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Impact of sporadically enhanced river discharge on the climatological distribution of river water in Suruga Bay

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Abstract — In Suruga Bay the river discharge is sporadically enhanced by heavy rainfall, and its daily mean values often exceed by an order of magnitude the seasonal means. We have therefore investigated the impact of the sporadically enhanced river discharge on the climatological distribution of river water in Suruga Bay, performing numerical experiments with an ocean general circulation model. As the river discharge is enhanced, a larger amount of the Coastal Water (defined by salinity less than 33.0) is exported out of shallow areas such as the continental shelf, being less trapped by the bottom topography. Moreover, the high frequency (day-scale) variation in the river discharge causes large temporal variations of the surface salinity distribution in the bay. However, it has only a minor influence in the time-averaged field (under the same condition in terms of the total amount of the discharged river water). It is therefore suggested that in the actual sea, the high frequency (day-scale) variability in the river discharge has only a minor influence on the climatological distribution of river water in the bay.

Key words: river water spreading, sporadically enhanced discharge, Suruga Bay, numerical experiment

Introduction

River discharge is one of the important factors controlling surface circulation in Suruga Bay (e.g., Nakamura, 1982). Recently, Tanaka et al. (2009, hereafter referred to as TMKI09) have investigated spreading processes of river water in Suruga Bay, using a numerical model to which climatological (seasonal mean) discharge of four large rivers (the Fuji, Kano, Abe and Oi Rivers) is applied. In the model the river water spreads over large areas of the bay in the rainy summer season.

Moreover, TMKI09 have pointed out the importance of the bottom topography to the river water spreading in Suruga Bay. That is, the Fuji River water tends to spread over a deep continental slope as a surface-advected plume, and therefore it extends far offshore. The Oi and Abe River waters, on the other hand, tend to flow parallel to isobaths (along a coastline) in narrow coastal areas on a shallow continental shelf as bottom-advected plumes. TMKI09 have, however, used only climatological (seasonal mean) values of the river discharge in the experiments.

In actuality, the river discharge is sporadically enhanced by heavy rainfall, and its daily values often exceed by an order of magnitude the seasonal means, as will be discussed later. In other words, the large value of the summer mean discharge, which was used in TMKI09, is attributed to frequent occurrence of the sporadically enhanced river discharge (on the time scales of a day to several days). It is, however, not evident whether the climatological (seasonal mean) discharge and the sporadically enhanced discharge have the same or different effects on the river water spreading in the bay. In this study, therefore, we investigate the impact of the sporadically enhanced river discharge on the river water spreading in Suruga Bay to confirm the validity of the climatological model used in TMKI09, performing numerical experiments.

Materials and Methods

Daily variation of river discharge

We begin by examining daily variation of the Fuji River discharge. Figure 1 shows daily mean values of the Fuji River discharge during June–September (in the rainy summer season) from 1990 to 2002, using River Discharges Year Book of Japan (Ryuryo-Nenpyo in Japanese) edited by Ministry of Land, Infrastructure and Transport, Government of

