The Anoxic Water Mass in Hiuchi-Nada
Part 2. The Heat and Oxygen Budget Model*

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Abstract: Temporal variation of the anoxic water mass in Hiuchi-Nada was investigated. Vertical diffusivities at the thermoclines and oxygen consumption rates in the middle and lower layers were estimated by box model analysis using the results of field observations. On the basis of the obtained diffusivities and consumption rates, the time scale for anoxia and the degree of anoxia were examined for various conditions. It was revealed that the time scale for anoxia is about a week in the case where serious anoxia occurs and the degree of anoxia is sensitive to the diffusivity at ‘the second thermocline’. The anoxia which occurred frequently in the 1960’s and 1970’s is deduced to be caused by oxygen consumption rates a few times larger than the average at present and by diffusivities a few tens of per cent smaller than those under normal conditions.

1. Introduction
In Part 1 of this study (Ochi and Takeoka, 1986), the spatial distribution of the anoxic water mass in the eastern part of Hiuchi-Nada (Fig. 1) was described through observations of the density field and several chemical properties of the water and sediment. A relatively cold water mass was found just above the bottom around Ibukijima Island and at the boundary between this water mass and the upper water layer a ‘second thermocline’ occurred. Significant oxygen depletion was observed not below the upper (the first) thermocline but below this second thermocline. In other words, distribution of the cold water mass coincided well with that of the anoxic water mass.

In this paper, temporal variations of the conditions of the anoxic water mass are investigated. From the observations, an oxygen budget of the anoxic water mass is estimated by box model analysis, and the time scale for anoxia and the degree of anoxia under various conditions are examined. Through these analyses, the effects of fundamental factors on anoxia such as the rate of oxygen consumption and vertical diffusivity are discussed quantitatively.

2. Temporal variation of the anoxic water mass
Two series of observations at Stn. T2 (Fig. 1) were carried out in 1982 and 1983. The former series, referred to as S1, was carried out nine times at about two-week intervals from June to September in 1982, and the latter, referred to as S2, was carried out ten times at about the same intervals from June to September in 1983 (for details see Part 1). Figure 2 shows the isopleths of temperature and dissolved oxygen (DO) during these periods of observation, together with daily hours of sunshine at Tadotsu and the daily mean wind speed at Nihamo (Japan Meteorological Agency, 1982, 1983).

During S1, oxygen depletion in the bottom water began in late June and almost disappeared in mid-September when the stratification was destroyed. Anoxia was not so serious throughout this year. After the start of oxygen depletion, DO in the bottom water recovered slightly on 27 July, probably due to destruction of the first and second thermoclines. Primary factors which cause destruction of the density stratification are a decrease in solar heating and mixing by wind. The destruction of the thermo-
clines on 27 July may mainly have been caused by a decrease in solar heating in the previous two weeks as shown in Fig. 2, because no significant change in wind speed can be seen during this period.

During S2, oxygen depletion in the bottom water also began in late June. DO in the bottom water gradually decreased until mid-August, and later recovered on 18 August. The thermoclines were also almost destroyed in this case. Although the changes in hours of sunshine and wind speed, due to typhoon 8305, were not so great, their combined effects may have caused destruction of the stratification. After recovery of stratification, DO in the bottom water decreased about 4 mg L\(^{-1}\) in only two weeks, and the most serious period of anoxia in the two series of observations occurred on 2 September below the second thermocline.

From the above results, let us consider the time scale for anoxia, that is, the time necessary for oxygen depletion to advance. Knowledge of time scale is useful when we come to consider the mechanism of generation of the anoxic water mass. If the time scale is as long as one month or more, change in conditions of less than a few weeks duration cannot be the cause of anoxia, so we need not take phenomena of such short-time scale into consideration. The temporal variations shown in Fig. 2 give a somewhat confusing indication of time scale. Except for the result of observations on 26 August and 2 September during S2, a fairly long time scale of a few months is suggested, because oxygen depletion advanced gradually from late June to early August during S2. If such a long time scale is assumed, the less pronounced oxygen depletion during S1 may be attributed to the recovery of DO on 27 July. However, the temporal change from mid-August to early September during S2 shows that DO can decrease in only two weeks and suggests a fairly short time scale for formation of the anoxic water mass. Thus, whether the time scale is long or short cannot be directly determined from the observational results. The oxygen budget should be examined quantitatively in order to establish the time scale.
3. Estimate of oxygen consumption rate and vertical diffusivity

The oxygen budget is determined by the balance between DO production by photosynthesis, consumption by respiration or degradation of organisms, and transport due to diffusion or advection. Here, from the results shown in Fig. 2, we estimate two important factors: the vertical diffusivity which determines the vertical transport and the net oxygen consumption rate. The net oxygen consumption rate is the consumption rate minus the production rate. The effects of horizontal advection and diffusion are neglected here, because the horizontal scales of DO and temperature are small compared with the vertical ones as shown in Part 1.

