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THE TIDAL FRONT AND EDDY IN OSAKA BAY: ITS IMPLICATION FOR DISTRIBUTION AND SURVIVAL OF FISH LARVAE

by

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ABSTRACT

In Osaka Bay, a high speed tidal-jet from Akashi Strait, northwestern entrance of the bay, generates moving eddies, contributing to vertical mixing of the water, while relatively weak tidal currents and freshwater discharge in the inner bay develop vertical stratification. A marked tidal front is usually observed between the well-mixed and the stratified waters even in winter. We made intensive investigations on the hydrographic structure and distribution of biological properties including fish larvae and their prey organisms in the vicinity of the front and eddy.

Since the stratification is mainly caused by river discharge, the stratified side of the front is characterized by nutrient-rich and more productive water compared to the well-mixed side. In fact, remarkably high copepod densities were observed at the front and its inner part in summer; the density of adult copepods (mostly *Paracalanus* spp.) was more than 1,600 indiv./l at the front and rapidly declined in the well-mixed water. This suggests that the front potentially provides an advantageous feeding condition for the larvae such as anchovy and gizzard-shad which are spawned in the inner bay.

On the other hand, the eddies in the well-mixed water have an effective function of trapping larvae into them and contribute to larval retention particularly in winter. The density of sand lance larvae originating from the spawning ground in the west of Akashi Strait was about 8 times higher in the eddy than that in the surrounding water. The pattern of larval trapping by the eddies can be demonstrated by a preliminary numerical model experiment.

Thus, the front and eddy sections described above strongly suggest that intermediate-scale physical features could be crucial for larval feeding and retention leading to the success in recruitment. Acqusition of time-series data on the dynamic physical and biological features is further necessary to give a full description of the front and eddy in Osaka Bay.

1. INTRODUCTION

During the last several decades, a number of field studies have been made on the interactions between larval distribution and hydrographic features (Norcross & Shaw, 1984; Nakata, 1989; Heath, 1992). Among various hydrographic features, tidal fronts are of great interest because they may function as a barrier for egg and larval transport and possibly contribute to larval retention (Iles & Sinclair, 1982; Richardson et al. 1986). Several studies have also revealed that much greater densities or elevated productivity of zooplankton can be observed in the vicinity of tidal fronts, so providing potentially favorable feeding conditions (Kiørboe & Johansen, 1986; Kiørboe et al. 1988). Nontheless field information on the functional roles of these intermediate-scale physical features in the egg and larval survival processes is still scattered and fragmentary; continuous efforts toward piling up the interdisciplinary data are further needed.

The Seto Inland Sea (Fig.1) in the western part of Japan is composed of narrow straits and wide basins, representing a strait-basin system (Fujiwara et al. 1994). The speeds of tidal current in the straits are large and often exceed 3 m/s; in contrast tidal currents in the wide basins connected with the straits are weak and rather stagnant. Due to the strong tidal current the water in and around a strait is well-mixed, while the water in a wide basin is stratified particularly in summer. This indicates that tidal fronts develop in between those well-mixed and stratified waters near the straits. The wide basin of Osaka Bay (Fig.1), which is located in the eastern Seto Inland Sea, and the Akashi Strait, northwestern entrance of the bay, forms a typical strait-basin system.

The aims of this paper are to describe the hydrographic characteristics of the strait-basin system in Osaka Bay, focusing on the implications of intermediate-scale physical features within the system for the distributions of biological properties such as fish larvae and their prey organisms, and to discuss the possible functional roles of the intermediate-scale physical processes in larval survival and recruitment.