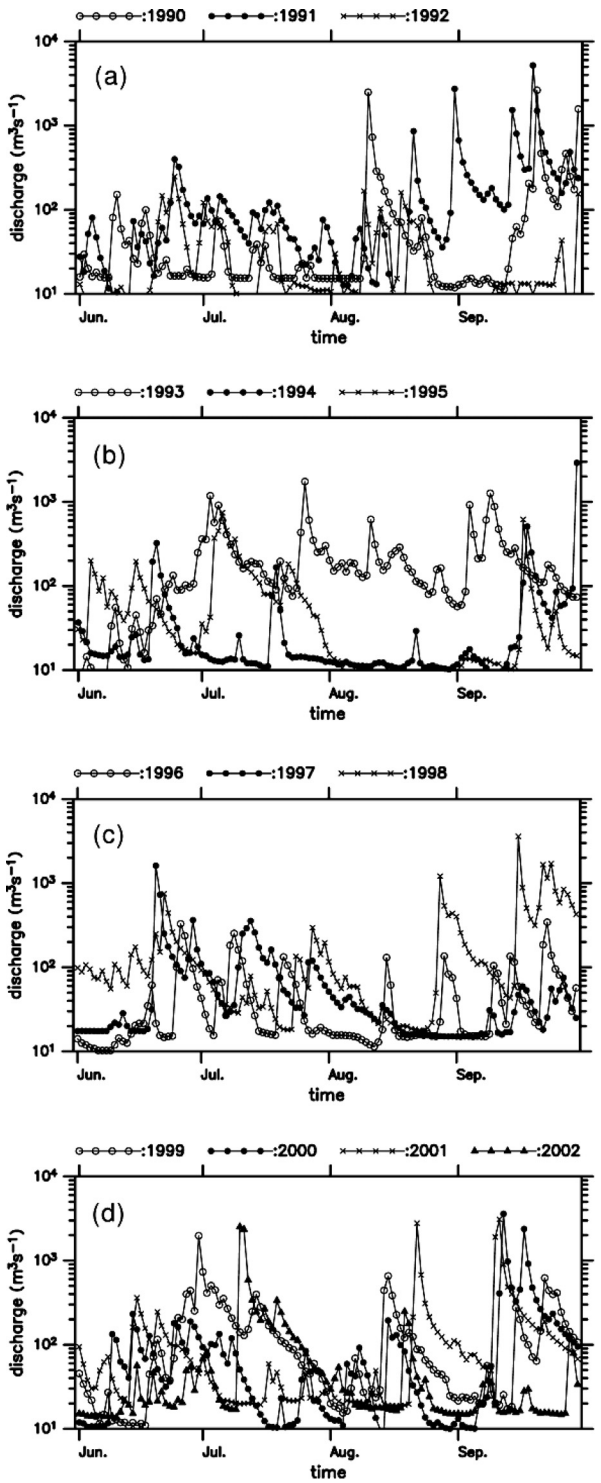

Fig. 1. Daily mean values of the Fuji River discharge (on a logarithmic scale) during June–September, which are estimated using River Discharges Year Book of Japan: (a) 1990–1992, (b) 1993–1995, (c) 1996–1998, and (d) 1999–2002.

Japan. The Fuji River discharge varies considerably on time scales of a day to several days, and its peak values often exceed $1000\,m^3\,s^{-1}$.

Many of the extraordinary discharges were due to heavy rainfalls associated with typhoons passing nearby. During the period 1990–2002, the largest value of the discharge is $5189.0\,m^3\,s^{-1}$ (on September 19, 1991). This value is about 40 times as large as the climatological summer mean discharge of $124.9\,m^3\,s^{-1}$, whose approximate value of 125 $m^3\,s^{-1}$ was used in TMKI09 to investigate the climatological spreading processes of river water. Similar features of the daily discharge variation are also seen in other rivers such as the Kano, Abe and Oi Rivers (not shown here).

