Effect of El Niño on migration and larval transport of the Japanese eel, *Anguilla japonica*

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ABSTRACT
To clarify the effect of El Niño events on the migration and transport of *Anguilla japonica* leptocephali in the Pacific, the migration difference of the eel larvae both in El Niño years and in non-El Niño years were compared quantitatively through numerical particle tracking model. There are two important ocean systems for affecting the migration of the eel. One is the meridional displacement of salinity front which is quite important for deciding a spawning point of the adult eels in the NEC region. The second is the position of the NEC bifurcation dividing the mass transport to the Kuroshio and the Mindanao Current in the western north-Pacific. In El Niño years, the meridional position of the NEC bifurcation was northernmost and the salinity front was southernmost while the NEC bifurcation occurred at its southernmost position and the salinity front moved to the north near average location (15 °N ) in non- El Niño years. According to the change of the ocean systems, in El Niño years, only 10 % of the eel larvae migrated into the Kuroshio while the rate in non-El Niño years was greater than 38 %. These quantitative results correspond well to statistic catch data of the glass eel around Japanese Islands. It is therefore suggested that the variation of ocean system by the interannual climatic change determine the recruitment of the Japanese eel in East Asia.

Keywords: Japanese eel, El Niño, salinity front, NEC bifurcation, larval migration
INTRODUCTION

Recent collection of 2 day-old pre-leptocephali of Japanese eel (*Anguilla japonica*) in the Pacific Ocean around the West Mariana Ridge gives us a clue for the further understanding of long-term and long-range migration of this species (Tsukamoto, 2006).

For the migration of the Japanese eel, salinity front in the North Equatorial Current (NEC) has been considered as an important oceanic condition and its interannual variability associated with ENSO probably lead to a reduction in the transport of the larvae to the Kuroshio, causing poor recruitment in East Asia (Kimura et al., 2001). Although there is a hypothesis which the salinity front works as a factor for adult eel to detect a spawning site, only the north-south shift of it does not influence directly the transport of the larvae. In addition to the fluctuation of the salinity front, the NEC bifurcation into the northward flowing Kuroshio and the southward flowing Mindanao Current east of the Philippines should be considered as another important feature of the ocean systems in the NEC (Toole et al., 1990). The NEC bifurcation occurs at the northernmost position in October and the southernmost position in February, while not the meridional migration of the basin-wide trade wind but the monsoonal wind along the low-latitude western Pacific is effective in inducing a large northward excursion of the NEC bifurcation in the fall season (Qiu and Lukas, 1996). They also suggested that no significant seasonal fluctuations are found in the transport of the NEC near the Philippine coast but those in the transport of the Mindanao Current and the Kuroshio tend to fluctuate 180º out of phase, due to the different speeds of the baroclinic Rossby waves at their respective latitudes. Qu and Lukas (2003) provided based on a climatology derived from historical temperature and salinity data that it occurs at the southernmost position in July and the northernmost position in December. Furthermore, the meridional migration is strongly influenced by El Niño/Southern Oscillation (ENSO); its northernmost position during El Niño years and its southernmost position during La Niña years (Qiu and Lukas, 1996; Kim et al., 2004). Like that it acts on as an indicator of the partition of the NEC mass, heat, and salt transport between the Kuroshio and the Mindanao Current, The NEC bifurcation is also probably involved in determining how much the larvae of the Japanese eel flow into the equatorial region via the MC and turns to East Asia via the Kuroshio.

Much collection of the eel larvae carried out during cruises in many years (Kajihara, 1988; Kajihara et al., 1988; Tsukamoto, 1992; Ishikawa et al., 2002) provided that they distributed mostly at the northern edge of the NEC, and their size was smaller at the more than eastern stations in the NEC (Tsukamoto et al., 2002). In the northern edge of the NEC region, there exist westward propagating meso-scale eddies, by which the larvae migrating to west are largely affected the dispersion of them. Because most meso-scale eddies in the western north-Pacific Ocean are formed north of salinity front and propagate westward, they have to be considered as another mechanism for changing the migration route of the eel larvae to the growth habitat of eastern Asia. In addition, Kimura et al. (1994) suggested that through the eel larvae transfer model, a northward Ekman transport caused by trade winds plays an important role in inducing the successful migration.

