Appendix 1

Comparison of the Seto Inland Sea with Other Enclosed Seas from Around the World

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Characteristics of the Seto Inland Sea can be better understood by comparing it with other coastal seas. Here the Seto Inland Sea is compared with the Chesapeake Bay, the Baltic Sea, the North Sea and the Mediterranean Sea. These seas are representative of enclosed or semi-enclosed seas throughout the world having much different characteristics from the Seto Inland Sea.

In Table A1.1 are listed the dimensions and characteristic factors of these seas including the average residence times. Several definitions of the average residence time have been applied to the coastal seas (Takeoka, 1984a), and the average residence times in the table use different definitions. However, they may be roughly regarded as the average residence times of nitrogen, except Chesapeake Bay, whose average residence times of the river water and nitrogen are listed separately. Although some of the values in the table are also quite rough because of the difference in the periods or methods of statistics, the characteristics of these seas are so different that the low accuracy of the values in the table would not affect the subsequent discussion. As the main focus of this volume is on the Seto Inland Sea, the characteristics of this sea are described in detail in the first section. The characteristics of the other seas are briefly summarized in the subsequent sections. In the last section, the high efficiency of biological production in the Seto Inland Sea is shown and its reasons are discussed on the basis of the comparison with other seas.

THE SETO INLAND SEA

The Seto Inland Sea is divided by many narrow straits into bays and seas called “nada” in Japanese (hereafter the seas and bays are called “compartments” of the Seto Inland Sea). These narrow straits containing strong tidal currents are called “seto” in Japanese, and they are most basic factor characterizing the Seto Inland Sea. Here the physical processes determining the nutrient concentrations are discussed classifying them into horizontal and vertical regimes, focusing on the roles of the narrow straits and the resultant strong tidal currents.

Horizontal currents and transport processes

Horizontal transport processes by the currents and mixing are the basic factors determining the concentration of nutrients in the water column. The currents in
Table A1.1. Dimensions and characteristic factors of five representative enclosed or semi-enclosed seas from around the world

<table>
<thead>
<tr>
<th></th>
<th>Seto Inland Sea</th>
<th>Chesapeake Bay</th>
<th>Baltic Sea</th>
<th>North Sea</th>
<th>Mediterranean Sea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface area (km$^2$)</td>
<td>21827(a)</td>
<td>11400(d)</td>
<td>37000(0)</td>
<td>525000(m)</td>
<td>2523000(q)</td>
</tr>
<tr>
<td>Average water depth (m)</td>
<td>37(a)</td>
<td>6.5(d)</td>
<td>56(0)</td>
<td>82(m)</td>
<td>1470(q)</td>
</tr>
<tr>
<td>Volume (km$^3$)</td>
<td>816(a)</td>
<td>51(d)</td>
<td>20900(l)</td>
<td>43000(m)</td>
<td>1708000(q)</td>
</tr>
<tr>
<td>Freshwater inflow (km$^3$/y)</td>
<td>44(e)</td>
<td>75(d)</td>
<td>440-473(f)</td>
<td>290(m)</td>
<td>430(q)</td>
</tr>
<tr>
<td>Average salinity (ppt)</td>
<td>33</td>
<td>20(e)</td>
<td>11.5(e)</td>
<td>34.8(e)</td>
<td>38.7(e)</td>
</tr>
<tr>
<td>Nitrogen and phosphorus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loading ($\times 10^4$ ton/y)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>total nitrogen</td>
<td>18.1(a)</td>
<td>8.06(d)</td>
<td>106(l)</td>
<td>135(n)</td>
<td>100(q)</td>
</tr>
<tr>
<td>total phosphorus</td>
<td>1.9(a)</td>
<td>0.38(d)</td>
<td>7.69(l)</td>
<td>13.6(n)</td>
<td>36(q)</td>
</tr>
<tr>
<td>Concentration (g/m$^3$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>total nitrogen</td>
<td>0.29(a)</td>
<td>1.59(d)</td>
<td>1.78(k)</td>
<td></td>
<td>0.027(k)</td>
</tr>
<tr>
<td>total phosphorus</td>
<td>0.029(a)</td>
<td>0.064(d)</td>
<td>0.128(k)</td>
<td>0.025(m)</td>
<td>0.0097(k)</td>
</tr>
<tr>
<td>Fish catch ($\times 10^4$ ton/y)</td>
<td>83 (38)(a)</td>
<td>7.46(d)</td>
<td>80(b)</td>
<td>300(o)</td>
<td>190(f)</td>
</tr>
<tr>
<td>Primary production (gC/m$^2$/y)</td>
<td>265(b)</td>
<td>125-295(d)</td>
<td>100(l)</td>
<td>100-300(m)</td>
<td>60(s)</td>
</tr>
<tr>
<td>Rate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average residence time (y)</td>
<td>1.2(c)</td>
<td>0.29(f)</td>
<td>35(b)</td>
<td>0.9(p)</td>
<td>100(f)</td>
</tr>
</tbody>
</table>