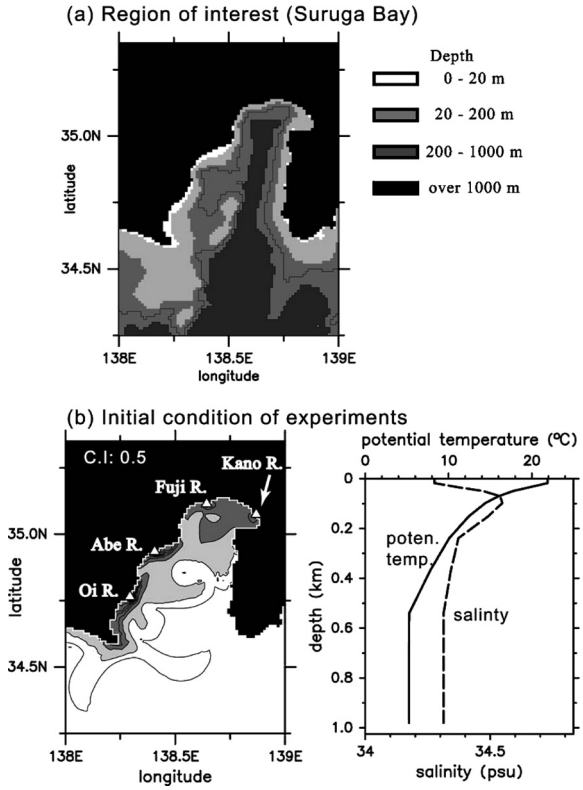

Fig. 2. (a) Model topography in the region of interest (, which is only part of the calculation domain). (b) Initial condition of the experiments. Left panel: horizontal distribution of sea surface salinity, which is taken from TMKI09 (the result on day 50 in the case where the climatological summer mean river discharge was applied to the summer stratification). Light and dark shaded regions indicate values lower than 33.5 and 33.0, respectively. Contour interval is 0.5. Triangles indicate locations of the river mouths. Right panel: background vertical profiles of salinity and potential temperature, which are taken from the 138.5°E and 34.25°N.

Model configuration

The numerical model configuration is almost the same as used in Tanaka et al. (2008) and TMKI09. A brief description follows. The model is based on the GFDL Modular Ocean Model (MOM) 3.1, and the governing equations are primitive equations with a free surface boundary condition (Pacanowski and Griffies, 2000). Although the region of interest is in Suruga Bay (Figure 2a), the calculation domain extends from 135.7°E to 142.0°E and 32.5°N to 35.71°N (not shown here). The longitudinal and latitudinal grid spacings are 0.0125° and 0.01°, respectively, in the region of interest.

There are 14 levels in the vertical, with a spacing of 5 m at the surface, smoothly increasing to about 240 m at the bottom; the maximum depth is 1100 m.

The Smagorinsky scheme is adopted with an adjustable constant of proportionality of 0.8 for horizontal mixing (Smagorinsky, 1963). With regard to vertical mixing, simple forms are used to reproduce the surface boundary layer. That is, below 20 m depth, coefficients of vertical turbulent viscosity and diffusivity are constant values of $1.0\times10^{-3}\,m^2\,s^{-1}$ and $3.0\times10^{-5}\,m^2\,s^{-1}$, respectively. Above 10 m depth, both values are $1.0\times10^{-2}\,m^2\,s^{-1}$. They are interpolated between depths 10 m and 20 m. The surface boundary layer with a thickness of about 20 m has been indeed observed in the bay (e.g., Nakamura, 1972; Nakamura and Muranaka, 1979).

The model is driven only by the river discharge, which is applied at the mouths of the Fuji, Kano, Abe and Oi Rivers as freshwater flux through a surface boundary condition. The initial (day 0) state of the experiments is taken from TMKI09, which is the result on day 50 in the case where the climatological summer mean river discharge was applied to the summer stratification (Figure 2b). Since Nakamura and Muranaka (1979) has defined the summer surface waters with salinity S less than 33.0 and 33.0–33.5 as the Coastal Water and Mixed Water, respectively, these waters are shaded darkly and lightly, respectively, in the left panel of Figure 2b.

Our experimental design is presented in Figure 3. In a control experiment (case A) the climatological summer mean river discharge continues to be applied until the end of the experiment, i.e., until day 40, which corresponds to day 90 in TMKI09 (Figure 8a in TMKI09). Then, we perform four experiments, in which the river discharge is enhanced, but it is sporadically applied so that the time-integrated amount of the discharge is the same as in case A. That is, the river discharge is increased by factors of 5, 10, 20 and 40 in cases B, C, D and E, respectively (Table 1), while it is applied for a duration of one day every 5, 10, 20 and 40 days in cases B, C, D and E, respectively.

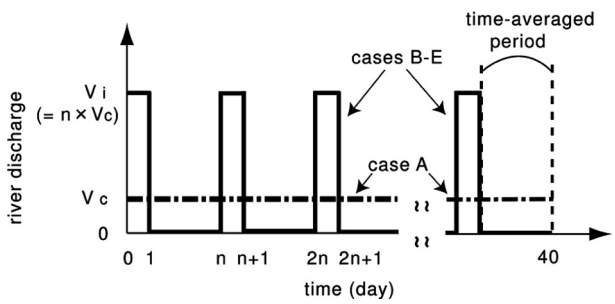

Fig. 3. Diagram of experimental design. In case A (control experiment), a temporally constant river discharge (Vc) is applied during the experiment (indicated by a dash-dotted line). In cases B, C, D and E, the discharge is enhanced (up to Vi by a factor of n=5, 10, 20 and 40, respectively), but it is applied for a duration of one day every n=5,10, 20 and 40 days (solid line).