2. HYDROGRAPHIC CHARACTERISTICS OF OSAKA BAY

Osaka Bay has a mean depth of 28 m and an elliptic shape with a long axis of 60 km. In the western bay, there is a gently sloping sandbank named Okino-se, which has the shallowest depth of 23 m. The width and the maximum depth of the Akashi Strait are about 4 km and 140 m, respectively. The tidal current speed through the strait reaches 3 m/s during the spring tides, while tidal currents in the eastern part of Osaka Bay are less than 0.1 m/s. As illustrated in Fig.2, the high speed tidal-jet from the Akashi Strait generates moving eddies: a pair of counter-rotating vortices with the distance of 6 km between the centers of the vortices, which contribute to vertical mixing of the water. On the other hand, relatively weak tidal currents and freshwater discharge in the inner bay develop vertical stratification (Fujiwara et al. 1994). In addition, the accumulation of negative vorticity carried by the clockwise vortex drives the clockwise residual circulation around Okino-se; we call it Okino-se Circulation thereafter. The sea water around Okino-se rotates clockwise all day long regardless of the tidal phase.

A satellite image of Osaka Bay is shown in Fig.3 together with the sketch of the bay system based on the image. The tidal current in the Akashi Strait is maximum westward. The whitish mushroom-like structure to the southeast of the Akashi Strait represents the vortex pair visualized by turbidity. The blob of high turbidity water to the south of the Okino-se Circulation is presumed to be a trace of anticlockwise vortex formed in the previous tidal-period. The dark area surrounding the Okino-se Circulation indicates the spread of Yodo-river water discharged into the inner part of Osaka Bay, representing stratified areas. A marked tidal front is usually observed between the well-mixed and the stratified waters.

The physical features of the front and eddy in the bay were already described including the flow characteristics and their implications for water and bottom quality of the bay (Fujiwara & Nakata, 1991, Fujiwara et al. 1994, Yanagi et al. 1994). However there has been still little information on the distribution of biological properties such as fish larvae and their prey organisms in the vicinity of the front and eddy. We therefore made intensive surveys on the hydrographic and biological features along the transects crossing the tidal front in June-July 1991 and crossing the tidal eddy in January 1993.

3. DISTRIBUTIONS OF FISH LARVAE AND THEIR PREY

Observation in the vicinity of a tidal front in summer

Figure 4 shows the spatial distributions of fish larvae and copepods collected from the surface water on 2 July 1991. The samplings of the larvae were carried out by a 5-min tow with the Ocean Research Institute (ORI) net, made of 0.33mm mesh filtering cloth, and the copepods were collected by pumping up 10 l of surface water simultaneously with the net tows.

Since the stratification is mainly caused by freshwater discharge from Yodo River (Fig. 3b) into the innermost part of the bay, the stratified side of the front is characterized by nutrient-rich and more productive water compared to the well-mixed side in summer (Matsuda, 1990). This probably leads to remarkably high density of adult copepods in the inner bay of the front as seen in Fig.4. In particular, the densities of adult copepods (more than 1,600 indiv./l) and nauplii (about 600 indiv./l) both had a marked peak corresponding to the front, and those densities rapidly declined in the well-mixed water.

On the other hand, the larval density of gizzard-shad (*Konosirus punctatus*), one of the most dominant species collected in this survey, also had a peak at the front, while total abundance of the larvae including Blennioidae sp. as a dominant species was appreciably large in the front and its stratified side with a peak on the stratified side near the front. In addition, enormous amount of the eggs of anchovy (*Engraulis japonicus*) and *K. puncutatus* were collected only in the innermost part of the bay (not shown). These results suggest that the front potentially enhances larval retention and provides an advantageous feeding condition for the larvae originating from the spawning ground localized in the innermost part of the bay.

Observation in the vicinity of a tidal eddy in winter

Another important physical feature related to recruitment is the tidal eddy in the well-mixed water and its function of larval retention. Figure 5, demonstrating the distributions of sand lance (*Ammodytes personatus*) and scorpionfish (*Sebastiscus marmoratus*) larvae collected along a longitudinal transect in Osaka Bay (on 24 Jan. 1993) together with temperature, salinity and chl-a sections, exemplifies that tidal eddies and Okino-se Circulation (Fig.3b) driven by the tidal eddies appear to have an effective function of trapping the larvae and contribute to larval retention. The density of sand lance larvae at Stn.4, where vertical mixing due to the eddy motion was detectable from the hydrographic sections, was about 8 times higher than that at the surrounding stations. Similar tendency was found in the distribution of scorpionfish.

