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Numerical studies focusing on the early life stage of Pacific bluefin tuna (*Thunnus orientalis*)

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Introduction

Compared to other tuna species, the Pacific bluefin tuna (PBF), *Thunnus orientalis,* is known to have the most restricted spawning grounds near the Nansei Islands and the Sea of Japan, which also serve as nursery grounds of the larvae and juveniles of this species. This numerical study on the early life stages of PBF has two objectives; one is to estimate the spawning grounds of this species based on larval samples and ocean environmental characteristics, and the other is to estimate where the juveniles cross the Kuroshio Current from offshore areas as they move to coastal areas.

Methods

To simulate the transport process of individual larvae and the swimming process of juveniles, the following equations are applied to individual PBFs at discrete time intervals starting with certain initial conditions:

$$d\overrightarrow{X}/dt = \vec{v}_{adv} + \vec{v}_{diff} + \vec{v}_{swim},$$

$$\vec{v}_{diff} = RC_{horcon}\sqrt{u_x^2 + v_y^2 + u_y v_x},$$

$$\vec{v}_{swim} = rL\vec{\nabla}H_c(x,y)/|\vec{\nabla}H_c(x,y)|,$$

$$H_c(x,y) = \log(C(x,y)/C_1)/\log(C_2/C_1),\ C_1 \le C \le C_2,$$

where v_{adv} is the ocean current velocity obtained from an ocean general circulation model, FRA-JCOPE, v_{diff} is a random velocity due to oceanic horizontal diffusion expressed by the Smagorinsky scheme, R is a random number between -1 and 1 selected at each time step for each individual particle, and C_{horcon} is a constant in the Smagorinsky scheme, and is assumed to be 0.05. v_{swim} is the swimming velocity of juveniles at 20 days after hatching (DAH) and older. Magnitude of v_{swim} is proportional to the body length, L, with ratio, r = 2.0, 2.5, 3.0 s^{-1} for 20-30, 30-40, 40-55 DAH, respectively (Sabate *et al*., 2010; Fukuda *et al*., 2010). Juveniles were assumed to swim along the gradient of the habitat suitability index (HSI), H_c. High chlorophyll concentrations, C, were assumed to be preferable for juvenile development. The minimum and maximum chlorophyll concentrations were taken as C_1 = 0.07 mg/m^3 and C_2 = 0.22 mg/m^3, respectively, based on field observations (Segawa and Tanabe, 2010).

Estimating the location of the spawning ground of Pacific bluefin tuna

Larvae collected southeast of the Nansei Islands in May 2004 (Tanaka *et al*., 2006) were traced back to their spawning grounds by estimating their age using a linear regression of their standard length to the age in days (Satoh, 2010), plus one day for hatching. Then, at each sample location of total 37 points, 10000 particles with no swimming ability ($v_{swim} \equiv 0$) were advected horizontally backward in time ($dt < 0$) at a depth of 10 m with random walking ($v_{diff} \neq 0$). Using a 10-minute grid with more than 100 particles as the spawning ground, the spawning grounds were estimated within two degrees of the sample points to the southeast of the Nansei Islands