(a)Nakanishi (1993) (the fish catch in parentheses denotes the aquaculture).  
(b)Chapter 3 in this volume.  
(c)Takeoka (1984b).  
(d)Boynton et al. (1995).  
(f)The average residence time of river water obtained from the average salinity and the rate of river discharge.  
(g)The average residence time of nitrogen obtained from the standing stock of the nitrogen and the nitrogen loading rate.  
(h)Kullenberg (1982).  
(k)Obtained from the loading rate and the average residence time.  
(m)Zijlstra (1988).  
(n)Dederen (1992), nitrogen and phosphorus in the North Sea exclude the flux from the Atlantic Ocean.  
(q)Miller A. R. (1983), the river discharge rate excludes those from the Black Sea and the Nile.  
(s)The larger value of the eastern Mediterranean Sea (30-60 gC/m$^2$/y, Azov (1991)) is employed.  
(t)Lacombe and Richez (1982).
coastal seas are divided into tidal currents and residual currents. The residual currents have time scales of variability that are larger than the tidal periods.

Characteristics of the tidal currents in the Seto Inland Sea can be understood from Fig. A1.1 showing the distributions of the tidal range and the phase lag of the $M_2$ tide and Fig. A1.2 showing the distributions of the amplitude and phase lag of the $M_2$ tidal current and the directions of the flood tidal currents (Yanagi and Higuchi, 1981). In the Pacific Ocean, south of the Seto Inland Sea, the tidal wave propagates from east to west at a large speed since the water depth is large. Hence the phase of the tides at the mouths of the Kii and Bungo Channels are nearly the same (Fig. A1.1(a)). In the Seto Inland Sea, however, the tidal wave propagates at a much lower speed because of its shallow water depth. Hence the tidal waves propagate from the two channels into the inland sea taking a very long time. They finally meet with each other between Bisan Strait and Hiuchi-Nada in the central part of the inland sea, where the phase lag of $M_2$ tide is the largest. They have been delayed by about 150° from the mouths of the channels (Fig. A1.1(a)). Both tidal waves entering from the two channels are dissipated during the propagation. Therefore, the amplitudes of the tidal waves propagating eastward and westward are nearly the same in the central part of the inland sea, while in the eastern and western regions the amplitude of the tidal wave from the nearer channel is larger than that from the farther channel. Thus
Fig. A1.2. Distributions of (a) amplitude and (b) phase lag of $M_2$ tidal current and (c) directions of flood tidal currents in the Seto Inland Sea (after Yanagi and Higuchi, 1981).
the tidal wave in the central region becomes a stationary wave, while those in the eastern western regions are progressive waves. These features can be seen from the phase distributions of the tide and the tidal current in Figs. A1.1 and A1.2. The phase of the tide is almost the same in the central region and differs spatially in the eastern and western regions, and the phase difference between the tide and tidal current is about 90° in the central region and is much smaller in the eastern and western regions. As a result of such tidal features, the flood tidal currents are directed to this meeting area of the tidal waves as shown in Fig. A1.2(c). Moreover, the volume transport of the tidal current is larger in the outer region, and almost vanishes in the meeting area of the tidal waves. Therefore, except in the narrow straits, the amplitude of the tidal current is generally larger in the outer regions and smallest in the eastern part of Hiuchi-Nada (Fig. A1.2(a)). In the narrow straits the amplitudes of the tidal currents are much larger than those in the interior of the compartments. The amplitudes of four major tidal current constituents in the main straits are shown in Table A1.2. The maximum tidal speeds at some straits attain nearly 5 m/s in the spring tides.

Table A1.2. Amplitudes of four major tidal current constituents in the main straits of the Seto Inland Sea (after Yanagi and Higuchi, 1981)

<table>
<thead>
<tr>
<th>Strait</th>
<th>M₂ (cm/s)</th>
<th>S₂ (cm/s)</th>
<th>K₁ (cm/s)</th>
<th>O₁ (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tomogashima Strait</td>
<td>105</td>
<td>25</td>
<td>40</td>
<td>35</td>
</tr>
<tr>
<td>Naruto Strait</td>
<td>330</td>
<td>90</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Akashi Strait</td>
<td>160</td>
<td>60</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Bisan Strait</td>
<td>95</td>
<td>35</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>Kurusima Strait</td>
<td>250</td>
<td>100</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>Tsurushima Strait</td>
<td>90</td>
<td>45</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>Ohbatake Strait</td>
<td>250</td>
<td>75</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>Hayasui Strait</td>
<td>155</td>
<td>70</td>
<td>35</td>
<td>25</td>
</tr>
<tr>
<td>Kanmon Strait</td>
<td>225</td>
<td>80</td>
<td>65</td>
<td>45</td>
</tr>
</tbody>
</table>

Fig. A1.3. Distribution of the residual currents in the Seto Inland Sea (after Yanagi and Higuchi, 1979).
Figure A1.3 shows the distribution of the residual currents, which consist of tide-, wind- and density-induced currents. Their speeds are usually a few cm/s, but in some places they are up to about 10 cm/s. These residual currents tend to form closed circulations in each compartment, and do not communicate with each other between the compartments. In addition to these residual currents, a current through the entire inland sea can exist, because the Seto Inland Sea by itself forms a large long channel opening to the Pacific Ocean by two mouths. Fujiwara and Higo (1986) reported that the eastward current through the inland sea is generated in winter by the strong northwesterly monsoon. The total flux of this current in winter (from December to February) is $3.3 \times 10^{10}$ m$^3$, which is about 4% of the total volume of the Seto Inland Sea.