Main spawning grounds of the sand lance are located in the west of Akashi Strait, therefore strong westerly winds in winter, main spawning season, and the tidal-jet through the Akashi Strait would be responsible for the larval transport from the spawning grounds to Osaka Bay (Nakata, 1988). Then most of the larvae could be trapped in the eddies and subsequently transferred to the Okino-se Circulation; this mechanism contributes to preventing the larvae from being dispersed toward the offshore and failing to remain in their nurseries.

In order to confirm the mechanism, an attempt to track the particles released at 2 hours after the maximum westward current from the west of the Akashi Strait (see Fig.6a) during a tidal cycle has been made by computer. Figure 6 illustrates the particle distributions at various tidal phases after the release; the tidal current at the Akashi Strait corresponding to each phase is indicated by a solid arrow on the top of each figure. The tidal phase shown in Fig.6f (maximum westward current at the Akashi Strait) is similar to that of the satellite image previously shown in Fig.3a. It is noticeable that the convoluted structure of the vortex-pair in the image is reproduced in the simulated particle distribution. Evidently most particles are trapped in the inner part of tidal eddies and then in the frontal zone of the Okino-se Circulation despite excluding the effect of convergence at the front and eddy from the present preliminary calculation. This must be a part of the mechanism behind the remarkably high density of sand lance larvae at Stn.4, though tracking of the particles for a longer period is further required.

4. DISCUSSION

Regarding biological features of the tidal front in the Bungo-Suido (Channel), western entrance of the Seto Inland Sea, Uye et al. (1992) reported that numerical abundance of copepod nauplii were lower in the frontal area than in adjacent stratified and mixed areas despite increased chlorophyll concentration and elevated fecundity of adult copepods at the front. They also suggested that apparent high mortality of the copepod nauplii is probably due to predation by surface-dwelling carnivores like jellyfish and pelagic fish larvae accumulated at the front surface. Taggart et al. (1989), in fact, found a marked peak of jellyfish density at a tidal front in the Canadian coast, while the density of fish larvae was quite low at the front: they rather suspected possible predation of the jellyfish on the fish larvae.

In the case of Osaka Bay, since the biological production in the stratified water of the front is largely maintained by the nutrient supply from Yodo River, vertical mixing due to the frontal disturbances may have a minor role in the production and its variability, compared to the other cases where the nutrient sources were mainly in the lower layer under the thermocline. In other words, the tidal front and its stratified side plays a significant role in providing potentially favorable feeding conditions to fish larvae due to the continuous nutrient supply and subsequent enhancement of the production of prey organisms like copepod nauplii. In addition, the tidal front and eddy act as a barrier/trap, thus keeping the larvae retained in the nurseries where high densities of prey organisms are available.

In conclusion, intermediate-scale physical features we observed in Osaka Bay could be crucial for larval feeding and retention leading to the survival and successful recruitment. There is still serious lack of the information on the dynamic behavior of the front and eddy. Acquisition of time-series data covering the whole sequence of biological and ecological changes for a longer period of time (more than a spring-neap tidal cycle) is therefore indispensable to give a full description of the tidal front and eddy in Osaka Bay.