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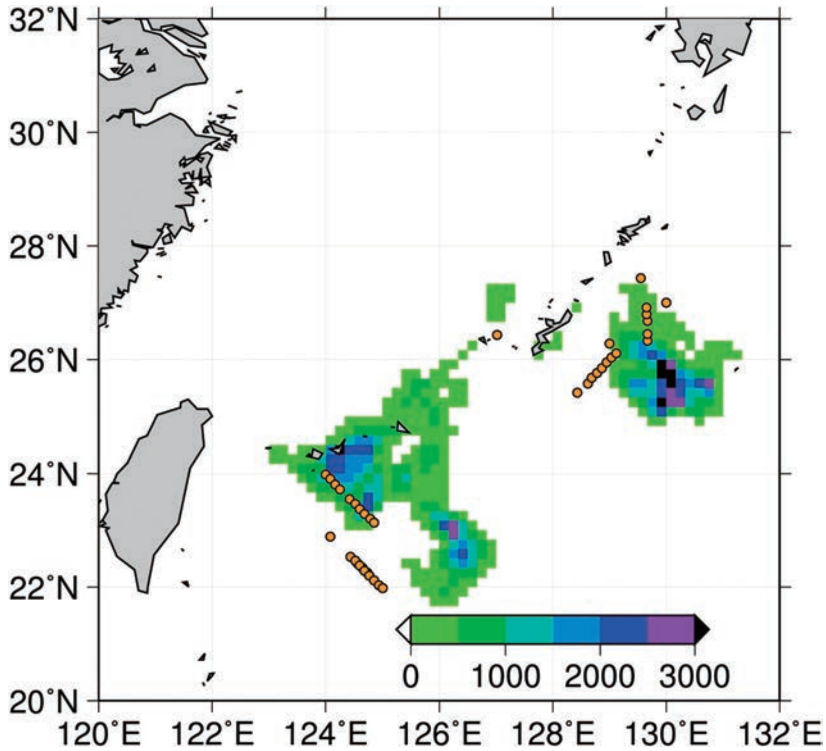

Fig. 1. Spawning grounds estimated using a backward calculation from larval sampling locations recorded on the *Shunyo-maru* cruise in 2007.

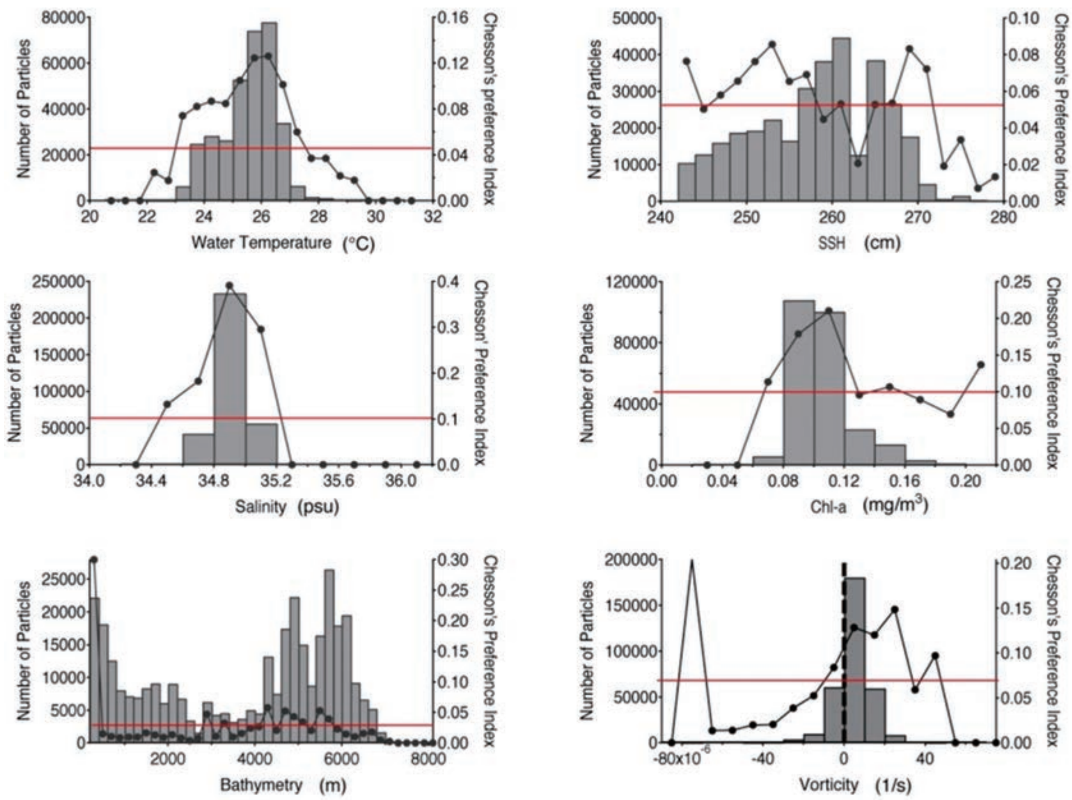

Fig. 2. Histogram and Chesson's index values (Chesson, 1978) for oceanographic parameters within the estimated spawning ground: temperature (top left), salinity (middle left), bathymetry (bottom left), sea surface height (right top), chlorophyll (middle right), relative vorticity (bottom right). Bar and line graphs denote histograms and Chesson's index values, respectively.