The annual catch of glass eel which is necessary for eel aquaculture because there is no artificial eel
seed was about 130 tons on average in the 1960s in Japan but was 17 tons in late 1990s (Tatsukawa, 2003). This value was only 13 % of the average catch in 1960. The catch in Taiwan which is estimated to be composed of a single panmictic population (Ishikawa et al., 2001) catch also had a similar tendency to decrease (Tzeng, 1997).

Purposes of the present study are firstly to investigate the qualitative-quantitative transport of the eel larvae from a spawning site and to understand how the transport is related to a climate change such as El Niño events. Secondly, how the meso-scale eddies and the Ekman transports are linked with the transport of the eel larvae. Finally, the results of the larval migration will be discussed in relation to the interannual variation in the recruitment of Japanese eel in Japan.

MATERIALS AND METHODS

Samplings of leptocephali of Anguila japonica and hydrographic surveys

Three times samplings for A. japonica leptocephali were carried out from 10 June to 6 July 2004, and 29 May to 13 June and 30 June to 15 July 2005 (Fig. 1) by the RV ‘Hakuho Maru’ of the Ocean Research Institute, The University of Tokyo in the western north-Pacific. Leptocephali were collected with 3 m Isaacs Kidd Midwater Trawls (IKMT) (8.7 m² mouth opening; 1.0 or 0.5 mm mesh) in 2004 and with the IKMT and ORI net (Big Fish Net) with 3 m in diameter (7.1 m² mouth opening; 0.5 mm mesh) in 2005. Collections were made at 109 stations in 2004, and 65 and 116 stations in 2005, respectively.

CTD observations were conducted at all sampling stations of the leptocephali. Current velocities were measured along the cruise trajectories by shipboard Acoustic Doppler current profiler (ADCP).

Lagrangian study

a. OFES Model

Lagrangian study for the migration of the eel larvae is based on a high-resolution circulation field that has been developed by Frontier Research System for Global Change, Japan. The high-resolution ocean model for the Earth Simulator (hereafter referred to 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 except for the Arctic Ocean, with horizontal grid spacing of 1/10º. There are 54 vertical levels, with varying distance between the levels from 5 m at the surface to 330 m at the maximum depth of 6,065 m. The model topography is constructed from the 1/30 bathymetry dataset created by the OCCAM project at the Southampton Oceanography Centre. Monthly mean wind stresses averaged from 1950 to 1999 from the NCEP/NCAR reanalysis data are used for the climatological seasonal integration. The surface heat flux is calculated by the same bulk formula with Rosati and Miyakoda (1988), using the monthly mean values from the NCEP/NCAR reanalysis outputs for the necessary datasets. Also, the precipitation rate from the same reanalysis date is utilized to obtain the fresh water flux. In addition to this fresh water flux, the monthly mean sea surface salinity of the World Ocean Atlas 1998 (henceforth WOA98) was adopted as additional restoring. The restoring time-scale of the model is set to be 1 day,
and the model is integrated for 50 years from the annual mean temperature and salinity fields (WOA 98) without motion. A detailed description on the basic setting in the model has been introduced in Masumoto et al. (2004). The flow fields with a 3-day interval were applied for the calculation of larval migration.

b. Conditions for Lagrangian model

We consider some conditions in relation to this Lagrangian study. Leptocephali greater than 5 mm TL of Atlantic eel (*Anguilla rostrata* and *A. anguilla*) performed a diel vertical migration distribution (Castonguay and McCleave, 1987). The two species, ranging from 5.0 to 19.9 mm TL, mostly occurred between 100 and 150 m by day and between 50 and 100 m by night. A similar distribution pattern is suggested for *A. japonica* leptocephali, too (Otage et al., 1998). They also suggested through the differences between vertical distribution-depths with body length including Kajihara et al. (1988) that the night-time distribution of *A. japonica* leptocephali tends towards shallower depths with increasing body length. In our migration model, the vertical distribution depths by day and night are adopted by using flow field at fixed depth (150 m by day and 50 m by night).