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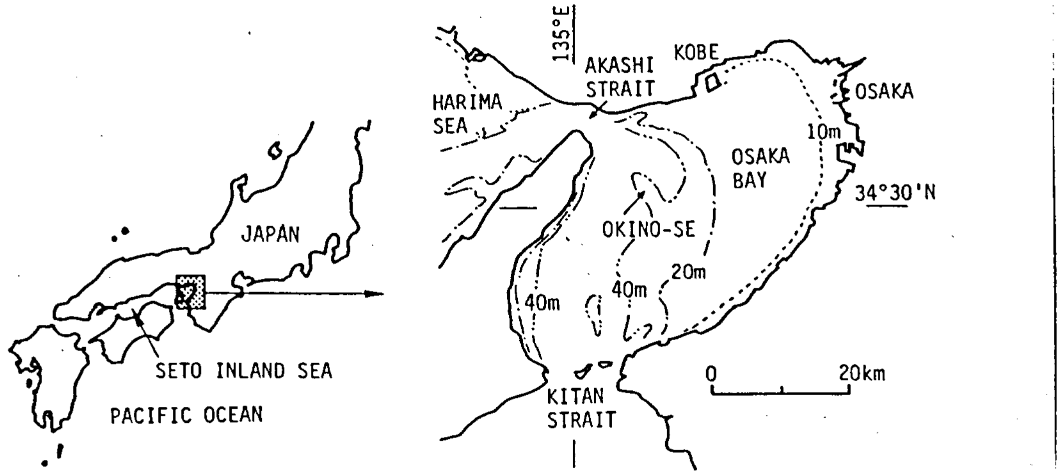

Figure 1. The Seto Inland Sea (left), and topography of the Akashi Strait and Osaka Bay (right): a typical example of a strait-basin system.

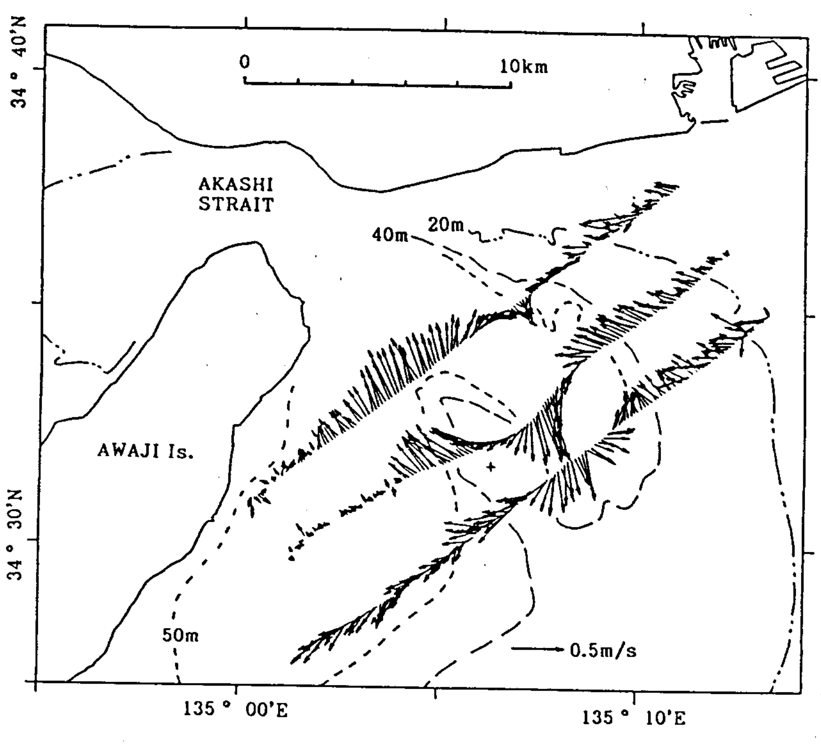

Figure 2. Flow pattern observed with ADCPs at the end of westward current in the Akashi Strait on 16 December 1986 (after Fujiwara et al. 1994).

