Wind Effects on the Transport of Japanese Sand Eel Larvae in the Eastern Part of the Seto Inland Sea

Hideaki Nakata*¹

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The effects of the wind-induced surface drift on the larval transport of the Japanese sand eel *Ammodytes personatus* in the eastern part of the Seto Inland Sea are here discussed on the basis of the results of a drift-card experiment and an analysis of the historical data on the distribution of the larval fish. The wind-induced changes on the recovery distribution of the drift-cards released from Shikano-se, one of the main spawning grounds located in the Sea of Harima, suggest that the prevailing wind, particularly its westerly component, affects the drift pattern of the sand eel larvae originating from this spawning ground. The strong westerly wind after the hatching of the larvae also contributed to the eastward transport of the larvae from the spawning ground in the Bisan-Seto to the Sea of Harima. The positive correlation between the strength of the westerly wind and the catch ratio of the 0-age sand eels in the Sea of Harima suggests that the wind-induced eastward transport of the larval sand eels originating from the Bisan-Seto has a great influence on the subsequent abundance of the 0-age fish in the Sea of Harima.

The Japanese sand eel *Ammodytes personatus* Girard is one of the commercially important fish in the coastal waters of Japan. In the eastern part of the Seto Inland Sea, its annual catch amounts to approximately 39,000 tons (average during 1975-1984), which accounts for about 22% of the total fisheries production in this area.^{*2} It is also known that the catch varies considerably due to the recruitment success or failure of the 0-age fish.^{*3} Thus the environmental factors related to the survival of the sand eel larvae have become a matter of great importance for catch forecasting.

Among various processes responsible for the recruitment, interest has been focused mainly on the wind-induced larval drift, because the main spawning period of this species is in winter (early December-early January)²⁾ when the strong northwesterly wind prevails. In fact a positive correlation between the frequency of the strong westerly wind after the main spawning period and the catch of the 0-age fish was reported³⁾ in the Sea of Harima and Osaka Bay (Fig. 1), though a clear explanation of the wind effects on the transport and distribution of the larval fish has not been

achieved. Smith *et al.*³⁾ also reported that the changes of the prevailing wind around Georges Bank affected the abundance of the sand lance larvae (*Ammodytes* sp.) retained on the Bank.

On the other hand, the ecological aspects of the recruitment of the Sanriku population of the Japanese sand eel have been intensively studied in recent years.⁴⁻⁸⁾ Around the coastal spawning grounds off the Sanriku coast, the prevailing eastward wind could possibly sweep the hatched larvae of the sand eel into the offshore waters, where some unfavorable survival conditions were expected.^{7,9)} However, a detailed description of the wind-induced larval drift has not yet been given.

In this paper, the author considers the wind-induced changes of the surface drift and their effects on the transport of the sand eel larvae from the main spawning grounds in the eastern part of the Seto Inland Sea, and discusses the implications of the wind changes for the catch fluctuations of the 0-age fish.

*1 Ocean Research Institute, University of Tokyo, Minamidai, Nakano, Tokyo 164, Japan (中田英昭: 東京大学海洋研究所).

*2 Japan Fisheries Resource Conservation Association: Showa 27-59 Nen Setonaikai Gyogyo Nadabetu Gyokaku Toukei Ruinenhyo, 1986, 139 pp.

*3 The young and immature fish (35-85 mm in BL) which are the main target of the fishery during April-June in the eastern Seto Inland Sea.¹²⁾

Fig. 1. The spawning grounds of the sand eel in the eastern part of the Seto Inland Sea (revised from Fig. 2 in Takamori²²). The shaded areas denote the spawning grounds. The 3-hourly wind data of Tozaki (a), Takamatsu (b) and Kobe (c), and the daily temperature data of Akashi Port (d) were used for this study.

Fig. 2. Variation of the daily average wind at Tozaki during the period of the drift-card experiment. The length and direction of each line indicate the daily average of the wind speed and leeward direction, respectively. They were both computed using 3-hourly wind data of Tozaki. Short arrows (A-G) in vertical direction denote the dates of the drift-card releases (see Table 1).