Results

Figure 4 shows surface salinity distributions on day 1. In case A (control case, Figure 4a) the Coastal Water ($S\leq33.0$, shaded darkly in the figure) is confined to relatively narrow coastal areas, especially around the Oi and Abe River mouths, where it is particularly localized within a few to several km of the coast. This is because in the climatological state, the Oi and Abe River waters tend to flow parallel to isobaths (along the coastline) as bottom-advected plumes, as discussed by TMKI09. The bottom-advected plumes form on the shallow continental shelf, the depth of which is almost the same as the river plume thickness (15–20 m, Figure 2a).

In case E (Figure 4e), on the other hand, the Coastal Water ($S\leq33.0$, shaded darkly) extends relatively farther offshore (greater than 10 km from the coast) on day 1, because the huge river discharge is abruptly applied during a short time. In case E, as compared to case A, a larger amount of the Coastal Water is exported out of the shallow areas. The exported Coastal Water into the deep basin can rapidly extend offshore as a surface-advected plume, because it is not trapped by the continental shelves, as pointed out by TMKI09. The patterns obtained in cases B–D are between those of cases A and E.

Figure 5 shows the surface salinity distributions on day 20 and day 40 in cases A and E. In case A the surface salinity distributions show no drastic change from that on day 1, indicating that the bay circulation reaches a nearly steady state. In case E, on the other hand, the salinity distribution varies greatly with time: the bay becomes relatively saline with time, since a large amount of low-salinity water is swept out of the bay.

Next, we investigate time-averaged effect of the sporadi-

Table 1. River discharge in the experiments (m^3s^{-1}).

	Fuji R.	Kano R.	Abe R.	Oi R.
case A (constant discharge: V_c)	125	50	45	140
case B (temporally enhanced: $V_i=5\times V_c$)	625	250	225	700
case C (temporally enhanced: $V_i=10\times V_c$)	1250	500	450	1400
case D (temporally enhanced: $V_i=20\times V_c$)	2500	1000	900	2800
case E (temporally enhanced: $V_i=40\times V_c$)	5000	2000	1800	5600