In the western equatorial Pacific, larger precipitation than annual average net evaporation forms the dilution of seawater due to a high rainfall (Weare et al., 1981; Donguy, 1987; Lukas and Lindstrom, 1991) but during El Niño event, the precipitation is reduced and the anomaly of evaporation minus precipitation is larger in the central and eastern equatorial Pacific (Kessler and Taft, 1987; Ando and McPhaden, 1997). Thereby a salinity front is generated by the low-salinity dilution waters and the high-salinity subtropical gyre. Water in the upper layer of the NEC is characterized by three water masses (Fig. 2): southern, low-salinity surface water (<34.2 psu) diluted by precipitation; high-salinity NPTW (>34.8 psu) at depths between 100 and 200 m, caused by excessive evaporation; and the low-salinity water deeper than 150 m originating from the North Pacific Intermediate Water (NPIW).

The fluctuation of precipitation was highly correlated with the fluctuation of the salinity front without time lag, and precipitation at Yap fluctuated quite significantly at 4 month time lag with the Southern Oscillation Index (henceforth SOI). Therefore, the southward movement of the salinity front is probably explained by reduction of the extent of low-salinity water during El Niño in the western North Pacific. Kimura et al. (1994) pointed out that a long-distance migrating *A. japonica* spawns just south of the salinity front in the NEC, and its larval transport in the NEC seems to control the abundance of the eel in eastern Asian countries. Therefore, the location fluctuation of the salinity front is very important factor in determining a start point of *A. japonica* migration. In the present study, we will apply the variation of the meridional displacements of the salinity front suggested by Kimura et al. (2001).

The estimation of the spawning season of the Japanese eel has usually been made based on age determinations using the otoliths of their glass eels, because the daily deposition of increments in their otoliths has been validated as a reliable measure at both larval and juvenile stage. Using collected specimens from various localities in Japan throughout a whole fishing season, Tsukamoto (1990) estimated the hatching dates of the Japanese eel ranged from April to November with a peak season in
July. However, Lee (1999) suggested that the spawning season estimation of the Japanese eel by using the otoliths of their glass eel has two possibilities to occur an error; one is due to difficulty in recognizing the daily deposition of increments late of its leptocephalus stage, another is a possibility for the otolith increments to stagnate. His estimation of the spawning season based on the otoliths of *Aguilla japonica* leptocephali was from April to July. However, another otholith measurement of the leptocephali and the glass eel of *A. japonica* in the ECS revealed that the spawning season of this species was from April to November. Therefore the spawning season of the Japanese eel was established by from April to November for the present lagrangian study.

From an estimation of the daily age of leptocephali collected in the NEC in July 1991, it is indicated that the leptocephali of about 10 to 30 mm TL were clearly separated into two groups, May-born and June-born individuals and they roughly coincided with the new moon period of each month (Tsukamoto et al., 2003). It means that the Japanese eel does not spawn continuously throughout the long spawning season but may spawn periodically once a month during the new moon. Therefore, the timing to start the larval migration is based on the day of the new moon. All conditions for the eel larval migration model are listed in Table 1.

In the present study, we selected some specific years of El Niño (1982/1983, 1997/1998) and non-El Niño (1995/1996, 2000/2001) from the variation of the SOI in Fig. 3 to investigate the differences of transport of *A. japonica* leptocephali by the climate change.

The 1000 particles released in a spawning point changing with the climate change were tracked over a year. Transport of passive larvae released on a site was simulated using a three-dimensional advection-diffusion scheme. The position \[ X_p(t+\delta t) \] of a particle at a time step \( t+\delta t \) is given by

\[
X_p(t+\delta t) = [X_p(t)+u(t)\delta t]+\delta l_{diff}
\]

\( X_p(t) = (x_p,y_p,z_p) \) 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 3-day mean velocity fields from OFES. The particle is advected with velocity \( u(x_p,y_p,z_p,t) \), which weighted by the distances from each grid point for four velocities in a grid field was used for the advection calculation. \( \delta l_{diff} \) is a diffusion scheme added to the position of a particle by advection. For diffusion of particles, \( 1 \times 10^2 \, \text{m}^2\text{s}^{-1} \) was adopted as the horizontal eddy diffusivity.