Methods

According to Hamada,⁹⁾ the main spawning grounds of the sand eel larvae appearing in the eastern Seto Inland Sea are located around Shikano-se in the northeast of the Sea of Harima and the central part of the Bisan-Seto (Strait) (Fig. 1). In other words, it has been supposed that the fishery production of the sand eel in the Sea of Harima, the most productive area in the Seto Inland Sea, would be supported by the larvae originating from Shikano-se and additionally by those transported from the Bisan-Seto.

Therefore I first focused my attention on the transport from the Shikano-se spawning ground and carried out a drift-card experiment in Shikano-se (marked × in Fig. 3) during January-April in 1979 in order to examine actual responses of the

surface drift to the wind changes. Fig. 2 shows the variation of daily average wind at Tozaki (Fig. 1) during the period of the drift-card experiment. The length and direction of each line in the figure indicates the vector-average wind speed and leeward direction, respectively, which were computed using 3-hourly wind data at the Tozaki observatory station of the Honshu-Shikoku Bridge Authority.

The short arrows (A-G) in the vertical direction denote the dates of the drift-card release. As seen from Fig. 2, a total of 7 releases were made from 13 January to 6 April 1979. The dates of each release, the number of the cards released at each time and the number of recoveries are summarized in Table 1. 2,200 cards (in total) were released, of which 514 cards (23.4%) were recovered. In case E (dated 24 February), the drift-cards were released from the Akashi Strait

Table 1. Data on the release and recovery of the drift-card

No.	Release				Recovery				
	Date (1979)	Time	Tide	Tidal current	Stn.	Number	Within 15 days	Total	Recovery rate
A	13 Jan.	11:00	S	Fmax+2.5 h	Sh	400	8	53	13.3%
B	25 Jan.	11:25	N→S	E _{max} -1 h	Sh	200	23	70	35.0
C	29 Jan.	9:20	S	Fmax+1 h	Sh	400	47	117	29.3
D	6 Feb.	10:55	N	E _{max} +0.5 h	Sh	200	40	70	35.0
E	24 Feb.	10:30	N→S	E _{max} -2.5 h	Ak	400	29	95	23.8
F	6 Mar.	11:30	N	S1 (E→F)	Sh	400	14	64	16.0
G	6 Apr.	12:20	N	S1 (E→F)	Sh	200	10	45	22.5
Total						2200	171	514	23.4

Stn. Sh: Shikano-se, Ak: Akashi Strait. Tide S: Spring tide, N: Neap tide. Tidal current (at the Akashi Strait) F: Flood current (westward flow), E: Ebb current (eastward flow), max: Time of maximum speed, S1: Slack time.

(marked × in Fig. 3E) because of rough seas. The cards were released at various phases of tidal current and there is a suspicion that the difference of the phase possibly affect the recovery distribution. However results of another drift-card experiments conducted in the Akashi Strait showed that there was almost no difference in the recovery of the cards released at the different tidal phases.¹⁾ Hence I consequently treated the recovery data shown in Table 1 together for the present analysis. The drift-cards used for this study were made of plastic casing in which a post card for reporting the time and place of recovery and small weights to keep the card floating vertically on the sea surface were enclosed.¹⁰⁾

In addition to the above drift-card experiment, the data on the abundance and size distribution of the sand eel larvae collected in the Bisan-Seto were analysed in connection with the wind effects on the larval transport from the Bisan-Seto spawning ground. Larvae collections by a horizontally-towed Marutoku-net (45 cm mouth diameter and 0.35 mm mesh aperture) have been made during daytime from 39 stations in the Bisan-Seto every January and February by the Okayama Prefectural Fisheries Experimental Station.^{*1} Each net towing was made in a layer 5 m deep for 3 minutes at tow speed of about 3 knots. The data obtained from the above surveys during 1976–1977, which were published in Bulletin of Okayama Prefectural Fisheries Experimental Station (1976–1977), were used in the present analyses. The 3-hourly wind data obtained at Takamatsu meteorological station (Fig. 1) were also used for the

analyses of the wind conditions in the Bisan-Seto.