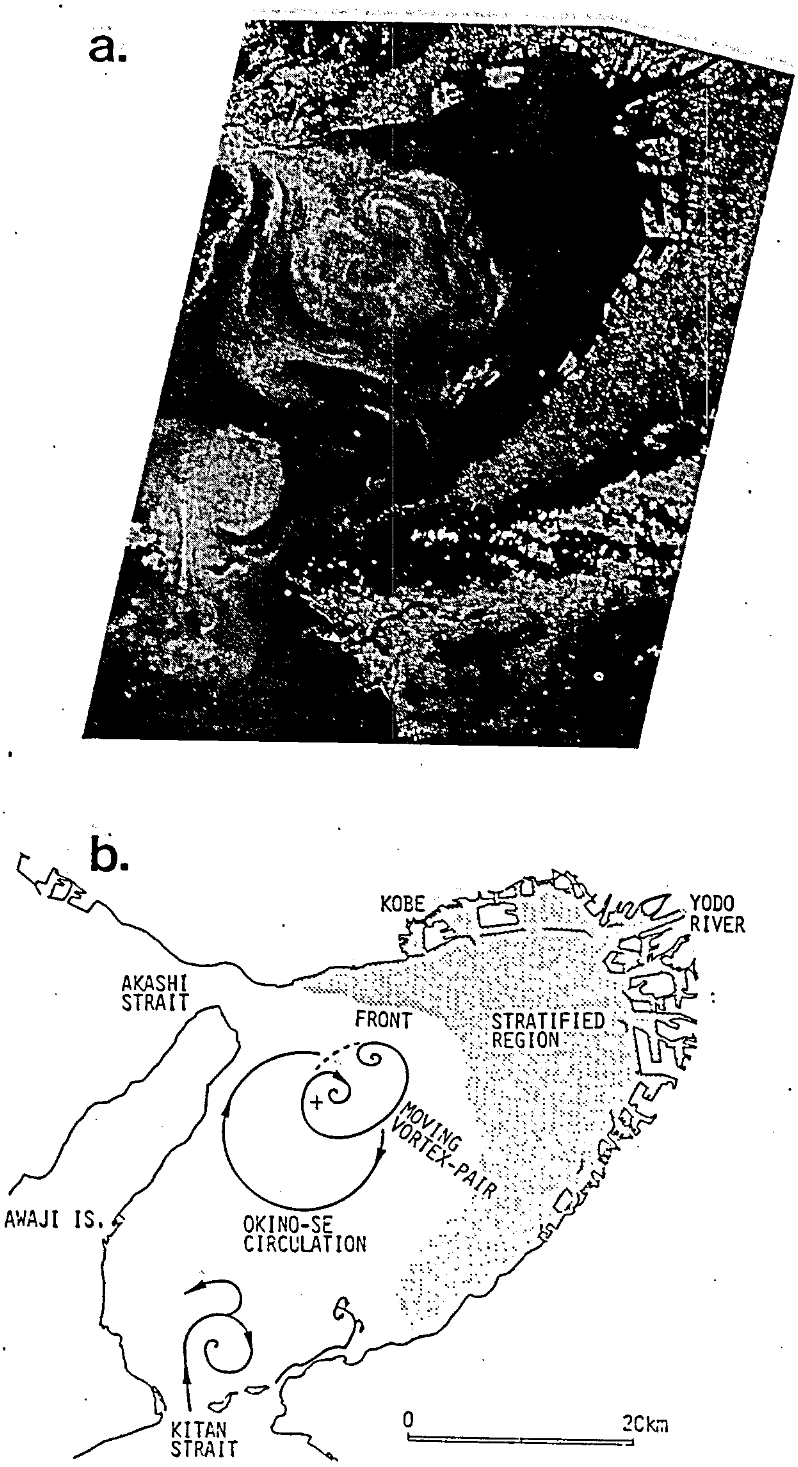

Figure 3. (a) Tidal eddies in Osaka Bay, observed from the artificial satellite MOS-1 (the tidal current in the Akashi Strait is maximun-westward), (b) A sketch of the eddy systems in the western Osaka Bay (after Fujiwara et al., 1994). Tidal fronts develop in between western well-mixed and eastern stratified waters.