(Fig. 1). This is consistent with Kitagawa *et al.* (2010) which suggests that the spawning ground of PBF is restricted to east or south of Taiwan because of optimal thermal conditions for growth and survival.

Figure 2, a simple histogram and Chesson's preference index (Chesson, 1978), shows the existence of favorable oceanic conditions (e.g., temperature, T, vorticity, ζ, salinity, S and chlorophyll concentration, C) for the estimated spawning ground. Using a generalized linear model, suitable values were statistically estimated as T = 25.4℃, $\zeta = 1.02 \times 10^{-5}$ s^{-1}, S = 34.98 psu, C = 0.41 mg/m^3. The temperature of 25.4℃ considered optimal for egg hatching, and the positive vorticity suggests that the spawning ground is likely to be in the cyclonic eddies.

Simulation of Pacific bluefin tuna juveniles crossing the Kuroshio Current

The likelihood and location of juveniles crossing the Kuroshio current around the Nansei Islands was simulated. It is known that such crosses occur because juveniles have been caught around the Gotoh Islands and in Tosa Bay, which are both oceanographically separated from the Nansei Islands by the Kuroshio current. 1500 particles of 20 DAH were released at depths of 0, 10, 20, 30, 40 m ($v_{swim} \neq 0$, $v_{diff} \equiv 0$) starting from near the Nansei Islands outside the Kuroshio Current (Fig. 3) from July 1 to 31 in each of the years 2002-2007 and 2009. Except for 2007 and 2009, 0.1-8.3 % of the 7500 particles successfully crossed the Kuroshio Current to reach western Kyushu (Fig. 3), while 0.1-5.2 % reached Tosa Bay continuously during the year (Table 1). These findings suggested that juveniles were able to

