Annual Meeting of Korean Society of Coastal and Ocean Engineers
Korea Ocean Research and Development Institute, 11-12 October 1996

Physical processes related to coastal water quality problems

Hidetaka Takeoka*

Introduction

Industrialization and urbanization of coastal areas in recent years have brought about a lot of coastal marine environmental problems. Water quality problems such as eutrophication or pollution by toxic chemicals are especially serious, threatening coastal ecosystems. These problems are mainly induced by anthropogenic loads of materials from the land. In order to design suitable counter measures, we should well understand the processes causing the problems. Our subjects in such understandings may be classified into two categories such as (1) how the concentration of a material is determined in a coastal sea and (2) what happen at the determined concentration of the material in the coastal sea. Here I will present two topics on the physical processes related to these two subjects.

What we should solve in the subject (1) is the relation between a flux, *F*, of a material to a coastal sea and a standing stock, *M*, of the material in the coastal sea. The ratio of *M* to *F*, that is, $\tau_o = M/F$, has a dimension of time and is often called an average residence time (or turn-over time) of the material*1. This time scale τ_o is mainly determined by movements of the water. For example, if the source of the material is a river and a sink is an outer ocean, τ_o is an average of the time for the particles of the material to travel from the river mouth to the outer ocean. These travels are carried out mainly by movements of the water such as advection and diffusion. However, in some cases this time scale is modified by biogeochemical processes. How it is modified is the first topic related to the subject (1).

In the water quality problems of toxic materials such as organochlorines or heavy metals, what happen at the given concentrations are mainly biogeochemical or toxicological matter, and the roles of the physical processes seem to be less important in the subject (2). In the eutrophication problems, however, not only the level of eutrophication but also intensity of vertical mixing (or intensity of stratification) is often a decisive factor. Since the intensity of light is vertically quite different, primary production by phytoplankton and, accordingly, concentrations of nutrients and oxygen are much influenced by the intensity of vertical mixing. Hence, red tide and oxygen deficiency, which are major undesirable phenomena related to the eutrophication, are controlled by the vertical mixing. For example, anoxic water is never formed in a narrow strait of strong tidal currents, even though the water is highly eutrophic. The second topic presented here, related to the subject (2), is on the benthic thermocline which is formed in many seas in the Seto Inland Sea and plays very important roles in the occurrence of red tide and hypoxic or anoxic water mass.

Transport including biogeochemical processes

Here we consider a material whose source is a river and a sink is an adacent ocean. If the

---

* Dipartment of Civil and Environmental Engineering, Faculty of Engineering, Ehime University Bunkyo 3, Matsuyama 790-77, Japan (takeoka@coe.ehime-u.ac.jp)

*1 We can define other time scales related to the transport problems. Moreover, there are some sources for some materials, and the time scales should be defined for each source. Therefore, the transport time scales are rather complicated. As for the details, see Takeoka (1984a, 1984b).

material is permanently dissolved and moves with the water, its average residence time is the same as that of the river water, which is determined by only the physical processes. Bioelements such as nitrogen and phosphorus are, however, transformed into particles by the primary production, and they sink toward the lower layer. Hence, their average residence times are no longer the same as that of the river water, but usually they are enlarged by the following process.

In a coastal sea, there is often offshore mean flow in the upper layer and onshore one in the lower layer mainly due to inflow of river water. In such a flow system, some part of particulate organisms produced from the dissolved nutrients in the upper layer settles down to the lower layer, and is carried back to the inner region by the onshore flow. Further it is decomposed to dissolved nutrients, and returns to the upper layer by upwelling or vertical mixing (Fig.1(b)). Succession of such processes makes the average residence time of the bioelements larger than that of the river water, which mostly stays in the upper layer and rapidly flows out to the outer sea (Fig.1(a)). The bioelements are thus trapped in the coastal sea due to the coupled effect of the flow system with vertical shear and the transformation between dissolved and particulate forms by biogeochemical processes. Such a mechanism causing elongation of the average residence time of bioelements is called a "nutrient trap". Basic idea of this mechanism was given by Redfield (1956).

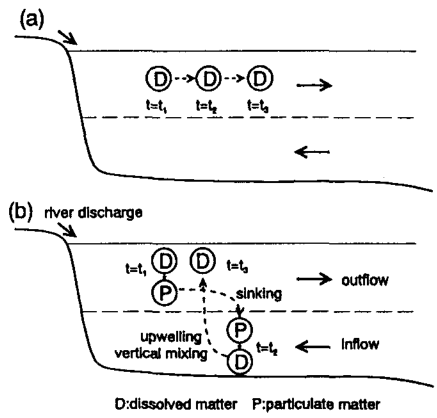

Fig.1 Schemtics of the nutrient trap mechanism.