Since the Seto Inland Sea is surrounded by small islands, the catchment area of the rivers flowing into the inland sea is small compared with the other seas which are dealt with in this chapter. Hence, the river discharge is rather small and the salinity is comparatively high (Fig. A1.4). Therefore, estuarine circulation is not developed well except in Osaka Bay and Hiroshima Bay into which fairly large rivers flow. One example of the rather small horizontal density gradient in the Seto Inland Sea is seen in the currents associated with the tidal fronts. As shown in the next section, the interior of the compartments is stratified in summer while the water column in and around the straits is vertically well mixed by the strong tidal currents throughout the year. The tidal fronts are formed between these stratified and mixed areas in summer. If the difference between the vertical mean densities of stratified and mixed areas is small, the density-induced currents between these areas will be three-layered as shown in Fig. A1.6, intruding from the mixed area into the middle layer of the stratified area. Such a structure was found in the tidal front in Iyo-Nada by Takeoka et al. (1993a) and in Kii Channel by Yanagi et al. (1996). Another example showing the weak estuarine circulation of the Seto Inland Sea is the kycho in the Bungo Channel. Warm water originating from the Kuroshio flowing south of the Bungo Channel occasionally branches out and a part of it flows into the Bungo Channel, resulting in a sudden and swift current and sudden rise of water temperature in the Bungo Channel (Takeoka et al., 1993b). Such a phenomenon is called a kycho in Japanese. This intrusion from the ocean to the upper layer is opposite to estuarine circulation.

Transports of water and materials in the coastal sea are carried out by the currents described above and the mixing associated with these currents. Since the current through the Seto Inland Sea is small, the transport in the direction of the axis of the inland sea is mainly governed by longitudinal dispersion. In the interior of the compartments, the horizontal shear of the residual currents and the tidal mixing are coupled and generate effective longitudinal dispersion. On the other hand, longitudinal dispersion through the straits is generated by strong tidal mixing and the Stokes drift associated with the tidal currents having strong spatial contrast (Awaji et al., 1980). The bulk longitudinal dispersion coefficient for the whole area of the Seto Inland Sea is about $10^7$ cm$^2$/s (Hayami and Unoki, 1970).
Fig. A.1.4. Distribution of surface salinity in the Seto Inland Sea in summer (after Environmental Agency, 1995).
Vertical transport processes

Since nutrients tend to be carried to the lower layer by the biological pump, the nutrient concentration in the upper euphotic layer is much influenced by vertical mixing or stratification. The parameter, $\log_{10}(h/U^3)$, proposed by Simpson and Hunter (1974), where $h$ is the water depth and $U$ the amplitude of $M_2$ tidal current, is a convenient indicator for mixed and stratified regions. Figure A1.5 shows the distribution of $\log_{10}(h/U^3)$ obtained by Yanagi and Okada (1993) on the basis of observational data. In the Seto Inland Sea, tidal fronts appear along the contour of $\log_{10}(h/U^3) = 2.5$ ($h$ and $U$ in cgs units). Hence the water is vertically well mixed in the regions where this parameter is less than 2.5, and stratified during the heating season where it is more than 2.5. In most of the straits, $h$ is larger than in the surrounding areas, increasing the value of $\log_{10}(h/U^3)$, but, due to larger $U$’s, it is still less than 2.5 in and near the main straits as shown in Fig. A1.5, resulting in the permanent mixing there. This vertical mixing due to the strong tidal currents effectively carries the rich nutrients in the lower layer to the upper euphotic layer, while in the stratified regions nutrients tend to decrease in the upper layer except in the regions of large river influence such as Osaka Bay and Hiroshima Bay. Therefore the many straits in the Seto Inland Sea play a significant role in the primary production. Moreover, this role of the straits is not limited to the mixed region in and around the straits as explained below.

Figure A1.6(a) schematically shows the density structure and the resultant density currents in a vertical cross section of stratified and mixed regions. Since the density of the water in the mixed region is between those of the upper and lower layers in the stratified region, the mixed water tends to intrude into the middle layer of the stratified region, while the water in the upper and lower layers flows into the mixed region. As a result of heat transport by these currents, the upper layer of the stratified region gives heat to the mixed region and the lower layer receives heat from the mixed region. This means that there is a route for heat transport from the upper layer to the lower layer via the mixed region as shown by the thick solid line in Fig. A1.6(b) in addition to a route of the direct heat transport by the vertical mixing as shown by the thin solid line. Such a heat transport via the mixed region can be generated also by horizontal mixing between the mixed and stratified regions. This route of vertical heat transport via the mixed region is called a heat bypass (Takeoka, in preparation). Dissolved oxygen produced by primary production in the upper layer is transported to the lower layer also through this route, which in this case may be called an oxygen bypass. Moreover, rich nutrients in the lower layer can be transported to the upper layer through the route shown by the thick broken line in Fig. A1.6(b), which can be called a nutrient bypass.