**RESULTS**

**Variation of the salinity front and of the NEC bifurcation**

Meridional locations of the depth-averaged salinity front which was detected by 34.5 psu (Kimura et al., 2001) at a depth range of sea surface to 30 m depth were averaged in a zonal range of 137 to 142 °E (Fig. 4). The salinity front occurred at its southernmost location during El Niño events (1982/1983, 1997/1998) relative to an average location of 15 °N while near a average location line during non-El Niño events (1995/1995, 2000/2001).

According to Kim et al. (2004), with the OFES model climatology, we define the NEC bifurcation as a point where 2° longitude averaged meridional velocity from the Philippine coast is zero. Annual
mean meridional velocity averaged within a 2° longitude band off the Philippine coast shows that the bifurcation shifts to the north with increasing depth, extending north of 16.6 °N at 500 m, and the northward Kuroshio is evident north of the Mindanao Current (Fig 5). Figure 6 shows the time series of the NEC bifurcation latitude in the upper 461 m. We smoothed the time series with a 12-month Butterworth low pass filter (Roberts and Roberts, 1978) to remove variances associated with seasonal cycle. The NEC bifurcation occurred at its northernmost position during El Niño events and went to south during non-El Niño events.

**Relation of distribution of A. japonica leptocephali to the hydrographic structure**

In the first and the second grid surveys in range 13-20 °N, 137-144 °E in June 2004, we collected 15 individuals of *A. japonica* leptocephali, and they were inclined to be concentrated south of salinity front. The third grid survey, which caught 46 individuals, showed the inclination of the concentration south of the salinity front, too (Fig. 7a). Particularly a station which showed a largest collection was located close at a cyclonic meso-scale eddy. It was also the most distinctive feature in the first grid survey in 2005 that a number of 2-day-old pre-leptocephali after hatching were collected. Most stations showing a large number collection of the pre-leptocephali were located at the north of an anti-cyclonic eddy, which was indicated by the vertical profiles of salinity on an CTD observation line along 142.25 °E where the pre-leptocephali were collected largely (Fig. 7b,c). The profile of current velocities along 142.25 °E observed by shipboard-ADCP also revealed the formation of the anti-cyclonic eddy (Fig. 8). It may mean that the anti-cyclonic eddy is a mechanism to draw up and to diffuse the pre-leptocephali which were spawned in deep water.

**Effect of meso-scale eddies on the migration of the eel larvae**

There was an anti-cyclonic eddy with 140 km in diameter north of the stations showing large collections on a sampling line of 142.25 °E 8 Jun 2005 (Fig. 9a), when the diameter of the eddy is larger than the Rossby deformation radius; i.e. the eddy formation bring about a upwelling by effect of the rotation of the earth. Although a larger anti-cyclonic eddy with about 300 km in diameter was formed north of the former, no distribution of *A. japonica* leptocephali was shown around the eddy. In the NEC, meso-scale eddies are usually generated north of 12 °N and arrive to propagate westward at the western boundary current region (Fig. 9b). Furthermore, considering the NEC as only a broad westward flow, showing the restricted narrow distribution of the eel larvae in the eastern region of the NEC and a broader distribution in the western region suggests the existence of another mechanism such as eddies for the diffusion of the eel larvae.