Yanagi and Takahashi (1988) pointed out that the average residence time of the nitrogen is larger than that of the river water by 1.7 times in Osaka Bay in the Seto Inland Sea. Takeoka and Hashimoto (1988) showed by the simplified numerical model experiments that such difference can be explained by the nutrient trap mechanism. Takeoka and Hashimoto (1988) also showed that the nutrient trap is more effective in a longer bays. Chesapeake Bay on the east coast of USA is a typical example of such bays. Its length is about 300 km, and strong stratification with large current shear develops in summer. The average residence time of nitrogen in Chesapeake Bay is larger than that of the river water by as much as more than three times, and this causes the higher productivity in Chesapeake Bay than in other estuaries (Boicourt, 1992; Kemp and Boynton, 1992).

The nutrient trap seems to be less important in small scale bays, mainly because the materials go out of the bay before biogeochemical processes work well. However, in the bays having a sill at the mouth, the nutrient trap may be much effective, even though their scales are very small. In such bays the water bellow the sill depth is often quite stagnant and almost isolated from the upper water in the stratified season. Therefore, the bioelements which once settled into the lower water as particles hardly returns to the upper water, while the river water which initially carried the bioelements flows out of the bay through the upper layer in a short time. Thus the average residence time of the bioelements could be much larger than that of the river water. Example of the bays having the sill are Kumihama Bay (Kashiwai, 1989) and Lake Hamana (Mazda, 1995), which is a lake of brackish water. In these bays, the water which entered the bay during winter to spring, stays bellow the sill level persistently during summer, because the density of the offshore water becomes lower than that of the water below the sill level, and the offshore water cannot enter below the sill level. Accordingly, serious oxygen deficiency occurs in the lower water persistently in these bays in summer. Although the average residence times of the bioelements and the river water in these bays have not been reported yet, it is quite likely that they are significantly different.

Benthic thermoclines in the Seto Inland Sea

A benthic thermocline was first found in Hiuchi-Nada in the central part of the Seto Inland Sea by Ochi and Takeoka(1986) and Takeoka *et al.*(1986). In the eastern part of Hiuchi-Nada, anoxic or hypoxic water often occurred in 1970's mainly due to the organic waste from the paper factories. Examples of the vertical profiles of water temperature and dissolved oxygen are shown in Fig.2. In addition to the thermocline about 8m below the surface, another well-defined thermocline is formed about 6m above the bottom. This lower thermocline was called the second thermocline in Ochi and Takeoka (1986), but now we call it a benthic thermocline. Oxygen deficiency occurs below the benthic thermocline, while no significant change appears across the surface thermocline. Therefore, the benthic thermocline plays an important role in the oxygen deficiency in Hiuchi-Nada. According to the estimate of heat and oxygen budget of the middle and bottom layers by Takeoka *et al.* (1986), the oxygen was produced in the middle layer. Therefore, the reason of insignificance of the surface thermocline for the oxygen deficiency is supposed that the sufficient light for the primary production penetrates into the middle layer across the surface thermocline.

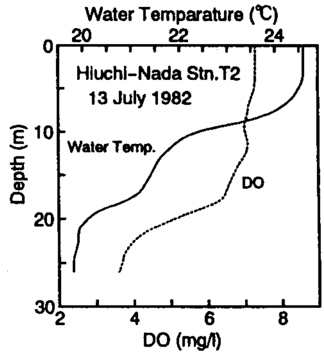

Fig.2 Benthic thermocline and oxycline in Hiuchi-Nada.

After Ochi and Takeoka (1986), we found benthic thermoclines in other seas such as Harima-Nada, Hiroshima Bay and Iyo-Nada. Among them, the benthic thermocline in Harima-Nada controls the occurrence of red tides. Large scale red tides often occurred in Harima-Nada in 1970's, and those occurred in summer 1972 was especially serious. They killed about 14 million cultured fish worth ¥7.1 billion. Yanagi (1990) compared the vertical distributions of water temperature in the years when the serious red tides occurred with those of the other years, and found that the vertical gradient of the water temperature in the lower layer was small in the years of the serious red tides. In Yanagi (1990), the benthic thermocline is not detected because of low vertical resolution of the observation layers; actually, there were no data between 20m and the bottom. Therefore, we can suppose that the gradient of the water temperature in the lower water denotes the intensity of the benthic thermocline.

Thus the benthic thermocline is quite an important phenomenon controlling red tide and oxygen deficiency in the Seto Inland Sea. Its generation mechanism is supposed as follows. Thermal stratification develops by surface heating in summer. If vertical diffusivity is uniform, vertical gradient of water temperature is the largest at the surface and decreases to the bottom as shown in Fig.3. Wind mixing unifies the water temperature in the surface mixed layer, and a steep gradient of the water temperature appears at the bottom of the mixed layer. Thus the surface thermocline is formed by the wind mixing. Similarly, the turbulence induced by the shear of the tidal current in the bottom layer mixes the bottom water, and the benthic thermocline is formed at the top of the bottom mixed layer.

