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Outflow and Three-dimensional Spreading of River Water in Enclosed Bay

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Physical processes of outflow and gravitational spreading of the Yodo River in the Osaka Bay are discussed by means of a three-dimensional, primitive equation model. The river water spreads out radiately over the sea water controlled by horizontal pressure gradients resulting from the density difference. On a large horizontal length scale in the order of the Rossby deformation radius, the earth's rotation exerts a strong influence on its outflow behaviour. The model prediction compares well with the satellite infrared image. The model study indicates that the deformation of outflow pattern and the formation of a coastal current are unique features of the river plume spreading in cases of high river discharges. Since the water quality of enclosed bays depends largely on the input of pollutants through rivers, it is of great importance to understand the outflow dynamics of river plume.

Introduction

Pollutants in the coastal waters can be generally thought to be transported by the tidal flow and the long-term averaged current systems such as the tidal residual flow and the wind-driven or buoyancy-driven flow. In enclosed bays, however, the water quality structure depends largely on the stratification due to the temperature and salinity differences and the input of contaminants through rivers as well as the flow system. That is the problem hydrodynamically concerned with the density flow. In particular, since more man-made waste effluents enter the bays through rivers, the initial dilution of river water or the mixing with sea wateris of prime concern from environmental and engineering aspects.

The seaward expansion of the river flow is usually called a plume. The boundary of the plume forms a front against the open sea. The river plume is well known to exhibit various outflow patterns in response to the discharge and the density difference. Outflow dynamics near the river mouth in the order of 1 km is mainly controlled by inertia and the action of gravity. The river water spreads out radiately over the sea water controlled by horizontal pressure gradients, while it does like a jet flow under the strong inertia. Large variations appear within the tidal cycles. When the horizontal length scale of river plume attains the order of the Rossby deformation radius and that the density differences keep an advantage over the disturbances due to tidal flows and coastal currents, the river plume tends to deflect anti-cyclonically in the Northern Hemisphere affected by the earth's rotation. Inhomogeneities like the above may lead to significantly different outflow patterns depending on the river discharges.

In this study, aspects of the three-dimensional structure of the Yodo River plume spreading in the Osaka Bay are numerically examined. Emphasis is on the density structure and its time and spatial variability as it is a tracer for the outflowing river water.

Outflow of the Yodo River Water in the Osaka Bay

Figure 1 shows the distribution of sea surface temperature of the Osaka Bay observed in the infrared image taken by an air plane and the satellite NOAA. Figure 1(a) demonstrates the typical pattern at average discharge on 13 September 1985. (Ueshima et al., 1987) Higher temperature region spreads from the mouth of the Yodo River to the south direction along the eastern coastline with an obvious front against the sea in deeper depths. As seen from Fig. 1(b), the long-term averaged current system in the Osaka Bay is characterized by two tidal residual flows induced by the strong tidal flow through the Straits of Akashi or the Tomogashima Channel. Among them the large-scale clockwise Akashi circulation greatly governs the current system and the water quality. In summer, the current system becomes more complicated affected by the stratification due to river water inputs and heat exchange at the surface. Generally speaking, the Yodo River water is thought to flow southwards along the eastern coastline drawn by the clockwise circulation as observed in Fig. 1(a).

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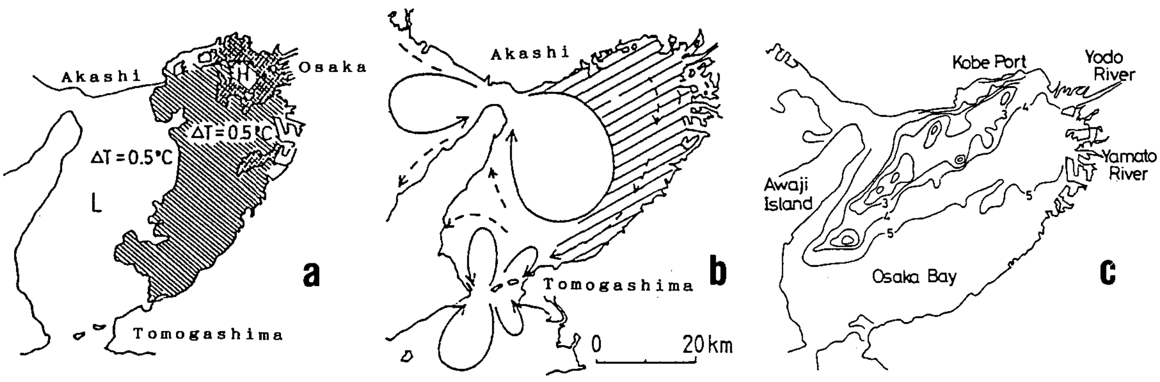

Fig. 1 Infrared image of surface temperature at average discharge on 13 Sept. 1985 (a), and the long-term averaged current system of the Osaka Bay (b) from Ueshima et al.(1987), and the infrared image of surface temperature at flood discharge on 2 Aug. 1982 from Nakatsuji et al.(1989).