It is qualitatively quite certain that the mixed region works as a bypass for the vertical transport of the heat, oxygen, nutrients and other materials in the stratified region. Therefore, our concern is whether the bypass is quantitatively significant or not. Theoretical studies based on the energetics of vertical mixing or box-model analysis of heat budget show that the heat flux to the lower layer through the heat bypass is as much as a few times the direct vertical heat flux in Hiuchi-Nada, the
Fig. A1.5. Distribution of $\log \langle H/U \rangle$ in the Seto Inland Sea (after Yanagi and Okada, 1993).
Fig. A1.6. (a) Density structure in the vertical section of mixed and stratified regions and the resultant density-induced currents. (b) Transport routes of heat (solid line) and nutrients (broken line). Thick lines denote bypasses via the mixed region.

region where the tidal currents are the weakest in the Seto Inland Sea and hence the effect of the heat bypass is expected to be the largest (Takeoka, in preparation). In other compartments, the fraction of the heat transport through the heat bypass is not as large as in Hiuch-Nada, but it is at least comparable to that of the direct vertical heat transport. Thus, the mixed regions around the narrow straits play an important role in the vertical transport of heat and materials not only in the mixed regions themselves but also in the stratified regions.

An example of a nutrient bypass can be found in the primary production in a tidal front. Figures A1.7(a) and (b) show the distributions of water density and chlorophyll $a$ in the vertical transect along the stations in Iyo-Nada shown in Fig.
Fig. A1.7. Distribution of (a) water density and (b) chlorophyll $a$ concentration in the vertical section along the stations in Iyo-Nada shown in (c) (after Takeoka et al., 1993a).

A1.7(c) (Takeoka et al., 1993a). In Fig. A1.7(a), the water column in and around Hayasui Strait is vertically well mixed, while stratification is developed in the interior of Iyo-Nada, and a typical tidal front is formed around Stn. 7 between the mixed and stratified regions. A prominent chlorophyll $a$ maximum is formed in the subsurface of the tidal front. According to the analysis of the TS-diagram by Takeoka et al. (1993a), the nutrients supporting the chlorophyll $a$ maximum should be supplied not vertically from the lower layer but horizontally from the mixed region around Hayasui Strait. This supply of the nutrients is regarded as transport through the nutrient bypass. In Fig. A1.7(b), one may notice the low chlorophyll $a$ concentration in the mixed region. This is because the water depth in the mixed region is much larger than the thickness of euphotic layer, and the chlorophyll $a$ produced only in the euphotic layer is sufficiently diluted. The vertically integrated chlorophyll $a$ is even larger in the mixed region than in the frontal region. Thus we may conclude that
the mixed regions play an important role in the biological production in the entire Seto Inland Sea. The role of the mixed region is discussed again in the last section.

THE CHESAPEAKE BAY

The Chesapeake Bay is a representative enclosed coastal sea located north of Cape Hatteras on the eastern coast of the United States (Fig. A1.8). Its coastal geometry is quite complicated with a number of tributaries. The surface area, including the tributaries, is about one half that of the Seto Inland Sea. The average water depth is less than 10 m including the tributaries and about 20 m excluding them; the latter value is about half the depth of the Seto Inland Sea. The water depth at the bay mouth is shallower than the average depth, forming a sill against water flowing in and out of the bay. The average river discharge per unit area of the bay is up to 3 times larger than that of the Seto Inland Sea. This results in the much lower salinity (20 psu) of the bay compared to the Seto Inland Sea. The river discharge is maximum in spring, since thawing water largely contributes to the river discharge. The water in the upper layer of the bay is made lighter by this river discharge and the

Fig. A1.8. The Chesapeake Bay.
surface heating, and a prominent estuarine circulation develops flowing outward in the upper layer and inward in the lower layer. Oceanic water flows into the lower layer making the lower water even heavier, and an intense pycnocline is formed between the upper and lower layers (Fig. A1.9). This strong pycnocline persists until the following autumn.

Here we discuss the difference in the mechanisms of the water exchange in the Chesapeake Bay and the Seto Inland Sea. The compartments forming the Seto Inland Sea are connected by narrow straits with strong tidal currents. The oscillatory tidal currents are less effective in material transport than the density-induced currents which usually flow in a constant direction. Density-induced currents cannot be developed in the narrow straits in the Seto Inland Sea because the water is always vertically well mixed. Therefore, the water exchange through the narrow straits is mainly carried out by the tidal and tide-induced residual currents in and around the straits. In the Chesapeake Bay, the tidal range is smaller than that in the Seto Inland Sea, and there are few narrow straits with strong tidal currents. Moreover, the buoyancy flux forcing the density currents is much larger than in the Seto Inland Sea. Therefore, the density currents are believed to be main mechanism of the water exchange in the Chesapeake Bay. As shown in Table A1.1, the average residence time of the river water, given by dividing the stock of the river water in the bay by the river discharge, is only about 0.3 year in the Chesapeake Bay, suggesting the effective water exchange by the density currents. However, the average residence time of nitrogen is about one year, more than three times that of the river water. This difference is due to the effect of the following nutrient trap. Dissolved inorganic nitrogen or phosphorus is transformed to particles by primary production in the upper euphotic layer and settles down to the lower layer as detritus. The detritus is then decomposed to dissolved form while being carried back to the inner bay by the current in the lower layer and returns to the surface. Accordingly the nitrogen or
Fig. A1.10. Distribution of dissolved oxygen (ml/l) in the vertical section along the main axis of the Chesapeake Bay in September (after Miller C. B., 1983).

phosphorus stays in the bay longer than the river water which stays mostly in the upper layer and rapidly flows out. There is, however, a considerable flux of nitrogen from the air into the Chesapeake Bay. The average residence time of the nitrogen loaded from the land would be less than one year when taking this flux into account, still significant difference would remain between the average residence times of the river water and nitrogen in the Chesapeake Bay. Actually, the primary production per unit area in the Chesapeake Bay is considerably larger than in the other estuaries, and this is said to be due to the higher retention of nutrients by the nutrient trap (Kemp and Boynton, 1992).