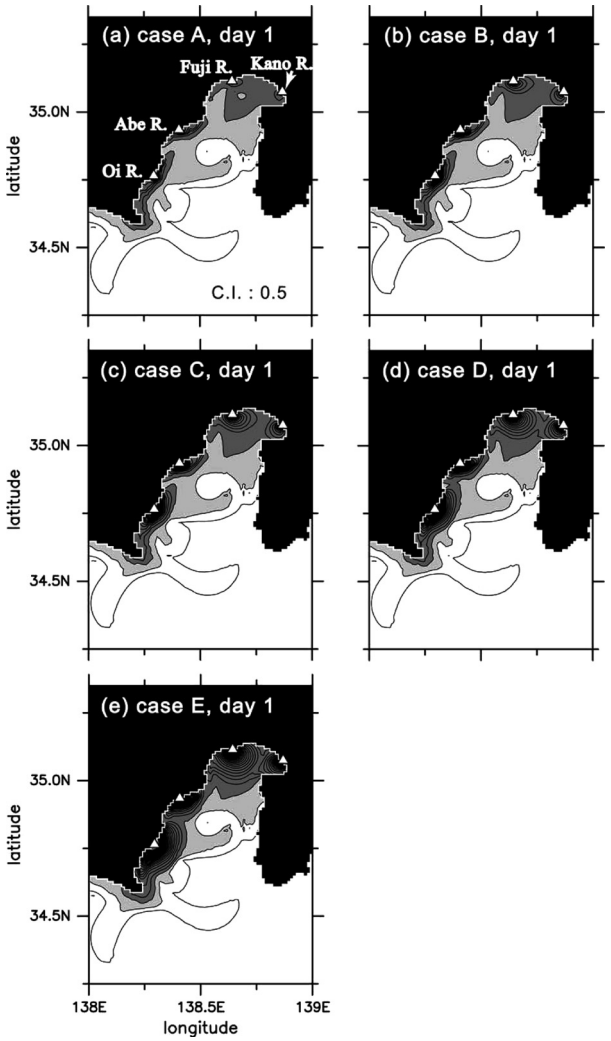

Fig. 4. Surface salinity distributions on day 1: (a) case A, (b) case B, (c) case C, (d) case D and (e) case E. Values in the shaded regions and contour interval are the same as in Figure 2b.

cally enhanced river discharge, which is closely related to the climatological distribution of river water in the actual sea. To do this, we produce time-averaged field. The dashed vertical lines in Figure 3 indicate the average period used in cases B–E: the time average is taken after the last river discharge finishes. With regard to case A, a snapshot at the end of the experiment (day 40) is taken. Thus, the comparison of the time-averaged field among cases is made under the same condition in terms of the total amount of the river water discharged into the sea.

Figure 6 shows the surface salinity distribution in the time-averaged field. As compared to case A (control case), the enhanced river discharge in cases B–E (relatively) increases somewhat the time-averaged salinity in the vicinities of the river mouths, whereas it slightly decreases the salinity over the other regions in the bay, which are also clearly seen in the salinity anomalies from the control case (Figure 7). These anomalies are interpreted as the result of the enhanced export of the Coastal Water ($S \leq 33.0$) out of the shallow areas into the deep basin, as mentioned above.

Around the Fuji River mouth in the time-averaged field (Figure 6), therefore, the surface area of the Coastal Water (shaded darkly in Figure 6) tends to increase as the river discharge is enhanced. It should be noted, however, that the increased area is not so large. Moreover, around the Oi and Abe River mouths, there is little or no significant difference in the Coastal Water area between the control case (A) and the other cases (B–E), since the river water that is exported out of the continental shelf regions is rapidly swept out of the bay, as seen in Figure 5. As a result, the total surface area of the Coastal Water tends to increase slightly as the river discharge is enhanced, as indicated in Figure 8, which shows surface areas of the low-salinity waters in the time-averaged field. Moreover, there are no clear trends in the surface areas

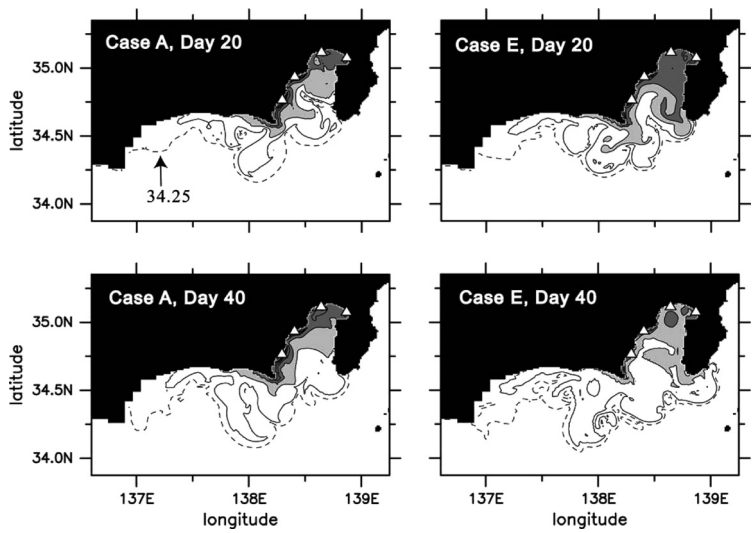

Fig. 5. Surface salinity distributions on day 20 (upper panels) and day 40 (lower panels). Left panels: case A. Right panels: case E. Values in the shaded regions and solid contour interval are the same as in Figure 2b. Dashed contour lines indicate the salinity of 34.25.