On the other hand, the infrared image of Fig. 1(c) is the case of a flood flow, which is taken after only 6 hours from the occurrence of the maximum discharge of 6270 m^3/s on 2 August 1982. It shows a quite different pattern from that of Fig. 1(a). That is, the river water can be identified to flow westwards offshore of Kobe coast at first and to deflect to the southwest direction along the coastline of Awaji Island. It is the question why such a difference can be seen in the Yodo River plume spreading.

Three-dimensional Computation

The three-dimensional model equations are derived from the generalized conservation for mass, momentum, and density difference under the Boussinesq and hydrostatic approximations. The equation set is closed by relating the unknown transport quantities to the corresponding local gradients by the use of turbulent viscosity or diffusivity coefficients. By dropping the vertical acceleration term from the vertical momentum equation, the free surface elevation is computed by performing a mass balance in the vertical. Since the velocity gradients contained in the continuity equation are integrated numerically using an implicit finite scheme, the free surface elevation can be expressed in the form of a two-dimensional Poisson-type equation. The SOR method is used for its calculation. Although the surface elevation is not so large, its gradients can exert a significant influence on the pressure field. The solution scheme is explicit in time except for the free surface elevation calculation. Details of computation scheme are described in the author's previous paper (Nakatsuji et al., 1989).

The model's resolutions are $\Delta x = \Delta y = 2$ km, $\Delta t = 6$s, and the 8 layer thicknesses Δz are chosen as 0.4 m to 20 m from top to bottom. Because of CPU time and storage limitation of computer, tidal flows are not taken into account here. However, the flow transition at the Straits of Akashi is considered in the following way that the Straits is treated as a solid boundary when the sea water of Harimanada Bay flows into the Osaka Bay through the strait while it is as an open sea boundary during the rest time based on the observation of tidal variation. The discharge of the Yodo River is given every moment according to the measured hydrograph between 1st and 4th of August, 1982. During that period, the typhoon 8210 and the succeeding passage of the low atmospheric pressure hit the Osaka district to cause a localized torrential downpour of the maximum discharge of 6270 m^3/s. The density difference between river water and sea water is 0.022 kg/m^3. The layer depth and and width of river discharge at the mouth are assumed to be 0.8 m and 2,000 m respectively. Consequently, the river discharges more than 1200 m^3/s might behave as a jet-type flow since the densimetric Froude number exceeds unity.

The parameter values of the present computation are as follows: The Coriolis parameter f is $0.8296 \cdot 10^{-4}$ s^{-1}. The values of horizontal and vertical eddy viscosities are taken to be 20 m^2/s and 0.0005 m^2/s, and so are the eddy diffusivities. They are commonly used values for numerical studies on coastal phenomena. The vertical eddy coefficients, however, are assumed to decrease with increasing gradient Richardson number taking the stratification effects into account. Following the study of Murota et al. (1988), the Webb's function (1970) is adopted to the vertical eddy viscosity and the Munk and Anderson's function (1948) is to the vertical eddy diffusivity.

Computational Results

Effects of Earth's Rotation on River Plume Spreading

Figure 2 shows the horizontal velocity and density fields in the surface layer of 0.4 m thickness after 20 hours from the beginning of flood flow for the cases with and without the earth's rotation. The discharge and the densimetric Froude number at the river mouth are 3100 m^3/s and 4.7, respectively. Contours of the density difference normalized by the initial difference are denoted by broken lines in intervals of 10 %. In the case without rotation the Yodo River plume shows to behave like a surface jet-type flow in the near field possibly accompanied by intense mixing with sea water. The mixed water, still of relatively large density difference, then spreads out over the sea water in the radial directions accompanied by a thinning in its vertical extent. It is a typical plume-like flow. It is because the horizontal pressure gradients arising from the buoyancy become dominant over the momentum with increasing distance away from the river mouth. The isopycnal contours tend to fan out with a concentric circle and the velocity vectors cross at the right angle to the isopycnal contours.