However, this explanation on the formation of the benthic thermocline seems to be insufficient. Fairly large gradient of water temperature in the middle and lower layers, and hence sufficient heating of the middle layer, is required for the intensive benthic thermocline to be formed by the bottom mixing. Heating from the upper layer would be, however, limited by the surface thermocline. Therefore, another mechanism heating the middle layer is necessary. We suppose

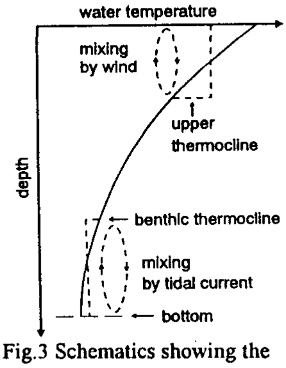

Fig.3 Schematics showing the formation of the benthic thermocline.

that a horizontal advective heat transport is such a mechanism. The seas in the Seto Inland Sea are connected each other by narrow straits, where the water column is always mixed by the strong tidal currents. Hence the stratified areas are always neighboring to the mixed areas, forming the density structure as shown in Fig.4, and the density currents denoted by the arrows in Fig.4 are induced. The intrusion from the mixed area to the middle layer of the stratified area is supposed to be the mechanism of heating the middle layer.

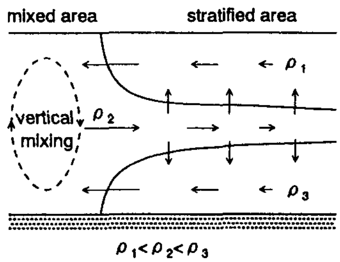

Fig.4 Density distribution in stratified and mixed areas and expected density currents.

This scenario of the formation mechanism of the benthic thermocline is supported by our recent numerical experiments with the vertical two-dimensional model and by the analysis of historical data in Harima-Nada and surrounding seas. The latter is as follows. For the occurrence of the intrusion from the mixed area into the middle layer of the stratified area, the density in the mixed area must be close to the vertical mean density in the stratified area. This requires that the vertical mean density in the surrounding seas are close to that in Harima-Nada, because the water in the straits is the mixture of the waters in Harima-Nada and surrounding seas. From the historical data, we found a relation such that the benthic thermocline in Harima-Nada is stronger in the years when the vertical mean density in Harima-Nada is closer to that of the surrounding seas. Further analysis showed that the relation between the mean densities in Harima-Nada and surrounding seas in summer are determined by the relation in the preceding winter and the change of the densities from winter to summer. This will enable us to predict the occurrences of red tides in Harima-Nada in summer from the density distribution in the preceding winter.

References

Boicourt, W. C. (1992): Influences of circulation processes on dissolved oxygen in the Chesapeake Bay. p.7-59. In, Oxygen dynamics in the Chesapeake Bay, eds. D. E. Smith, M. Leffler and G. Mackiernan, A Maryland Dea Grant Book, Maryland.

Kashiwai, M. (1989): Trial to suppress the anoxic water formation in the brackish lagoon, Kumihama-Bay. Bulletin on Coastal Oceanography, **26**, 129-140 (in Japanese).

Kemp, W. M. and W. R. Boynton (1992): Benthic-pelagic interactions: Nutrient and oxygen dynamics. p.149-221. In, Oxygen dynamics in the Chesapeake Bay, eds. D. E. Smith, M. Leffler and G. Mackiernan, A Maryland Dea Grant Book, Maryland.

Mazda, Y. (1995): Formation and changes of physical environment of Lake Hamana. Bulletin on the Japanese Society of Fisheries Oceanography, **59**, 171-175 (in Japanese).

Ochi T. and H. Takeoka (1986): The anoxic water mass in Hiuchi-Nada. Part 1. Distribution of the anoxic water mass. Journal of the Oceanographical Society of Japan, **42**, 1-11.

Redfield, A. C. (1956): The hydrography of the Gulf of Venezuela, Deep-Sea Research, 3, 115-133.

Takeoka, H.(1984a):Fundamental concepts of exchange and transport time scales in a coastal sea. Continental Shelf Research, **3**, 311-326

Takeoka, H.(1984b): Exchange and transport time scales in the Seto Inland Sea. Continental Shelf Research, **3**, 327-341.

Takeoka H., T. Ochi and K. Takatani (1986): The anoxic water mass in Hiuchi-Nada. Part 2. The heat and oxygen budget model. Journal of the Oceanographical Society of Japan, **42**, 12-21.

Takeoka, H. and T. Hashimoto (1988): Average residence time of matter in coastal waters in a transport system including biochemical processes. Continental Shelf Research, **8**, 1247-1256.

Yanagi, T. and S. Takahashi (1988): Response to fresh water discharge in Osaka Bay, Umi to Sora (Sea and Sky), **64**, 63-70 (in Japanese).

Yanagi, T. (1990): Physical processes relating to red tide. Memoirs of the Faculty of Engineering, Ehime University, **12-1**, 206-216.