It should be noted, however, that such a mechanism of high retention of nutrients requires developed two-layer density-driven currents, and this structure is necessarily accompanied by the strong stratification, which prevents supply of oxygen to the lower layer and causes oxygen depletion. In fact, serious oxygen depletion occurs as shown in Fig. A1.10, and such an oxygen depletion is a representative environmental problem in the Chesapeake Bay.

THE BALTIC SEA

The Baltic Sea is an inter-continental enclosed sea surrounded by the European Continent and the Scandinavia Peninsula (Fig. A1.11). The average depth is rather shallow, 56 m, but some regions are more than 400 m deep. Its southwestern part is connected to the North Sea via the Belt Sea, the Kattegatt, the Skagerrak and so on. These straits are narrow, and their depths are about 1/3 of the average of the Baltic Sea forming a high sill. Characteristics of the Baltic Sea are mainly determined by this sill and the large amount of river inflow, while tidal motions are less significant. The sill prevents the inflow of oceanic water, making the Baltic Sea the least saline sea in the world.

Schematic diagrams of the water exchange in the Baltic Sea is drawn in Fig. A1.12(a) (Nehring, 1992). The Baltic Sea is called a giant estuary, and, though being confined by the sill, its basic circulation pattern is estuarine. The heavy high saline oceanic water, once it passes over the sill, falls along the bottom slope, mixing with
Fig. A1.11. The Baltic Sea.

Fig. A1.12. Schematic structure of the water and phosphorus circulations in (a) the Baltic Sea and (b) the Mediterranean Sea (after Nehring, 1992).
the upper less saline water, and becomes the bottom water. This bottom water reaches the upper layer by being raised up by the continuous supply of new oceanic water and mixes with the upper water, finally flowing out back to the outer ocean. The average residence time of the water in the Baltic Sea, given by dividing the sea volume by the outflow of this circulation, is as long as 35 years (Kullenberg, 1982).

There are intermittent intrusions of the oceanic water into the Baltic Sea, in addition to the estuarine circulation (Stigebrandt and Wulff, 1987). This intrusion is driven by the sea level difference between the North Sea and the Baltic Sea due to the year-to-year variation of the European climate. The large amount of high salinity water entering during this event becomes heavy bottom water. This bottom water is so heavy that the water of usual density entering after the event cannot penetrate into the bottom water, resulting in a long stagnation of the bottom water. The volume of the stagnant bottom water is about 5% of the total volume of the Baltic Sea, and is equal to total volume of the Seto Inland Sea. This stagnation usually persists for several years until the bottom water is renewed by the next event. Since oxygen supply to the bottom water is mainly carried out by the inflow of the oceanic water, oxygen depletion develops during the years of stagnation, and a large scale, persistent anoxic water mass is formed in the bottom water.

This anoxic water mass is of enormous temporal and spatial scales, and physical processes such as the intermittent intrusion of the high salinity water mass play significant roles in its formation. Moreover, recent eutrophication induced by human activities is another important factor contributing to this anoxia. This is well demonstrated by the fact that the area of the bottom where hydrogen sulphide appeared increased from zero in 1929 to 26000 km² in 1959 and to 84000 km² in 1975 (Štirn, 1988). This eutrophication causes not only the extension of the area of anoxia, but also the decrease of the area of coastal submerged vegetation due to decrease of light penetration by shading from the increased phytoplankton in the surface layer. On the other hand, the eutrophication also caused increases in fisheries production such as the doubling of the catch of herring and cod from 450000 tons/year in 1960 to 900000 tons/year in 1980 (Nehring, 1992).

THE NORTH SEA

The North Sea is a semi-enclosed sea surrounded by the Scandinavia Peninsula, the European Continent and the United Kingdom, whose area is about 24 times that of the Seto Inland Sea. It is connected to the North Atlantic Ocean through its northern boundary, to the English Channel through the Strait of Dover at its southwestern end, and to the Baltic Sea through the Skagerrak. Its average depth is about 80 m, and the sea bed deepens from the southern coastal area to the shelf edge of 200 m depth at the northern boundary. There exists the famous Dogger Bank of 18 to 36 m depth in the central part of the southern half of the sea, and an undersea valley of about 400 m depth along the Scandinavia Peninsula.

