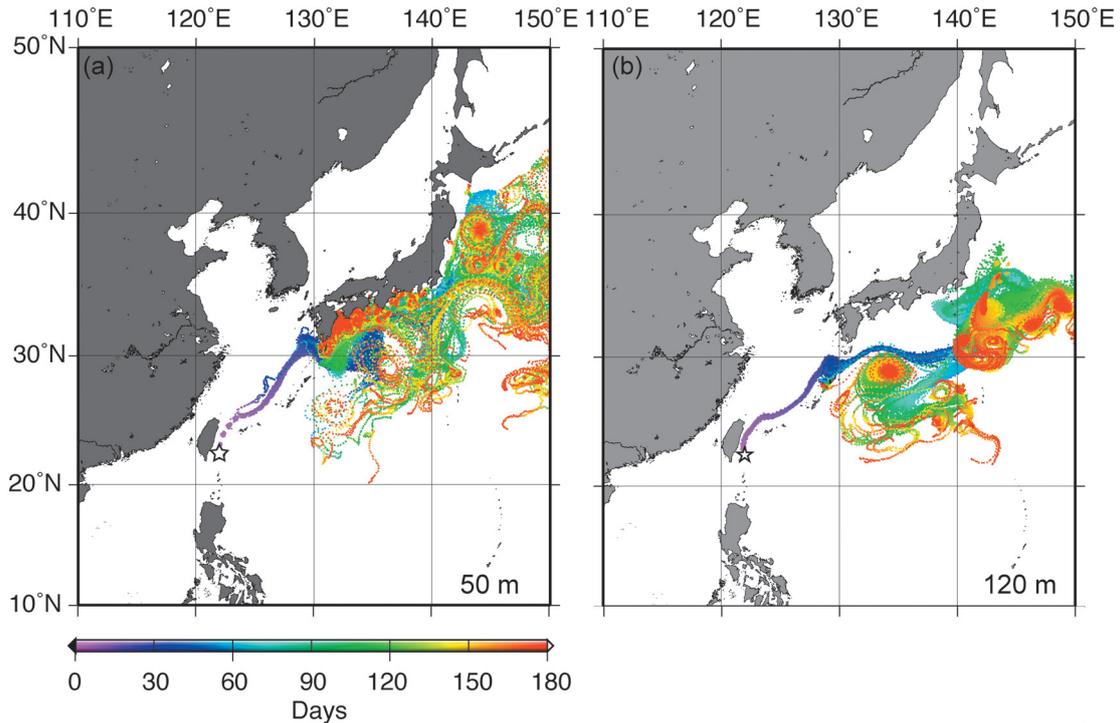
Fig. 2. Particle trajectories at 50 m (a) and 120 m (b) depths calculated by an advection and diffusion model. The trajectories are colored according to the time after release at the stars (22.5°N, 122°E in both panels).

Results

The larval trajectories were highly influenced by the Kuroshio Current based on the results of numerical particle tracking simulations. Most particles were transported from off southeastern Taiwan to the southern part of Kyushu Island by the Kuroshio Current. At the 50 m depth, after being transported to Kyushu Island, they reached the coast from Kyushu to Honshu Island about 90 to 150 days after being released (Fig. 2a). Some particles were transported further north and reached the Tohoku area 60 days later. Other particles were brought into eddies east of the Okinawa Islands and off the southern Kii Peninsula. At the 120 m depth however, many particles were transported eastward and were trapped in the eddies off the Kii Peninsula from 90 to 120 days after release and never reached the southern Japanese coasts of Kyushu, Shikoku Islands and Kii Peninsula within the 180 days of the study (Fig. 2b). Some particles were transported more eastward and many of them were also trapped in eddies.

The OLD of *S. japonicus* estimated by otolith daily increments showed a larger variation in comparison with the former study using specimens collected on just one day (Iida et al. 2008). The OLD of newly recruited larvae to the estuary of the Ota River from April to August 2007 ranged from 185 to 270 days (mean±SD, 229±23) (Fig. 3).
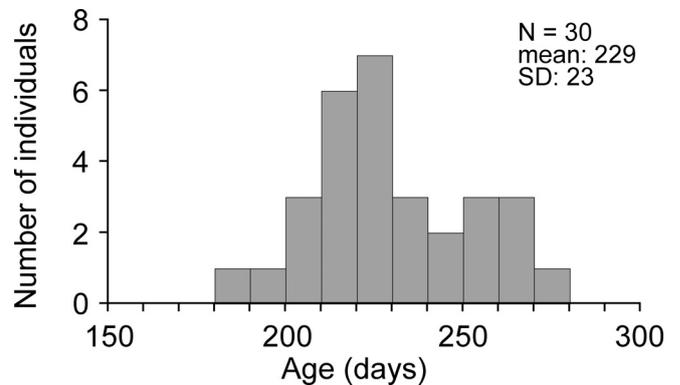
Fig. 3. Frequency distribution of oceanic larval duration (age in days) of newly recruited larvae of *Sicyopterus japonicus* collected at the estuary of the Ota River from April to August 2007.