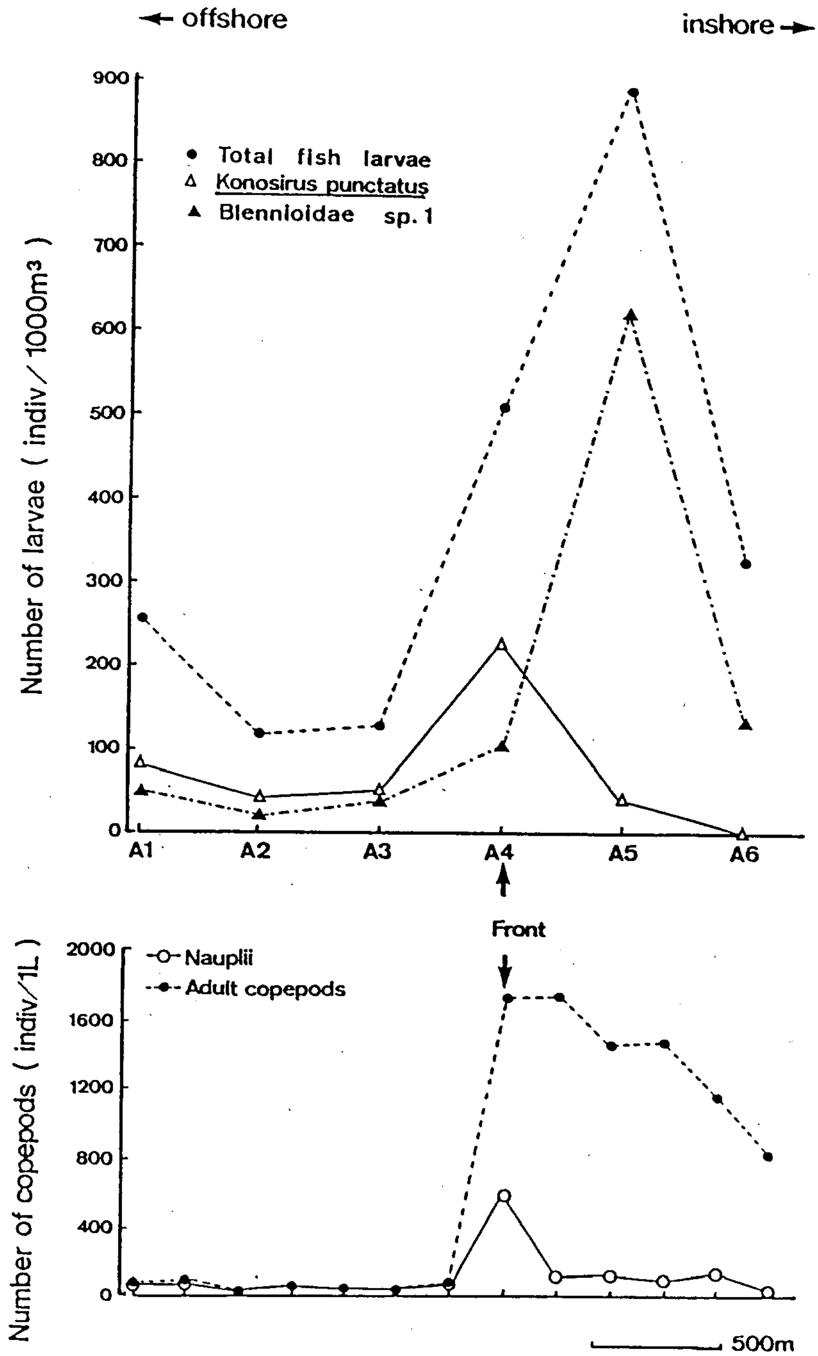

Figure 4. Spatial changes in the abundance of fish larvae (top), copepods and nauplii (bottom) in the surface water along the transect crossing the tidal front in Osaka Bay. The samplings were conducted on 2 July 1991 (see Yanagi et al. 1994 for the location of the transect).