In addition, the 3-hourly wind data (1961 and 1964) of Kobe meteorological station and data of the daily temperature (1966–1979) at the Akashi Port observed by the Hyogo Prefectural Fisheries Experimental Station were used in the discussion. The annual catch data of the sand eel in the Seto Inland Sea were based on the statistical table published by the Japan Fisheries Resource Conservation Association in 1986.^{*2}

Results

Wind-induced Changes of the Surface Drift around Shikano-se Inferred from the Drift-card Returns

Fig. 3 shows the distribution of the drift-card recoveries made within 15 days after their release from Shikano-se, except for case E, for which the cards were released from the Akashi Strait. The dates of release of cases A–G are given in Table 1, and correspondingly the short arrows in Fig. 2. As shown in Table 1, the drift-card recoveries made within 15 days after release account for about 33.3% of total recoveries and about 7.8% of total number of the cards released during this experiment. On the other hand, the average wind conditions after the drift-card releases are shown in Fig. 4. The vectors A–G indicate the vector-average wind speed and direction during a period of 10 days after the releases A–G, respectively.

It was evident from these figures that the surface drift around Shikano-se would be influenced by the prevailing wind conditions. In the case where

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*2 Japan Fisheries Resource Conservation Association: Showa 27–59 Nen Setonaikai Gyogyo Nadabetu Gyokaku Toukei Ruinenhyo, 1986, 139 pp.

Fig. 3. Distribution of the drift-card recoveries made within 15 days after release from Shikano-se (× mark in the figure). Cases A-G correspond to the dates of the drift-card releases shown in Fig. 2 and Table 1. Solid circles denote the recovery points. In the case of multiple recoveries at the same site, the numeral indicating the number of the recoveries is attached to the circle.

Fig. 4. Average wind conditions after the drift-card release. The vectors A-G indicate the vector-average wind speed and direction during a period of 10 days after the releases A-G, respectively.

the NW-NNW winds were dominant (cases A and E), all recoveries were made in Osaka Bay, which would indicate the occurrence of strong wind-induced eastward flow. When the wind speeds,

particularly those westerly component, became smaller (cases B-D), some of the recoveries were made along the western coast of Awajishima Island in the Sea of Harima as well as in Osaka Bay. Further, in the case of relatively weak N-NNE wind (case F), almost all recoveries were made along the western coast of Awajishima Island. In case G, with almost no prevailing wind after the drift-card release, most of recoveries were made around the release point and the extent of the dispersion of the recovery points was relatively small.

According to the relation between the larval size of the sand eel and the time elapsed after hatching,¹¹⁾ the larva 15 days after hatching is estimated to be about 5.5 mm in total length, which is regarded as a post-larval stage after yolk-sac absorption. Thus the results mentioned above suggested that the newly-hatched larvae could be transported from Shikano-se to Osaka Bay through the Akashi Strait and southern part of the Sea of Harima along the western coast of Awajishima Island. The ratio of the abundance of the larvae transported to Osaka Bay to that of the larvae staying in the Sea of Harima seemed to depend largely on the westerly component of the prevailing wind during the spawning period.

Here we mainly considered the possible range of the larval drift during a 15-day period, which is inferred from the drift-card returns, and related it to the average wind condition. However, there also exist some differences in the recovery distribution between the cases B, C and D (Fig. 3) despite the relatively similar average wind conditions (Fig. 4). This suggests an effect of the wind on the larval drift in a temporal scale within 15 days. Although it seems to be difficult to detect such a short-term change of the surface drift in the recovery data, the frequency and timing of the strong wind blowing during a 15-day period may be responsible for the differences.

Wind Effects on the Distribution of the Sand Eel Larvae in the Bisan-Seto

On the basis of the historical data (1966–1979) for the abundance and distribution of the sand eel larvae in the Bisan-Seto, Karakawa and Matsumura* reported that the larger larvae would have

a tendency to be distributed in the eastern side of this area. This suggests eastward drift of the larvae by prevailing westerly winds during the spawning period. Hamada further pointed out the eastward transport of the larvae originating from the Bisan-Seto would contribute to the increase of larval abundance in the Sea of Harima.⁶⁾ The author therefore looked at the resulting spatial shift of the main distribution area of the sand eel larvae together with the increase in the larval size and tried to relate them to the prevailing wind conditions before the larvae collections.