The tidal range in the North Sea is fairly large along the coasts of the United Kingdom, Belgium and Germany, attaining more than 6 m in spring tides at some regions. Tidal currents off the coasts are generally 20 to 150 cm/s, which are
comparable with those in the main body of the Seto Inland Sea excluding the narrow straits. However, the North Sea water is mainly exchanged not by the tidal currents but by the general ocean current inflowing from the Atlantic Ocean through the western half of the northern boundary, circulating anticlockwise in the interior and outflowing along the Norwegian coast. The average residence time of the water in the North Sea given by dividing the total volume by the flux of this current is about

![Diagram of ocean currents and distribution of phosphate-P in the North sea in summer](image-url)

Fig. A1.13. Distribution of phosphate-P in the North sea in summer (after Zijlstra, 1988).
0.9 year (Otto, 1983). This value is comparable with that of the Seto Inland Sea, but, considering the volume of the North Sea, the water exchange there is quite effective.

The source of nutrients to the North Sea is essentially different from those to the other seas considered here. The values of the nitrogen and phosphorus fluxes shown in Table A1.1 are for the flux from the land. The flux of phosphorus from the Atlantic Ocean by the ocean current attains as much as 1800000 tons/year (4900 ton/day) (Zijlstra, 1988), an order larger than that from the land. The nutrients supplied by the ocean current are consumed in the North Sea, resulting in lower nutrient concentrations in the North Sea than that in the Pacific Ocean (Fig. A1.13).

Since the oceanic source of nutrients is much larger than the source from the land, the nutrients from the land cannot cause the eutrophication over the whole area of the North Sea. However, several eutrophication problems such as red tides have arisen recently in the southern shallow areas which are directly influenced by river discharge. Moreover, pollution by organochlorines such as PCB’s or heavy metals and damage to benthic ecosystem by net trawling are recently becoming serious problems in the North Sea (Hoogweg et al., 1991).

THE MEDITERRANEAN SEA

The Mediterranean Sea is a large water body, whose area is about 120 times that of the Seto Inland Sea and the average depth is up to 1500 m. Its interior is divided into a number of seas and bays by the complicated geometry. The Mediterranean Sea is connected to the Atlantic Ocean through the Strait of Gibraltar at its western end. Though the depth of the Strait of Gibraltar is rather deep, about 300 m which is even deeper than the average Baltic Sea, it forms a relatively shallow sill against the Mediterranean Sea. Hence, like the Baltic Sea, the Mediterranean Sea is highly closed, and the tides and tidal currents are small.

The Mediterranean Sea is completely different from the Baltic Sea in terms of the freshwater budget. Due to the arid weather, total evaporation in the Mediterranean Sea exceeds total precipitation and river discharge, and the salinity is higher than that of the Atlantic water by about 10%. The Mediterranean water is exchanged with the Atlantic water by the density-induced currents due to the salinity difference, inflowing in the upper layer and outflowing in the lower layers at the Strait of Gibraltar. This structure is opposite to that of the Baltic Sea (Fig. A1.12). The average residence time of the water in the Mediterranean Sea given by dividing the total volume by the inflow from the Atlantic Ocean is about 100 years (Lacombe and Richez, 1982).

The nutrients in the lower layer are effectively discharged by the lower outflow from the Mediterranean Sea. Moreover, hardly any of the nutrients in the lower layer can return to the upper layer because of the high stability of the water column. Therefore, except in shallow coastal regions and regions of direct river influence, the upper layer in the Mediterranean Sea is quite oligotrophic, especially in its eastern half. Hence the chlorophyll concentration in the eastern area is even lower than that in the equatorial Pacific Ocean (Azov, 1991). The Nile flows into the Levant Sea, the easternmost sea in the Mediterranean. The river discharge of the Nile was about 43
billion tons/year before the construction of the Aswan High Dam, but it decreased to 1/10 after its construction. As a result, the total fish catch in Egypt drastically decreased from 24500 tons in 1965 to 3300 tons in 1974 (Azov, 1991), though the total fish catch recovered later by switching the catch to other species of fish. This fact clearly shows that the biological production in the Mediterranean is mainly dependent on the nutrient supply not from the lower layer but from the river.

Thus the Mediterranean Sea is hardly eutrophied at all as a whole because of its intrinsic structure. Nevertheless, in some areas such as the small enclosed bays and the areas of direct river influence eutrophication is becoming a serious problem due to the increasing anthropogenic loads of nutrients and organic materials from the land.

**COMPARISON OF THE SETO INLAND SEA WITH THE OTHER SEAS**

In this section, I will discuss the characteristics of the biological productivity of the Seto Inland Sea by comparing them with those of the other enclosed seas described in the previous sections. The rates of the primary production in terms of nitrogen in these seas are drawn in Fig. A1.14(a). These rates are translated from those in terms of carbon shown in Table A1.1. The primary production is large in the Seto Inland Sea, the Chesapeake Bay and the North Sea, about half of that in the Baltic Sea, and about half again in the Mediterranean Sea. In this section, the reasons for the difference in the rate or the efficiency of the primary production in these seas are discussed on the basis of their structures described above.

Since primary production requires nutrients, their concentrations are important factors determining the rate of primary production. The average concentrations in the sea of concern are basically determined by their input flux, average residence times and the volume of the sea. Here the problem is considered not on the whole sea but on the unit surface area of the sea, and only nitrogen is considered for simplicity. Figures A1.14(b) to (d) show the input flux to the unit sea area ($Q_S$), the average residence time ($\tau$) and the stock in the water column per unit area ($C_S$) for nitrogen in the seas of concern. These are related by the equation: $C_S = \tau Q_S$.