On the other hand, in the case with the earth's rotation, the velocity vectors turn to the right, so only alongshore velocities appear. The isopycnal contours show to be stretched out in parallel to the coastline and even the outermost 10 % contour is confined inside the extent of about 10 km offshore. It is a clear indication of the river plume being a geostrophic current. The radius of Rossby deformation appropriate for the present model may be $\sqrt{(\Delta\rho/\rho)gh}/f$ = 10 km where $\Delta\rho/\rho$ is the initial density difference and h is the layer thickness of river plume. It indicates that the offshore expansion of river plume fixes the limits of the Rossby deformation radius. The plume reattaches to the right-hand side coast forming a coastal current. Such a flow can be often visible in the river water effluents even from the air plain due to the colour contracts in the different water masses.

It can be observed clearly from the comparison between two computational results that the earth's rotation forces the river plume spreading to deflect anticyclonically and to form a baroclinic boundary current that keeps the coastline on its right-hand side.

Development of the Yodo River Plume

Figure 3(a) shows the surface velocity and density fields after 35 hours computed with the earth's rotation, which corresponds to the infrared image taken from the satellite NOAA shown in Fig. 1(c). The Yodo River plume at this time behaves basically the same as that observed in Fig. 1(c). It indicates that the Coriolis force may significantly affect the Yodo River plume spreading. The point of interest here is that the isopycnal contours have a close distribution one another at the tip of river plume. Because of the geostrophic adjustment, the rotation may suppress offshore spreading but accelerate alongshore spreding that leads the formation of frontal structure mentioned later. The front can be seen to propagate southwestward along the coastline of Awaji Island as a narrow current with its width of 6 km. It is worthy emphasizing that its speed is about 0.4 m/s away 55 km from the river mouth. Its propagation speed is considerably larger beyond one's expectations.

Figure 3 demonstrates the time-variation of the Yodo River plume spreading after 35 hours to 60 hours from the beginning of flood. Although the propagation speed shows a slight decrease, the river plume continues to move along the coast with keeping a frontal structure. It is interesting that the Yodo River water reaches the Tomogashima Channel after only 60 hours. Since the distance between the river mouth and the

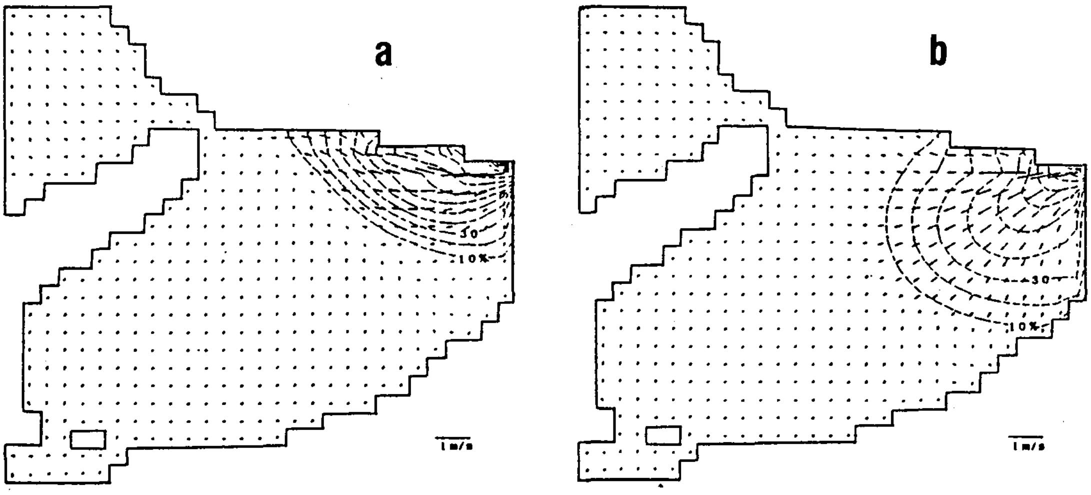

Fig. 2 Surface velocity and density fields of the Yodo River plume spreading after 20 hours from the beginning of flood; the left side (a) is the case with earth's rotation and the right side (b) is the case without earth's rotation. Isopycnal contours are denoted by dotted lines in intervals of 10 % of the initial density difference, 0.022 kg/m^3.