Volume 23/1991/EMECS '90

Flow Characteristics Governing the Distribution of Water and Bottom Quality in a Semi-enclosed Sea

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Semi-enclosed seas are generally composed of narrow straits and wide basins, forming a strait-basin system. Tidal currents through the strait have a jet-like characteristic. This tidal-jet flows into a stagnant basin and forms a pair of tidal-vortices (vortex dipole). In the strait-basin system, sea area is divided into two regions: well-mixed region around the strait (WM-region), and stagnant and stratified region in the inner part of the basin (SS-region). The WM-region is the region where highly turbulent water comes from the strait, and the SS-region is the opposite of it. Whether a point is included in the WM-region or the SS-region does not depend on a local parameter, but on the hysteresis of the water. In the WM-region, mass and volume transport are driven by the tidal-vortices. The strait-basin system is characterized by "the high energy tidal-jet flowing from the strait into the stagnant basin with a certain period and intensity". The concept of this system is new and could be interesting in future studies of mass transport in semi-enclosed seas.

This paper is concerned with the hydrodynamics and mass transports of a strait-basin system, which is composed of narrow straits and wide basins. Many semi-enclosed seas in Japan form the strait-basin systems, and tidal currents in the strait amount to several meters per second, while a typical tidal current speed in the basin is only 0.1 m/s. Tidal currents through the strait have a jet-like characteristic. This tidal-jet flows into a stagnant basin and forms a vortex dipole. The kinetic energy density in the straits is two or three orders of magnitude larger than that in the basins, and the kinetic-energy source of the strait-basin system is located exclusively in the strait.

In the strait-basin system, sea area is divided into two regions: well-mixed region around the strait (WM-region), and stagnant and stratified region in the inner part of the basin (SS-region). Water and

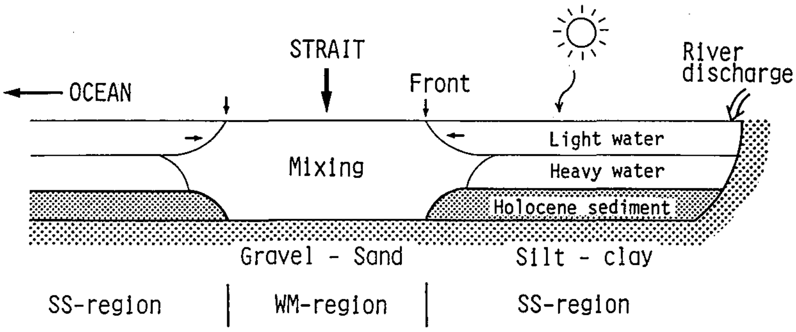

Fig. 1. A schematic view of the distribution of water and bottom quality in a strait-basin system.

Marine Pollution Bulletin, Vol. 23, pp. 675–678, 1991.
Printed in Great Britain
0025-326X/91 $3.00+0.00

bottom quality in the WM-region is clearly different from that of the SS-region. Although there exists a similarity among water quality distribution, bottom quality distribution and bottom topography, very little is known about the mechanism causing this similarity.

In this paper, we clarify this mechanism using the data from detailed observations around the Akashi Strait and Osaka Bay in the Seto Inland Sea of Japan.

Feature of the strait-basin system

A schematic view of the water and sediment properties in summer is illustrated in Fig. 1. In the WM-region, tidal mixing is very intense, so that the vertical diffusion coefficients amount to $10^3 \sim 10^4$ cm^2/s (Fujiwara, 1986), and the DO (dissolved oxygen) is almost saturated in this region.

On the contrary, a typical value of the vertical diffusion coefficient is only $1 \sim 10$ cm^2/s in the SS-region (Okubo, 1970). Warm and fresh water (light water) covers the upper part of this region, and the concentration of DO exceeds 100 % in this layer in summer. Clear discontinuity of surface water properties (front) can be seen between the SS-region and WM-region; warm and low salinity in SS-region, and cool and high salinity in WM-region. Water in the lower layer (heavy water) is lower in salinity and cooler than the water in WM-region. The concentration of DO in the lower layer is low in late summer; and in some eutrophic basins, this becomes nearly zero.

The bottom quality in the WM-region ranges from gravel to sand, on the other hand, it ranges from silt to clay in the SS-region. Since the Holocene sediment has been accumulated during the postglacial period in the SS-region, this region is shallower than the WM-region. Isobath of 20 m depth is a dividing line between two regions in Osaka Bay. This line coincides with the front of the surface water properties.

Tidal-jet in the Well Mixed region

Tidal-jet flowing into Osaka Bay is observed with ship-board ADCPs (acoustic Doppler current profiler) (Figs. 2 and 3). Crosses in the figures represent the location of "Okino-se", which is a sand-bank having the shallowest depth of 23 m. The speed of the tidal-jet exceeds 3 m/s at the maximum eastward current in the Akashi Strait (Fig. 2). After a half tidal

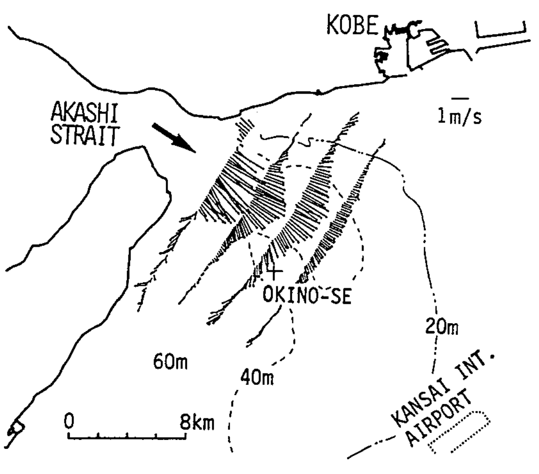

Fig. 2. Flow pattern observed with ADCPs at the maximum eastward current at the Akashi Strait. [From Fujiwara and Nakata (1990).]