Discussion

The present study is the first to examine the larval transportation process of amphidromous goby larvae using numerical modeling. The long OLD of *S. japonicus* would enable them to be transported from Taiwan to the northern part of their species geographic range. However, the processes of transport were greatly different at the two water depth layers. There are eddies in the northwestern part of the subtropical gyre to the east of the Ryukyu Islands and southern Japan, and many particles were trapped by those eddies especially at the 120 m depth. Although the larvae of *S.*

japonicus were collected from an area that was 120 m depth in Tosa bay (Watanabe et al. submitted manuscript), that sampling was conducted with an open mouth trawl and so the larvae might have been caught in shallower layers than 120 m. At a 50 m depth near the Izu Islands, some larvae resembling *S. japonicus* were collected, though the number of specimens were only a few (H. Maeda, personal communication). If larvae could reach the coastal waters after their downstream migration from the middle reaches of the river and would stay at a 50 m depth in the ocean, the transport modeling clearly shows that they could be transported from Taiwan to their northern distribution area such as Kyushu and Honshu Islands.

The OLD data of *S. japonicus* in this study (185–270 days) appear to give larvae enough time to reach even Fukushima, the northernmost area of their range. The mean OLD estimated by this study (229 days) was longer than the 180 days that was used for this simulation estimated from larvae collected on 30 April 2005. This difference of OLD might be explained by the larval durations sometimes being longer during different months or the retention time of the larvae in the coastal waters such as in a bay or surf zone before or after they may have been transported by the Kuroshio Current.

The present study used OFES oceanographic data and particle tracking modeling to estimate the larval transport of *S. japonicus*. Another study conducted in the same area using another type of modeling, The Hamburg Ocean Primitive Equation Model, HOPE, to estimate egg and larval transport of *Trachurus japonicus*, also showed that eggs and larvae hatched near Taiwan waters could be transported to Kyushu Island by the Kuroshio Current (Kasai et al. 2008). *Trachurus japonicus* is a marine fish that spawns in coastal waters and their ecology would be different with that of amphidromous *S. japonicus*, but the process of transport of *T. japonicus* may be similar to that of *S. japonicus*. Since both of the two modeling studies showed similar estimations of transport, the hypothesis that *S. japonicus* larvae could be transported northward would be reasonable.

Watanabe et al. (2006) suggested that *S. japonicus* has a single population structure using the specimens from Okinawa, Kochi, Wakayama and Shizuoka in an analysis of their control region of mitochondrial DNA (mtDNA). Another genetic study using specimens from Taiwan and Amami Island that analyzed the mtDNA D-loop and 16s rRNA also showed that there was no difference between those two areas (Ju 2001). By combining these two studies, this species may have only one population within its species range. If there were any spatial genetic heterogeneity in *S. japonicus*, the genetic differences among localities would be expected. However, there were no significant differences within their species range. Though those results could not indicate whether mixing of recruits among areas occurred every year

or not, that type of population structure indicates that at least not all the recruits return to their natal river after their long larval duration in the ocean. Their size at hatching is as small as 1.5 mm and they hatch in undeveloped condition such as with an unopened mouth and unpigmented eyes (Dôtu and Mito 1955, Iida et al. 2010a), so they would be transported passively during at least part of their early life stage.

The spawning season of *S. japonicus* has been reported to be in summer (July-September) in Wakayama (Iida et al. 2009) and about one third of the newly recruited post larvae collected there were estimated to hatch during the spawning season in Wakayama by otolith analysis (Iida unpublished data). Assuming that one third of the larvae were hatched in the same river and the others were from different areas where this species has a longer spawning season, the percentage of return of *S. japonicus* larvae to their natal river would be roughly one third from this assumption. Collection of oceanic life stage larvae and an understanding of the mechanisms of retention and transport of larvae are needed to understand their natal homing and larval transportation.

The amphidromous ayu larvae have been reported to stay in the surf zone and surface layer of coastal waters through their oceanic life stage (Tsukamoto 1988), while *S. japonicus* appear to use the open ocean rather than coastal areas and estuaries based on the lack of their collection in surf zone in winter (Iida unpublished data). Though *S. japonicus* larvae collected in the surf zone near the river mouth in Taiwan, all of the specimens were just before recruiting to the river (Shen and Tzeng 2008). The amphidromous ayu has a land-locked type that is a non-migrant type spending their whole life history in freshwater. On the other hand, there is no report of non-migrant types of *S. japonicus*. Those differences of larval distribution areas and presence and absence of non-migrant types between the two types of fishes might be related to differences in amphidromy in terms of how they use the ocean for their life history. *Sicyopterus japonicus* may have a necessity of spending time in the ocean during their early life history stages even though ayu larvae have no necessity for that.

Although this study clearly shows that larvae can be transported from south to north throughout their species range, if too many larvae drift offshore and are then passively transported northward by the Kuroshio Current, the loss of larvae throughout whole distribution area would be extremely high. Therefore, they likely have some mechanism of retention near coastal areas during their larval life. Newly hatched *S. japonicus* larvae have greater specific gravity than that of seawater (Iida et al. 2010a), so this might affect their retention mechanism during their larval stage.

Ocean currents have seasonal and annual changes and would affect the transport of larvae to offshore waters. The larvae of catadromous eels called leptocephali have been reported to have a diurnal vertical migration between about a

150 m depth in the day and shallower than 100 m at night in the open ocean (Castonguay and McCleave 1987, Otake et al. 1998). Though the depth of the larvae was fixed at 50 and 120 m in the present study, additional data at different depths or information on diurnal migration of goby larvae could give a more accurate simulation result. Biological data such as larval behavior or mortality also would be useful to estimate their transport in the ocean (Werner et al. 2007), and more research is needed to determine the marine habitats used by the larvae of this species. These are all subjects of future research to better understand the ecology of *S. japonicus* in the ocean.

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