In Fig. A1.14(d), $Q_S$ is very large in the North Sea because of the enormous flux from the Atlantic Ocean, about one third of that in the Seto Inland Sea and the Chesapeake Bay, half again in the Baltic Sea and extremely small in the Mediterranean Sea. The stocks per unit area ($C_S$'s) of the Seto Inland Sea, the Chesapeake Bay and the North Sea have similar relations to their flux ($Q_S$'s), because their average residence times ($\tau$'s) are close to each other. However, even though the flux to the Baltic Sea and the Mediterranean Sea are smaller than those of the other seas, their stocks are larger due to their very large average residence times. Consequently, the distribution of the stocks per unit area among the seas is quite different from the rates of primary production ($P_S$'s). Therefore, the efficiency of utilizing nitrogen in the water column for primary production differs significantly from one sea to another. In order to quantify this difference, the production efficiency should be defined strictly. There are some possible definitions for the production efficiency, and here we will consider two kinds of them.
Fig. A1.14. Comparison of the enclosed or semi-enclosed seas considered here. (a) Rate of primary production in terms of nitrogen. (b) Nitrogen loading rate ($Q_S$ in the North Sea is a sum of the flux from the land and the flux from the Atlantic Ocean. The latter is translated from the phosphorus flux stated in the section 4 by using the Redfield ratio). (c) Average residence time of nitrogen. (d) Stock of nitrogen per unit area. (e) Efficiency of primary production ($E_{PC}$). (f) Efficiency of primary production ($E_{PO}$). (g) Fish catch per unit area (cm/s).
One definition of the production efficiency is the ratio of the primary production rate to the stock of the nitrogen in the unit water column, which is given as

$$E_{PC} = \frac{P_S}{C_S}. \quad (1)$$

This efficiency, $E_{PC}$, has a unit of the reciprocal time, and denotes how many times the stock of the nitrogen in the water column is utilized for primary production per unit time. This also means how many times the total stock of nitrogen in the sea is utilized. Hence this efficiency may be called the cycling rate of nitrogen. $E_{PC}$’s of the seas are shown in Fig. A1.14(e). $E_{PC}$ is quite small in the Baltic Sea and the Mediterranean Sea, being 0.18/year and 0.27/year, respectively, and even in the North Sea it is only 1.5/year. On the other hand, $E_{PC}$ is as much as 4 to 5/year in the Seto Inland Sea and the Chesapeake Bay, meaning that the stock of nitrogen is utilized for the primary production about 4 to 5 times a year. Thus, judging from the efficiency $E_{PC}$, we can say that primary production is highly efficient in the Seto Inland Sea and the Chesapeake Bay.

The other definition of the production efficiency that is considered here is the ratio of the primary production rate to the input flux per unit surface area:

$$E_{PQ} = \frac{P_S}{Q_S}. \quad (2)$$

This $E_{PQ}$ may appear to be a more straightforward definition of the efficiency of primary production than $E_{PC}$, because it simply relates the input (input flux, $Q_S$) and the response (primary production, $P_S$). However, it is often much larger than unity as shown in Fig. A1.14(f). Hence, unlike our intuitive expectation, $E_{PQ}$ does not mean the fraction of nitrogen in the input flux that is utilized for the primary production. This is because nutrients regenerated from organic matter join the input flux from the land repeatedly. Therefore, $E_{PQ}$ may not be a better definition of the production efficiency. Nevertheless, it is useful for understanding the difference in the primary productivity in the various seas. This meaning is made clear by rewriting $E_{PQ}$ as

$$E_{PQ} = \frac{P_S}{Q_S} = \frac{P_S}{Q_S} \frac{\tau}{C_S} = E_{PC} \tau. \quad (3)$$

From the definitions of $E_{PC}$ and $\tau$, $E_{PQ}$ means how many times the nitrogen in the sea is utilized for primary production within its average residence time, in other words, how many times the nitrogen loaded to the sea is utilized for primary production before it goes out of the sea. Relations among the $E_{PQ}$’s shown in Fig. A1.14(f) are much different from those among the $E_{PC}$’s in Fig. A1.14(e). Contrary to the $E_{PC}$’s, $E_{PQ}$’s in the Baltic Sea and the Mediterranean Sea are larger than those in the other seas, as a consequence of the larger $\tau$’s in these seas. This means that nitrogen is utilized by primary production many times before it goes out of the Baltic Sea and the Mediterranean Sea.

From the above discussions based on Figs. A1.14(a) to (f), the characteristics of these seas are summarized as follows. In the Seto Inland Sea and the Chesapeake
Bay, high primary productivity is maintained by the ability to utilize the not-so-rich nitrogen in the water column rapidly and hence repeatedly. In the Baltic Sea and the Mediterranean Sea, although nitrogen inputs are poor, the nitrogen retention is high resulting in a large stock, and primary production utilizes only a small part of this large stock. On the other hand, primary production in the North Sea is easily supported by an abundant supply of nutrients, and thus production is not dependent on the efficiency. In short, the primary productions in the Seto Inland Sea and the Chesapeake Bay are mainly supported by the $E_{PC}$'s, those in the Baltic Sea and the Mediterranean Sea by the $E_{PQ}$'s and that in the North Sea by the $Q_S$. The large $E_{PQ}$'s in the Baltic Sea and the Mediterranean Sea are obviously due to the large $\tau$'s, in other words, the highly enclosed structure of these seas. Hence our next concern is the mechanisms leading to the large $E_{PC}$'s in the Seto Inland Sea and the Chesapeake Bay.