Some of the results are shown in Fig. 5. Cases A-C correspond to the results of larvae collections dated 26–28 January and 25–27 February in 1976, and 17–19 January in 1977, respectively. The main distribution areas of variously-sized populations of the larvae are indicated in the figure. The wind conditions during the 7 days before the larvae collections corresponding to the cases A-C are also shown in the upper-right of the figure.

Fig. 5. Spatial shift of the main distribution area of the sand eel larvae together with the increase of the larval size. The areas abundant in the larvae less than 4 mm, ranging 4–5 mm, ranging 5–6 mm and more than 6 mm in total length, i.e. those areas above the average of the whole area are enclosed by thick solid (covered with dark shadow), thin dashed, thin solid and thick dashed (covered with light shadow) lines, respectively. The wind conditions during the 7 days before the larvae collections corresponding to cases A-C are in the upper-right of the figure (see text for details).

* J. Karakawa and S. Matsumura: Showa 54 Nendo Nansei Kaiku Block Naikai Gyogyo Kenkyukai Houkoku, Nansei Kaiku Suisan Kenkyusho, Hiroshima, 1980, pp. 93–107.

The irregular polygons having 16 sides represent the integrated wind speed in each of 16 wind directions for the 7 days. The integration of the wind speed was based on the 3-hourly data obtained at Takamatsu.

In case A with the strongest westerly wind (the average speed: $w=3.4$ m/s), the larvae seemed to drift swiftly toward the east as their size became larger. Conversely, the larger larvae stayed around the spawning ground with newly-hatched larvae in case B, which had the weakest westerly wind ($w=0.6$ m/s) among these cases. In case C, with a westerly wind speed lying midway between the cases A and B, the larger larvae gradually drifted toward the east, but the drift speed seemed to be slower than that in case A. These results support the hypothesis that the eastward larval drift from the Bisan-Seto spawning ground depends strongly on the strength of the westerly wind after hatching of the larvae.

Discussion

Wind Effects on the transport of the Sand Eel Larvae

Though it was suggested that the sand eel eggs can be distributed in the surface water due to the strong tidal mixing,¹²⁾ the occurrences of the eggs and newly-hatched larvae were generally confined to the neighborhood of the spawning grounds.^{9),*} According to Hamada,^{2,11)} the majority of newly-hatched larvae are supposed to stay in the upper layer from the surface to 5 m deep in the Seto Inland Sea. It has been therefore considered that the wind-induced surface drift would have a strong effect on the larval transport from the neighborhood of the spawning grounds.²⁾ In fact, some assumptions based on the positive correlation between the frequency of the strong westerly wind and the catch of the 0-age fish have been made concerning the wind effects, and applied practically to the forecasting of yearly catches.^{13,14)} Nevertheless, there has been very little information on the actual response of the larval drift to changes of the prevailing wind.

The results of the drift-card experiment conducted in Shikano-se showed that the prevailing wind, particularly its westerly component, could affect the transport of the newly-hatched sand eel larvae around Shikano-se. The distribution patterns of the average size (total length in mm) of the

Fig. 6. (a) Distribution of the average size (in mm) of the sand eel larvae in 1961 and 1964 (after Fig. 5 in Hamada⁹⁾). (b) Distribution of the abundance (ind./m³) of the sand eel larvae in early February in 1961 and 1964 (revised from Fig. 7 in Hamada⁹⁾). The wind vectors shown below in the figure indicate the average wind speed and direction from mid-January to early February at Kobe.

larvae in 1961 and 1964 are shown in Fig. 6(a) after Hamada⁹⁾ for comparison. It is noticeable that the larvae seemed to be transported to Osaka Bay and southern part of the Sea of Harima along the western coast of Awajishima Island as they became larger. These movements of the larvae are quite similar to those inferred from the recovery distribution (Fig. 3) of the drift-card released from Shikano-se. Thus it may be concluded that the eastward drift induced by the prevailing westerly wind would be responsible for the larval transport from Shikano-se to Osaka Bay, while the southward drift during relatively slack conditions of the westerly wind would transport them along the western coast of Awajishima Island. The combination of these two dominant patterns of the larval drift would result in the distribution exemplified in Fig. 6(a).