By dividing the water column in the area concerned into three layers by the first and second thermoclines, we consider a vertical three box model as shown in Fig. 3. Positive $z$ is directed downward from the surface, and $H_U$, $H_M$ and $H_L$ are the thickness of the upper, middle and lower layers, respectively, while $K_1$ and $K_2$ are the vertical diffusivities at the first and second thermoclines, respectively. Water properties are assumed to be uniform in each layer. With this model, the heat and oxygen budgets of the middle and lower layers are calculated using the values of the upper layer as boundary conditions.

After integrating the one-dimensional diffusion equation of heat with respect to $z$, we have the following equations for the temperature of the middle and lower layers:
Fig. 3. Three-layer box model and schematic representation of the vertical profile of water temperature.

\[
H_M \frac{dT_M}{dt} = K_1 \left( \frac{T_U - T_M}{h_1} \right) - K_2 \left( \frac{T_M - T_L}{h_2} \right), \quad (1)
\]

\[
H_L \frac{dT_L}{dt} = K_2 \left( \frac{T_M - T_L}{h_2} \right). \quad (2)
\]

Here, \( T_U, T_M \) and \( T_L \) are temperatures of the upper, middle and lower layers, respectively, and \( t \) the time. Although \( h_1 \) and \( h_2 \) are sometimes defined conventionally as the distances between the centers of the layers, here they are defined as thickness of the first and second thermoclines, respectively. By using the data of \( T_U, T_M \) and \( T_L \), both \( K_1 \) and \( K_2 \) are calculated from the finite difference forms of Eqs. (1) and (2).

For the oxygen budgets of the middle and lower layers we have the following equations from the diffusion equation of oxygen including oxygen consumption term:

\[
H_M \frac{dC_M}{dt} = K_1 \left( \frac{C_U - C_M}{h_1} \right) - K_2 \left( \frac{C_M - C_L}{h_2} \right) - R_M H_M, \quad (3)
\]

\[
H_L \frac{dC_L}{dt} = K_2 \left( \frac{C_M - C_L}{h_2} \right) - R_L H_L. \quad (4)
\]

Here, \( C_U, C_M, C_L \) are the concentrations of dissolved oxygen of the upper, middle and lower layers, respectively, and \( R_M \) and \( R_L \) the net consumption rates per unit water volume in the middle and lower layers, respectively. \( R_L \) includes the contribution of oxygen consumption by bottom sediment. By using the data of \( C_U, C_M \) and \( C_L \) and the values of \( K_1 \) and \( K_2 \) estimated as above, \( R_M \) and \( R_L \) are calculated from the finite difference forms of Eqs. (3) and (4).

From the data of temperature and DO shown in Fig. 2, \( K_1, K_2, R_M \) and \( R_L \) are calculated following the above procedure using the given values of \( H_M = 10 \text{ m}, \ H_L = 6 \text{ m}, \ h_1 = h_2 = 2 \text{ m}, \) which are averages for the periods of observation. The results are shown in Fig. 4. The data on 19 August during S1 and on 14 July during S2 are not used in the calculation, because they are too close to the preceding or subsequent observations to give accurate results.

During S1, variations of \( K_1 \) and \( K_2 \) are not so large. They reach a minimum in mid-summer. \( K_1 \) is larger than \( K_2 \) on average. The large \( K_2 \) between 13 July and 27 July may reflect destruction of the second thermocline. \( R_L \) is much larger than \( R_M \) and consumption greatly exceeds production in the lower layer. \( R_M \) fluctuates over positive and negative values, and the average is slightly negative, that is, production exceeds consumption in the middle
layer.

During S2, variations are more remarkable than during S1. $K_1$ and $K_2$ gradually decrease until early August, and fluctuate widely after that. Large values of $K_1$ and $K_2$ between 9 and 18 August reflect the destruction of the thermoclines on 18 August. $R_L$ gradually increases, contrary to the case of S1, and $R_M$ gradually decreases until mid-August, then they suddenly attain a maximum between 18 and 26 August. This maximum in consumption rate occurs about a week later than the maxima of $K_1$ and $K_2$. The most remarkable features of S2 are discussed in the following section after the time scale of anoxia is established.

The average values in the two series are $K_1 = 0.16 \text{ cm}^2 \text{sec}^{-1}$, $K_2 = 0.12 \text{ cm}^2 \text{sec}^{-1}$, $R_M = -0.30 \times 10^{-4} \text{ mg l}^{-1} \text{sec}^{-1}$, $R_L = 3.3 \times 10^{-4} \text{ mg l}^{-1} \text{sec}^{-1}$. $R_L$ translated into the value in the water column of the lower layer is $1.0 \text{ g m}^{-2} \text{day}^{-1}$. This value agrees well with the value of $1.2 \text{ g m}^{-2} \text{day}^{-1}$ determined in Part 1 which was obtained by direct measurements at Sta. T2.