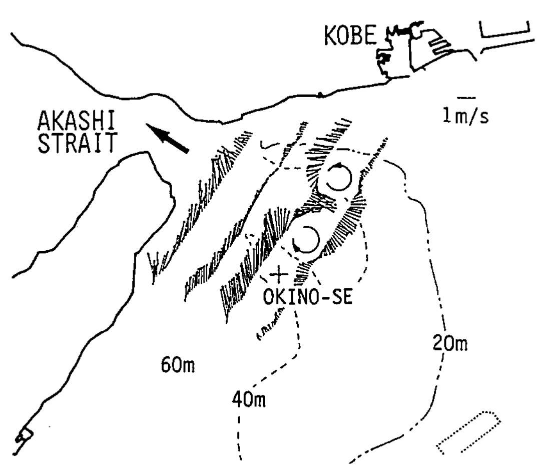

Fig. 3. Flow pattern observed with ADCPs at the maximum westward current at the Akashi Strait. [From Fujiwara and Nakata (1990).]

period, the tidal-jet has changed into a vortex dipole: a pair of counter-rotating vortices (Fig. 3). Although the current in the Akashi Strait is maximum westward, this vortex dipole continues to progress south-eastward and never returns to the strait. Then the clockwise vortex arrives at "Okino-se" and stays there. The clockwise vortices migrating from the strait to "Okino-se" every tidal period promote the clockwise circulation around "Okino-se". In the spring tide, the speed of this circulation exceeds the tidal current; accordingly, the current in the western Osaka Bay circulates clockwise around "Okino-se" all over the tidal period.

Since the tidal-jet and vortex dipole are highly turbid due to a lot of re-suspended sediment, we can see their forms in the images taken from the satellite as shown in Fig. 4. In this figure, the current in the Akashi Strait is maximum westward, and the turbid vortex dipole is shown as a whitish mushroom-like form.

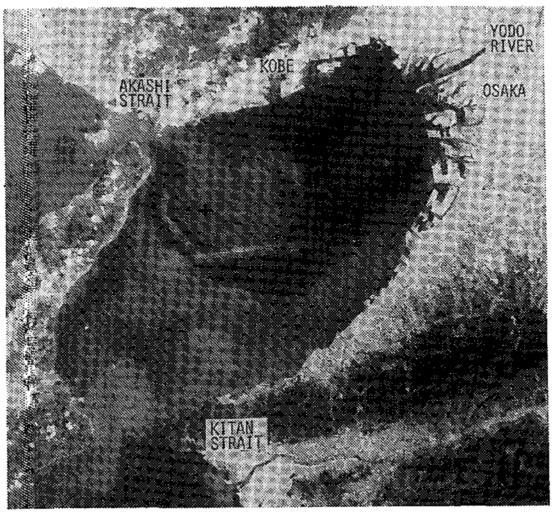

Fig. 4. Visible image of Osaka Bay taken from the satellite (LANDSAT). A cross shows the location of "Okino-se". Tidal current at the Akashi Strait is maximum westward.

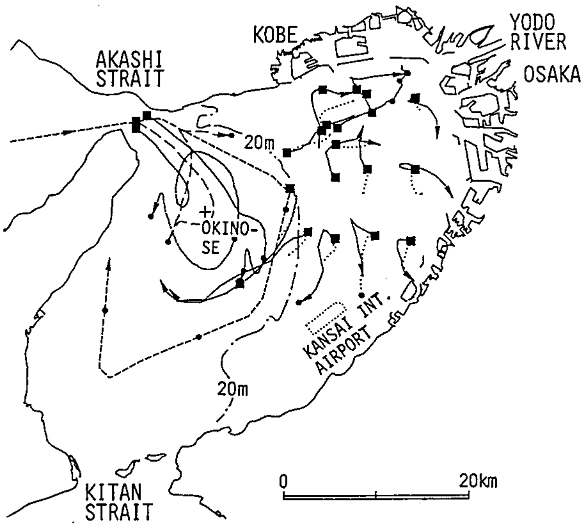

Fig. 5. Drogues trajectories in Osaka Bay and around the Akashi Strait. [From Fujiwara and Nakata (1990).]

Drogues trajectories

Loci of the drogues deployed in Osaka Bay are shown in Fig. 5 (Fujiwara and Nakata, 1990). Squares and circles represent the released points and the locations every 12 hours after the release, respectively. Solid and dotted lines in the eastern Osaka Bay denote the loci of the drogues deployed in the upper layer (depth = 1m) and the lower layer (depth = 3/4 of the bottom depth), respectively.

The drogues having passed through the Akashi Strait move around vigorously within the western Osaka Bay. On the other hand, those in the eastern Osaka Bay move slowly or are stagnant. In addition, the movements of the drogues in the upper layer is different from those in the lower layer; this suggests the existence of a density current. It is noted that the drogues deployed in the WM- and SS-region both stay within the same region. In other words, the water in the WM-region is the water that passed through the straits, on the contrary, the water in the SS-region tend to stay within the region for a long time. The water exchange rarely occurs beyond the front between two regions. In the strait-basin system, whether a point is included in the WM-region or the SS-region does not depend on a local