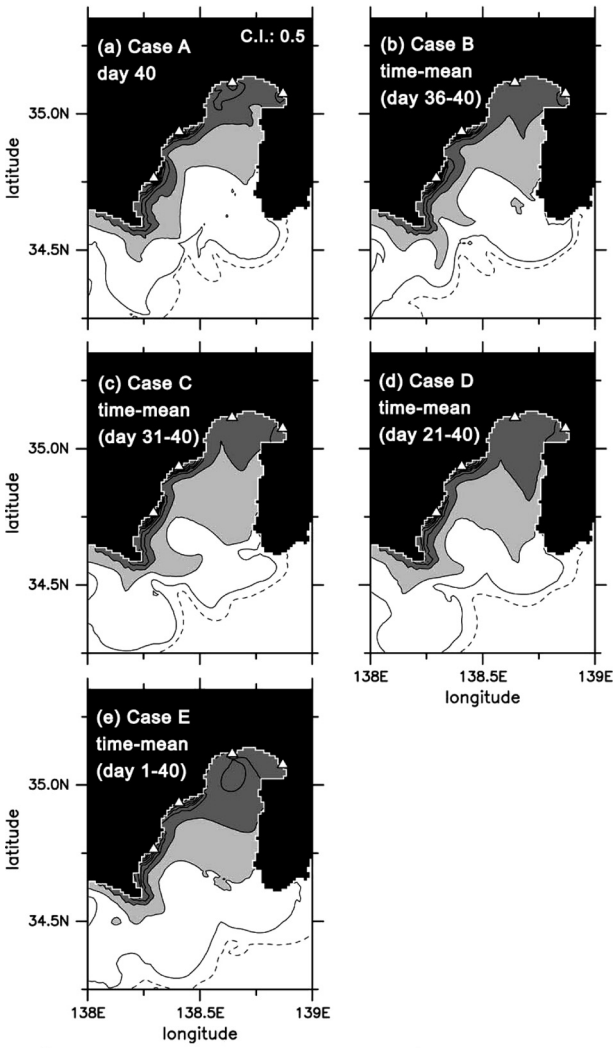

Fig. 6. Time-averaged distributions of the surface salinity after the last river discharge finishes: (a) case A, (b) case B, (c) case C, (d) case D and (e) case E. Values in the shaded regions and contour interval are the same as in Figure 5.

of the other low-salinity waters ($33.0<S\leq33.5$ and $33.5<S\leq34.0$), whereas they seem to be affected somewhat by complicated nonlinear processes of river water spreading with small scales.

Discussion and Conclusion

The difference among cases is slight in the time-averaged low-salinity water distribution, although the Coastal Water ($S\leq33.0$) is transported slightly farther offshore as the river discharge is enhanced. It was also suggested that this result is robust, performing additional experiments with another initial condition that is taken from day 0 instead of day 50 in TMKI09 (not shown).

The reason why the difference in the time-averaged salinity distribution is slight among cases is explained as follows. The spreading of river water in Suruga Bay is strongly

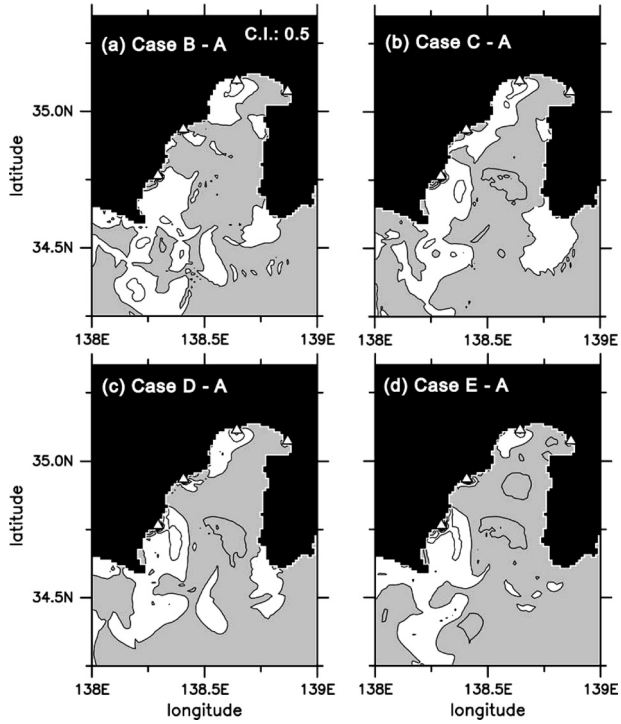

Fig. 7. Surface salinity anomaly from the control case (case A) in the time-averaged fields shown in Figure 6: (a) case B, (b) case C, (c) case D, (d) case E. Shaded regions indicate negative values, and contour interval is the same as in Figure 5.