* J. Karakawa and S. Matsumura: Showa 54 Nendo Nansei Kaiku Block Naikai Gyogyo Kenkyukai Houkoku, Nansei Kaiku Suisan Kenkyusho, Hiroshima, 1980, pp. 93-107.

Furthermore, Fig. 6(b) shows the distribution of the larval abundance (ind./m³) in February of the same years as shown in Fig. 6(a),⁹⁾ together with the average wind vector from mid-January to early February (the wind analyses are based on the data of Kobe meteorological station). The shaded areas denote that the larval abundance is higher than 1 (ind./m³). As seen from the figure, the westerly wind was most prevalent in 1961, which would contribute to the large dispersion of the high abundance area in Osaka Bay. In 1964, on the other hand, the wind was considerably weaker and the high abundance area was confined to the neighborhood of the Akashi Strait. These facts also seemed to be consistent with the wind-induced changes of the surface drift inferred from the drift-cards returns.

In addition, it can be seen from Fig. 6 that the strong westerly wind in 1961 was apparently responsible for the eastward transport of the sand eel larvae originating from the Bisan-Seto. Such effects of the prevailing wind on the larval transport from the Bisan-Seto were confirmed to a certain extent by the present analysis of the larvae collection data (Fig. 5). In other words, this suggests that the strong westerly winds enable large amounts of larvae in the Bisan-Seto to reach the Sea of Harima. I discuss later some details of its implication for the catch fluctuation of the 0-age fish.

There still exist some uncertainties in the relation between the wind-induced current and the actual drift of the sand eel larvae. In Fig. 6a, the average drift speed of the larvae transported to Osaka Bay seemed to be quite slow compared to that of the drift-cards (Fig. 3). One of the reasons for this difference is probably attributed to the reduction of the wind effect in the sub-surface water. According to Hill and Horwood,¹⁵⁾ the ratio of the wind-induced drift speed to the wind speed in the top 50 cm of water ranged from 1.0 to 1.9%, while the ratio in the top few mm of water ranged from 3.4 to 3.8%. The sand eel larvae are supposed to stay in the upper layer in the Seto Inland Sea,^{2,11)} detailed description of their vertical distribution has not yet given. Further consideration on the modification of the larval drift in the sub-surface water is necessary. In addition, the tidal vortices which occur in the northwestern part of Osaka Bay¹⁶⁾ may play a major role in the retention of the sand eel larvae. In fact, the larval density shown in Fig. 6(b) seemed to be appreciably higher in and around the vortices. The

larval mortality during the drift period may complicate the actual larval drift in addition to the consequences of the physical transport processes.¹⁷⁾

In order to consider the dynamic responses of the larval drift to the wind changes, it is essential to give a more detailed description of the distribution of the larvae at intervals of shorter than 1 month. Taking account of the variability of the wind in the coastal areas,¹⁸⁾ further investigation at intervals of several days is desirable.

The Implications of Wind Changes for the Catch Fluctuation of 0-age fish

Concerning wind effects on the survival of the sand eel larvae, Hamada suggested that the larval dispersion induced by the strong westerly wind may help avoid high mortality due to predation and the competition for food under aggregated conditions.^{9,13)} The positive correlation between the dispersion area of high larval density and the catch of 0-age fish (see Fig. 3 in Hamada¹³⁾) appeared to support this hypothesis. However, the wide dispersion of the high-density larval area indicates at the same time the abundance of the larvae in the area. Fig. 7 shows the correlation between the average number of the larvae (ind./haul) collected every early February in the Sea of Harima (1966–1972), and the catch of the 0-age fish during March–July according to data presented in Hamada.¹⁹⁾ It is evident that the larval abundance in the Sea of Harima during the main dispersion period of the larvae is closely related to the subsequent catch of the 0-age fish in this area.

Fig. 7. Correlation between the average number (ind./haul) of the sand eel larvae collected every early February in the Sea of Harima and the subsequent catch of the 0-age fish in number (10⁴ ind.) during 1966–1972. Both data sets used for this analysis were presented in Table 2 in Hamada.²⁰⁾ Numerals denote the years (1966–1972).