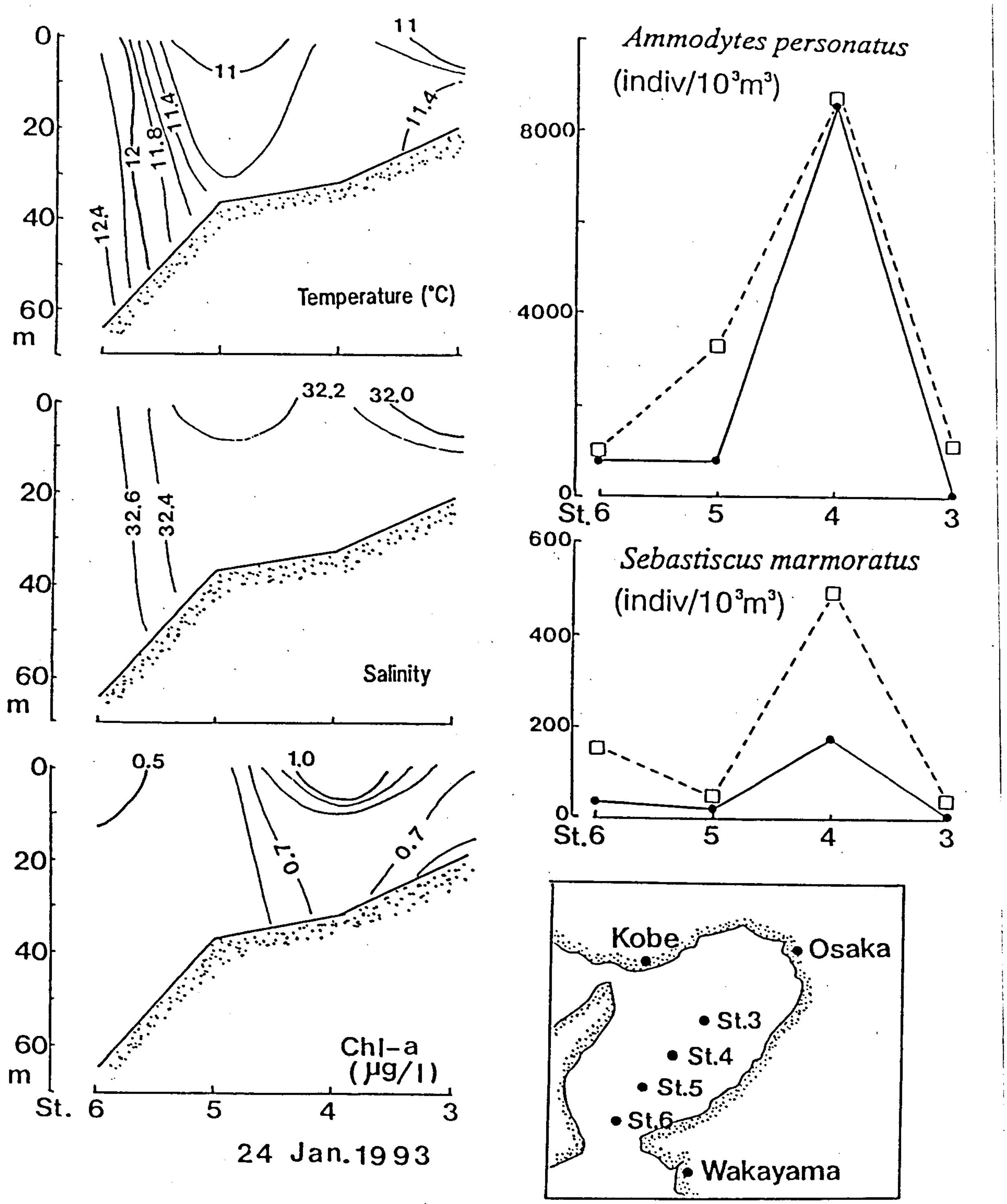

Figure 5. Cross-sectional distributions of temperature, salinity and chlorophyll-a concentration along the longitudinal line of Osaka Bay (shown in the right-hand side bottom) on 24 January 1993, and spatial changes in larval densities of sand lance (right-hand side top) and scorpionfish (right-hand side middle) along the same section. Solid lines and dashed lines denote the results obtained from horizontal tows under the surface and those from oblique tows from 0 to half of the water depth, respectively.