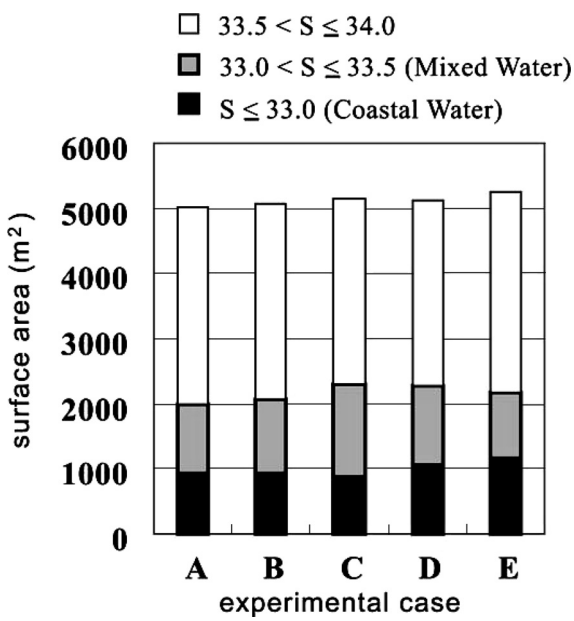

Fig. 8. Surface areas of the low salinity waters in the time-averaged field after the last river discharge finishes. The area integration is carried out over the entire region of the model.

influenced by the Earth's rotation, as discussed in TMKI09. The rotation effect can be measured by the Rossby number, which is defined by

$$Ro = \frac{U}{fL}, \quad (1)$$

where U is the current velocity scale in the river water plumes, f is the Coriolis parameter, and L is the length scale of the river water plumes. With values of $f = 8.4 \times 10^{-5}\,\mathrm{s}^{-1}$ (corresponding to 35°N) and $L = 10\,\mathrm{km}$ (estimated on the basis of the plume width), the Rossby number Ro is estimated to be smaller than 1.0 if $U < 0.84\,\mathrm{ms}^{-1}$, and this condition is, on the whole, satisfied in the model. That is, the river water spreading is basically considered as a geostrophic adjustment process, and the distribution of the river water (low-salinity water) is mainly controlled by the total amount of the river water (buoyancy) discharged into the sea, being affected by the complicated, coastal and bottom topography. Therefore, the difference among cases is minor in the time-averaged field, where the total amounts of the discharged river water are the same among all cases, and the spreading time scales are also almost the same among the cases (drift time of each river-water parcel after its discharge is, on average, about 20 days in the time-averaged field).

As mentioned above, the river discharge in Suruga Bay is sporadically enhanced by heavy rainfall, and its daily mean values often exceed by an order of magnitude the seasonal means. The high frequency (day-scale) variation in the river discharge causes large temporal variations of the surface salinity distribution. The result obtained in this study, however, suggested that the high frequency variability in the river discharge has only a minor influence on the climatological distribution of river water in Suruga Bay.

Although we have used the model based on the realistic topography, some conditions have been idealized and significant problems still remain. For example, we used the fixed profiles of vertical turbulent diffusivity and viscosity that depend only on the depth. Actually, however, these profiles depend on time and also vary horizontally, and they may be affected by the volume discharge of river water. To more precisely reproduce the surface boundary layer in which the river water spreads, we need to use a more realistic vertical mixing scheme with realistic atmospheric conditions in future work. Moreover, we should take account of other external forcings such as tides, winds, and intrusion of the Kuroshio water. Nevertheless, the present study advances our understanding of the river water spreading in Suruga Bay, since the impact of the sporadically enhanced river discharge has been scarcely investigated hitherto.

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