The water depth and the rate of vertical transport of the nutrients are the main factors controlling $E_{PC}$. In the Mediterranean Sea, even if the water column was well mixed, the nutrient content in the euphotic layer would be rather poor because of the large water depth. In fact, the supply of the nutrients from the lower layer to the euphotic layer is further restricted by the strong stratification. In the Baltic Sea, if the water column was well mixed, the nutrients in the euphotic layer would be rich and primary production would be high because the average concentrations of nitrogen and phosphorus over the entire water column are high as shown in Table A1.1. In the actual state, however, the strong stratification prevents the vertical transport of the nutrients and reduces primary production. Furthermore, less sunshine and low water temperature due to the high latitudes are supposed to be additional reasons for the small $E_{PC}$ in the Baltic Sea. In the Chesapeake Bay, the stratification is also rather strong and the vertical transport of nutrients is restricted like in the Mediterranean Sea and the Baltic Sea. However, the bay is very shallow and hence the fraction of the water in the euphotic layer is rather large. This may be a major cause of the large $E_{PC}$ in the Chesapeake Bay. The average water depth of the Seto Inland Sea is a few times larger than that of the Chesapeake Bay. Therefore, the efficient mechanism for vertical transport supplying the nutrients in the lower layer to the euphotic layer is believed to be the main reason for the large $E_{PC}$. However, some strong stratification develops in the interior of the compartments in the Seto Inland Sea in summer slowing the vertical transport, though this stratification is weaker than in the Chesapeake Bay. Therefore, we suppose that the straits play important roles in the vertical transport of the nutrients. As stated before, a narrow strait with strong tidal currents works as a bypass for the vertical transport of heat and nutrients in the neighboring stratified regions. The nutrients rapidly return to the upper layer through the bypass, and by the reverse bypass mechanism the oxygen in the upper layer is supplied to the lower layer, promoting the decomposition of the organic matter there. Moreover, the heat transport through the bypass prevents the development of stratification. Thus the straits play three important roles in the enrichment of the nutrients in the upper layer. There are many narrow straits and channels throughout the Seto Inland Sea, and their effects reach almost its entire area, resulting in the large $E_{PC}$. 
Thus, the Seto Inland Sea and the Chesapeake Bay maintain high productivity by different mechanisms. Moreover, there is another significant difference between the mechanisms that determine the nitrogen stock per unit area ($C_S$) in these seas, which must be rather large to support the high productivity. In the Chesapeake Bay, even though the average residence time of the river water is only 0.3 years, the average residence time of nitrogen is raised to about one year by the nutrient trap mechanism, maintaining a large $C_S$. However, as was stated before, this mechanism requires strong stratification and is accompanied by a high risk of oxygen depletion in the lower layer. On the other hand, in the Seto Inland Sea the highly enclosed geometry and the resultant weak water exchange retain water and nutrients about one year, maintaining a large $C_S$. Such highly enclosed structures usually have a risk of oxygen depletion due to stagnation of water movement in the interior and resultant strong stratification, especially in geometries having a sill at the bay mouth. In the Seto Inland Sea, however, vertical transport of heat and oxygen is maintained to some extent by the bypass mechanism of the many straits. Moreover, the straits in the Seto Inland Sea are usually deeper than the neighboring compartments, rarely forming a sill. Hence, in the Seto Inland Sea, large $C_S$ is maintained by its enclosed structure which has less risk of oxygen depletion than the nutrient trap mechanism of the Chesapeake Bay. Thus the straits in the Seto Inland Sea play quite important, essential roles in maintaining high biological production and preserving marine environments.

Figure A.1.14(g) shows the fish catch per unit area of each of the seas (the value of the Seto Inland Sea excludes the amount of fish culture). The fish catch in the Seto Inland Sea is much larger than those in the other seas. Hence the Seto Inland Sea could be called a superior sea in terms of fisheries production, though the values of the fish catch are influenced by anthropogenic factors. The fish catch is rather small in the North Sea in spite of the high primary production. This may be due to the expression of fish catch in terms of catch per unit area. The lower fish catch in the Chesapeake Bay compared to the Seto Inland Sea may be caused by the influence of oxygen deficiency on the biological production of the higher trophic levels. These problems require further quantitative investigations.

In conclusion, the Seto Inland Sea is a sea having extremely efficient biological and fisheries productions. These efficient productions are realized by the sea’s enclosed structure which keeps the nutrient concentrations high and by the role of the many straits as bypasses of heat, nutrients and oxygen which contribute to the rapid and repeated utilization of the nutrients. The remarkable effects of the straits deserve further quantitative investigations. However, we should note that such excellent effects of the straits are definitely limited as has been proved by the frequent occurrence of red tides and hypoxic waters which often caused mass mortalities of fish especially in 1970’s. Hence we should make conscious efforts for preserving the superior environment of the Seto Inland Sea.

REFERENCES