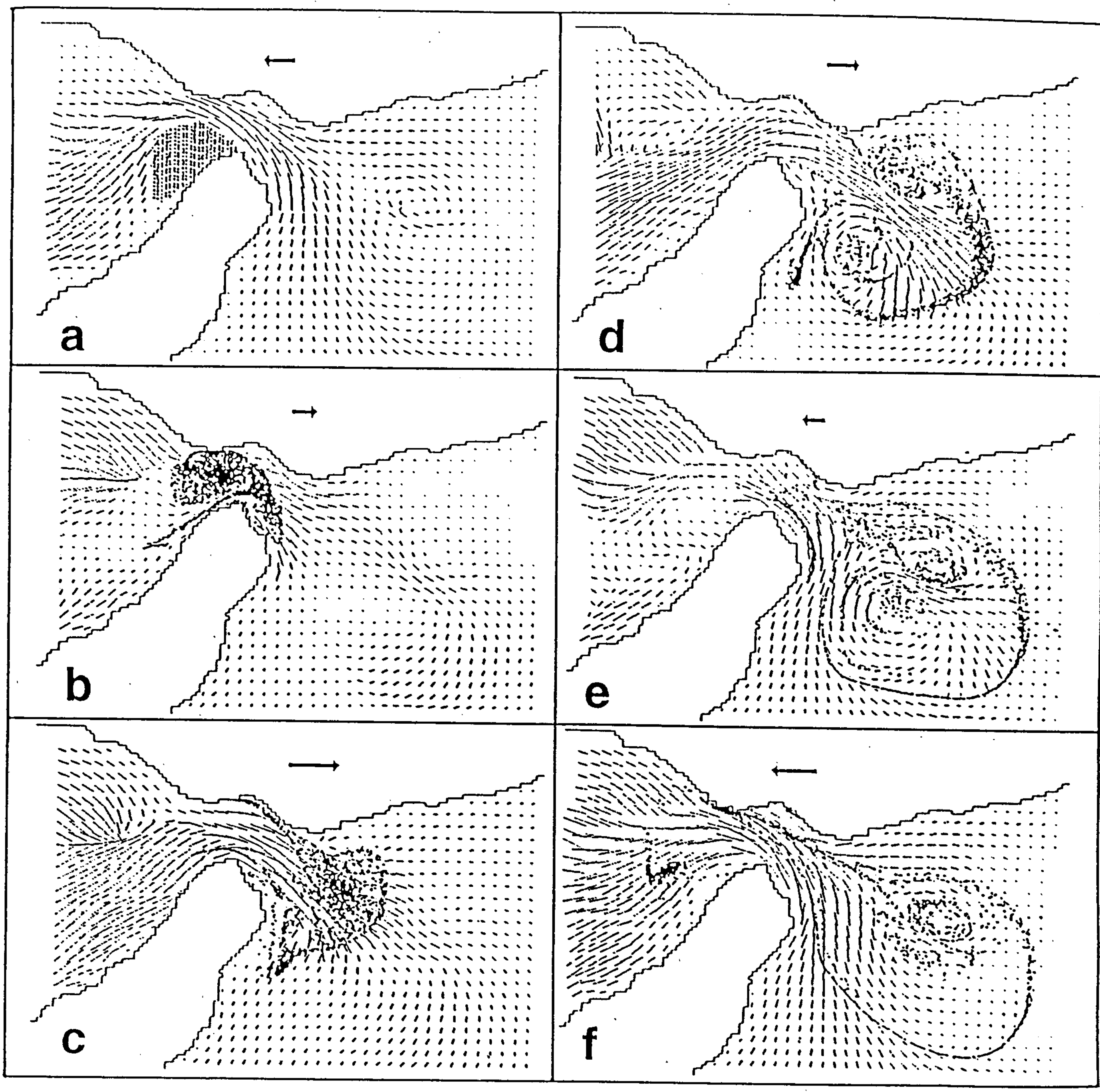

Figure 6. A serial dispersion pattern of the particles released from the west of Akashi Strait and transported by tidal currents into Osaka Bay during a tidal cycle. Solid arrows on top denote the tidal phases indicated by the tidal current at the Akashi Strait corresponding to each phase.

a: initial distribution of the particles (at 2 hours after the maximum westward current)