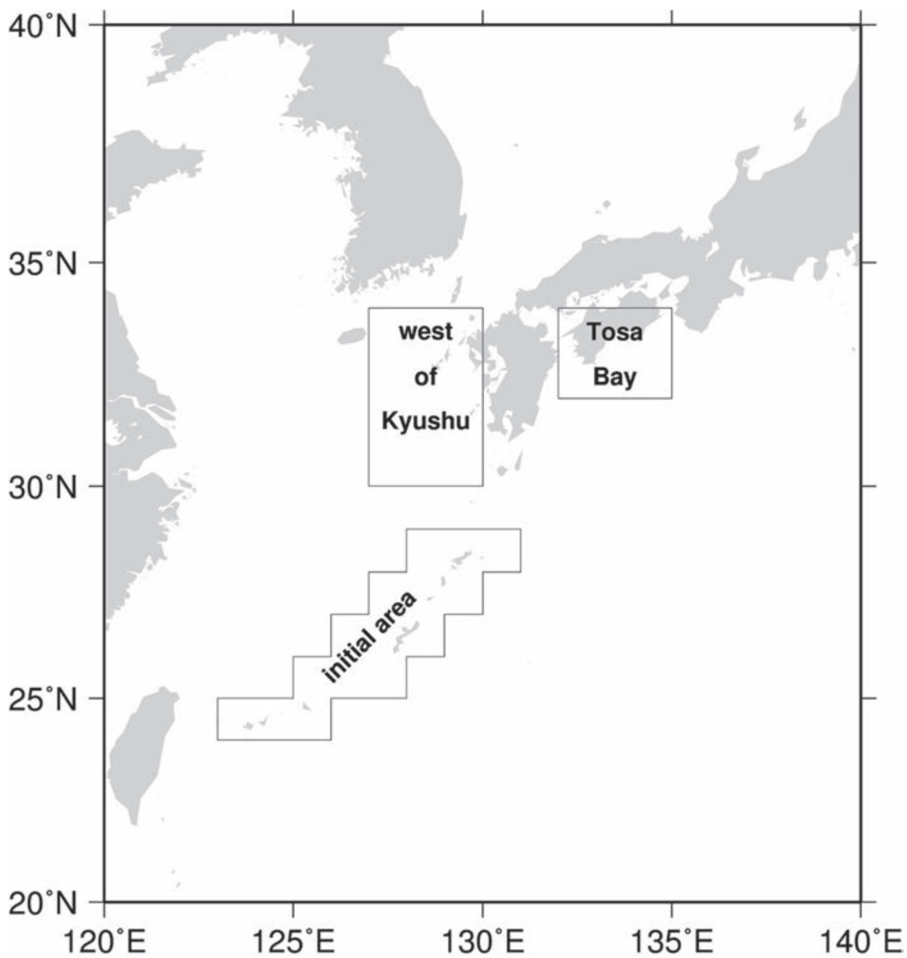

Fig. 3. Map showing initial particle release area, west of Kyushu and Tosa Bay.

	west of Kyushu (%)	Tosa Bay (%)
2002	1.5	5.2
2003	0.1	0.1
2004	0.4	2.8
2005	0.9	2.2
2006	8.3	1.5
2007	0.0	0.1
2009	0.0	0.1
average	1.9	1.7

Table 1. Annual proportion of particles reaching west of Kyushu and Tosa Bay to total particle number (1500 particles).

cross the Kuroshio Current before they were at 50 DAH, i.e., BL <140 mm (Miyashita, 2001). Thus, the model juveniles crossed the Kuroshio Current to the west of Kyushu where large curves in the tracks of the particles are apparent (see. Fig. 4). Preliminary results of recent field surveys by R/V Shunyo-Maru in 2011 focusing on the capture of PBF juveniles support these simulations, suggesting that PBF juveniles caught around the Gotoh Islands moved west of Kyushu from the Nansei Islands.

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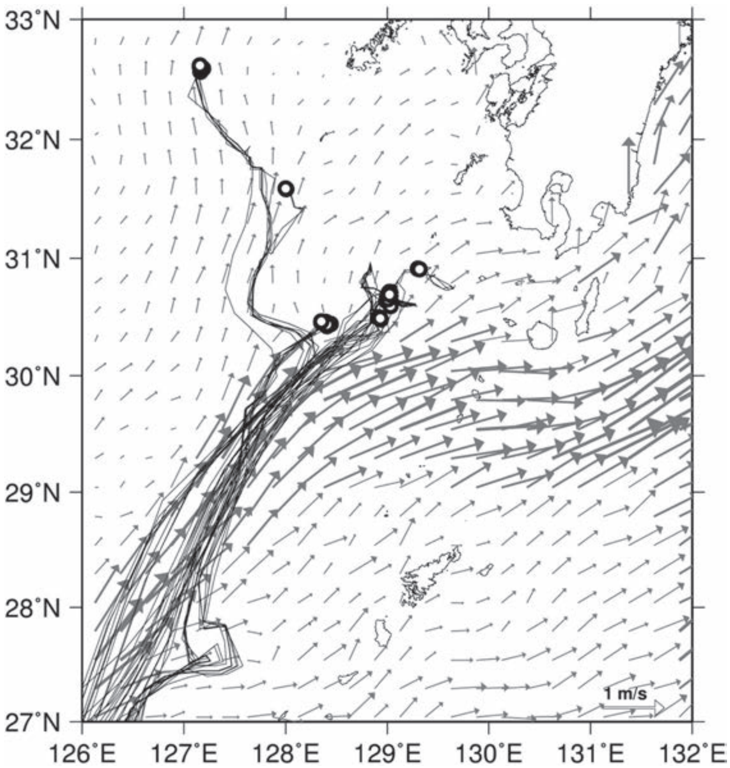

Fig. 4. Particle tracks crossing the Kuroshio Current from their release point near the Nansei Islands to west of Kyushu. Circles denote the position of the particles on 31 July 2002, black lines denote the tracks of the particles, and gray arrows denote surface velocity vectors from FRA-JCOPE. Large arrows indicate the Kuroshio Current.

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