**Transport of leptocephali in El Niño events and no El Niño events**

We selected spawning points in each experimental year as indicated in Table 1. Firstly, migration experiments of the eel larvae were carried out from a fixed spawning point, 15 °N (Fig. 10). In El Niño years (in 1982/1983 and 1997/1998), transports passing east of the Mindanao Island (Taiwan) were
42.3 (34.4) % and 63.4 (21.7) %, respectively while the transports in non-El Niño years (in 1995/1996 and 2000/2001) were 63.3 (22.8) % and 23.7 (38.7) %, respectively. The transport of the eel larvae from the fixed spawning point in El Niño and not-El Niño year did not show any distinct difference of the eel larval transport according to the change of ocean system affected by the specific climate change. Compared the annual catches of glass eel in Japanese Islands by Kimura et al. (2001), it is evident that the eel larval migration from the fixed spawning point cannot explain the differences of migration or transport of the eel larvae. However, the migration experiments from the spawning point depended on the meridional displacements of the salinity fronts showed explicitly the influences of the changing ocean system according to the climate change (Fig. 11). In El Niño years, transports along the Kuroshio were 9.5 % in 1982 and 12.5 % in 1997 relative to 84.0 % and 78.2 % along the Mindanao Current, respectively. However, in non-El Niño years the transport along the Kuroshio was over than 38 % and less than 30 %. Although no information about how much A. japonica leptocephali transported along the Mindanao Current survive is known, it will be assumed that the glass eels of A. japonica caught in eastern Asian countries are dominated by the eel larvae transported by the Kuroshio from the NEC region. In reality, the catch fluctuation of glass eel in the Kagoshima Prefecture, Japan agrees well with the transport rate of the A. japonica leptocephali along the Kuroshio in El Niño and non-El Niño years. It also means that the migration of A. japonica is affected largely by the variation of the ocean system according to the climate change. Figure 11 showed also that many larvae diffused by the meso-scale eddy migrated to the Okinawa islands directly. It supports another important mechanism of the eel larval migration excluding the westward NEC.

Summary

The variation of the SOI showed that El Niño events occurred in 1982/1983 and 1997/1998. In the El Niño years, the salinity front occurred at its southernmost location while near the average location (15 °N) in the non-El Niño years (1995/1996 and 2000/2001). Moreover, the NEC bifurcation shifted to its northernmost position in El Niño years while went south in non-El Niño years. The change of the ocean systems by the climate change generally influences the mass transport in the NEC region. Particularly in case of the eel larvae spawned just south of the salinity front around the West Mariana Ridge, their arrival to the coast of eastern Asian countries will be decided by a spawning point affected by the meridional displacements of the salinity front and the position of the NEC bifurcation deciding the transport to the Kuroshio and the Midanao Current near the western boundary. Through the migration model of A. japonica leptocephali, it is suggested that the meridional displacements of the salinity front and the NEC bifurcation according to the climate change were two important factors for controlling the eel larval migration and the transport change according to the change of the ocean systems agree well the variation of the catches of glass eel in Japanese Islands.

REFERENCES


Fig. 1. Distribution of leptocephali of *A. japonica* in 2004 and 2005
Fig. 2. Profile of salinity (psu) along 137 °E line by RV Ryofu Maru operated by Japan Meteorological Agency Jun 2000.
Fig. 3. Time series of the Southern Oscillation Index (SOI).
Fig. 4. Interannual variation of the meridional location of the salinity front in a zonal range of 137-142 °E. A red dotted line indicate an average location of the salinity front.
Fig. 5. Mean meridional velocity (cm/s) averaged within a 2° longitude band off the Philippine coast.
Fig. 6. Time-depth section of the NEC bifurcation latitude in upper depths above 461 m.
Fig. 7. (upper panels) Catch number of A. japonica leptocephali and (lower panels) profiles of salinity along lines showing a large collection of A. japonica leptocephali in (a) 2004, (b) and (c) 2005.
Fig. 8. Profile of E-W components of Acoustic Doppler Current Profiler along 142.25 °E jun. 2005.
Fig. 9. Absolutely dynamic topography 8 Jun 2005. White solid circles indicate stations showing large collection of *A. japonica* leptocephali.
Fig. 10. Particle trajectories from the fixed spawning site (15 °N)
Fig. 11. Particle trajectories from the changed spawning site according to the meridional displacements of the salinity front.