Therefore, the author first looked at the relation between the wind-induced eastward transport of the larvae originating from the Bisan-Seto and the abundance of the 0-age fish in the Sea of Harima. The major part of the sand eels catch, most of which is composed of 0-age fish, was made in the Sea of Harima (approximately 61% on the average during 1966–1979). The contributions of the Bisan-Seto and Osaka Bay are almost the same and average 18% and 15%, respectively.*¹ Hamada previously discussed the interrelations of the annual catches (1965–1974) in adjacent areas in the Seto Inland Sea and showed that weak negative correlation ($r = -0.13$) could be found between the catches in the Sea of Harima and the Bisan-Seto.²⁰⁾ However, it seems to be difficult to detect a definite relation in the fluctuations of the catch itself, because the catch of the sand eel has changed considerably with time partly due to the increase of the demand.^{14, 21)}

Let us look at the correlation between the catch ratio of each area to the total catch in the Seto Inland Sea. Fig. 8 shows the results of the analyses based on the catch data during 1966–1979.*¹ It

Fig. 8. Interrelation of the annual catch ratio of each area to the total catch of the Seto Inland Sea during 1966–1979. (a) Relation between the Sea of Harima and the Bisan-Seto. (b) Relation between The Sea of Harima and Osaka Bay.

can be seen from Fig. 8(a) that there exists an obvious negative correlation ($r = -0.93$) between the catch ratio of the Sea of Harima and the Bisan-Seto, while very weak correlation is found with the catch ratio of Osaka Bay (Fig. 8b) despite its catch being comparable to that of the Bisan-Seto. Furthermore, the significant negative correlation ($r = -0.56$) between the deviation from the mean of 14 years (1966–1979) of the westerly wind speed at Takamatsu*² in January and the catch ratio of the Bisan-Seto shown in Fig. 9 seems to reinforce the present discussion. It suggests that the strong westerly wind contributed to sweeping the sand eel larvae in the Bisan-Seto, which subsequently become the target of the fishery, toward the Sea of Harima. It is also consistent with the fact that smaller size 0-age fish considered to originate from the Bisan-Seto were more abundant when larger catches were made in the Sea of Harima.¹⁴⁾ On the other hand, the weak correlation between the catch ratio of the Sea of Harima and Osaka Bay (Fig. 8b) may result from the relative complexity of the surface drift around Shikano-se responding to the wind changes as seen in Fig. 3.

The strong westerly wind in winter is often accompanied by a drop of the water temperature, which may complicate the problems of the 0-age fish. Fig. 10 shows the correlation between the deviation of the westerly wind speed previously shown in Fig. 9 and that of the surface water temperature at Akashi Port in January. One can see that the strength of the westerly wind correlated closely with the cooling of the sea water ($r =$

Fig. 9. Correlation between the annual catch ratio of the Bisan-Seto and the deviation of the westerly wind speed at Takamatsu in January from its mean for 14 years (1966–1979).

*¹ Japan Fisheries Resource Conservation Association: Showa 27–59 Nen Setonaikai Gyogyo Nadabetu Gyokaku Toukei Ruinenhyo, 1986, 139 pp.

*² The westerly wind speed at Takamatsu (1966–1979) correlates closely with the difference of atmospheric pressure between Shimonoseki and Osaka ($r = 0.81$).

Fig. 10. Correlation between the deviation of the westerly wind speed (ΔW) shown in Fig. 9 and that of the sea surface temperature (ΔT) at Akashi Port in January. Numerals denote the years (1966–1979).

–0.88). This implies that the between-year difference of the temperature connected with the wind changes has a multiple effect on the recruitment of the 0-age fish in addition to the wind effects described in the present study. There exists a negative correlation ($r = -0.64$) between the deviation of the surface water temperature at Akashi Port in January and the catch ratio of the Sea of Harima.

Concerning the effect of temperature, it has been pointed out that the drop in temperature during December–January would promote the spawning of the sand eels and result in the catch increase of the 0-age fish.^{2,11)} Nevertheless the mechanistic aspects of the direct effect of the temperature change on the recruitment processes are still uncertain. It is therefore necessary to give more quantitative description of the wind-induced eastward transport of the sand eel larvae from the Bisan-Seto to the Sea of Harima. Further investigation on the effect of the wind-induced cooling of the sea water on the recruitment of the 0-age fish is also necessary.

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