4. The time scale for anoxia and the degree of anoxia

To obtain the time scale for anoxia, we need to know how DO decreases with time under given conditions. We consider this problem with the same model as before. Then the problem is reduced to solving Eqs. (3) and (4) for $C_M$ and $C_L$ as unknowns. From the solutions, we can also determine the degree of anoxia, that is the lowest DO level under given conditions. Since the degree of anoxia is useful for discussing the conditions which caused the frequent occurrence of serious anoxia in the 1960's and 1970's (see Part 1), both the time scale for anoxia and the degree of anoxia are examined here.

In Eqs. (3) and (4), the oxygen consumption rate was assumed to be constant, because it should not change significantly during the period of observation. However, under normal circumstances it should be a function of DO concentration at the place concerned. Thus we should treat it as such a function, because DO changes over a rather wide range. Here we assume that it is proportional to DO. Handa (personal communication) has shown that this assumption holds approximately for observational results at Sta. T2. Then, Eqs. (3) and (4) are rewritten as

$$H_M \frac{dC_M}{dt} = K_1 \left( \frac{C_M - C_M^0}{h_1} \right) - K_2 \left( \frac{C_M - C_L}{h_2} \right) - \frac{C_M}{C_0} \bar{R}_M H_M, \quad (5)$$

$$H_L \frac{dC_L}{dt} = K_3 \left( \frac{C_M - C_L}{h_2} \right) - \frac{C_L}{C_0} \bar{R}_L H_L. \quad (6)$$

Here, $\bar{R}_M$ and $\bar{R}_L$ are the consumption rates at the concentration $C_0$, where $C_0$ is the concentration of the upper layer and is assumed to be constant in this case.

Then, Eqs. (5) and (6) are linear simultaneous differential equations, and the solutions are,

$$C_M(t) = E_1 e^{\alpha t} + E_2 e^{\beta t} + \frac{BP_0 C_0}{AB - P_2 P_3}, \quad (7)$$

$$C_L(t) = \left( \frac{\alpha + A}{P_2} \right) E_1 e^{\alpha t} + \left( \frac{\beta + A}{P_2} \right) E_2 e^{\beta t} + \frac{P_2 P_0 C_0}{AB - P_2 P_3}. \quad (8)$$

where,

$$E_1 = \frac{1}{\alpha - \beta} \left( C_4 P_2 - (\beta + A) C_1 + C_0 \right)$$

$$E_2 = C_1 - E_1 - \frac{BP_0 C_0}{AB - P_2 P_3},$$

$$\alpha, \beta = \frac{-(A + B) \pm \sqrt{(A - B)^2 + 4P_2 P_3}}{2},$$

$$A = P_1 + P_2 + \frac{\bar{R}_M}{C_0}, \quad B = P_3 + \frac{\bar{R}_L}{C_0},$$

$$P_1 = \frac{K_1}{H_M h_1}, \quad P_2 = \frac{K_2}{H_M h_2}, \quad P_3 = \frac{K_3}{h_2}, \quad (9)$$

$C_1$ and $C_2$ are the initial conditions: $C_1=C_M(0)$ and $C_2=C_L(0)$. Through the following analysis, $C_1=C_2=5 \text{ mg l}^{-1}$ which is about the average for our observations. Figure 5 shows examples of the solutions with the values of $K_1=0.16 \text{ cm}^2 \text{sec}^{-1}$, $K_2=0.12 \text{ cm}^2 \text{sec}^{-1}$, $\bar{R}_M=10 \text{ mg l}^{-1} \text{sec}^{-1}$ and $\bar{R}_L=3 \times 10^{-4} \text{ mg l}^{-1} \text{sec}^{-1}$ which are the average values for our observations. These $\bar{R}_M$ and $\bar{R}_L$ are rather simplified values; their accurate values calculated from $R_M$ and $R_L$ and the average values
of $C_M$ and $C_L$ are $-0.30 \times 10^{-6}$ and $3.3 \times 10^{-8}$ mg l$^{-1}$ sec$^{-1}$, respectively. The above values of $K_1$, $K_2$, $R_M$ and $R_L$ are referred as the average diffusivities and average consumption rates hereafter. As shown in Fig. 5, oxygen depletion does not achieve a serious level in this case.

From the above solutions, we can define the degree of anoxia and the time scale for anoxia for the middle and lower layers, but here we deal with only those for the lower layer which is more important. In Eq. (8), the first and second terms in the right-hand side drop out for $t \rightarrow \infty$, because $\alpha$ and $\beta$ are usually negative. Then we have

$$C_L(\infty) = \frac{P_1 P_2 C_0}{AB - P_1 P_2}. \quad (9)$$

This $C_L(\infty)$ is defined as the degree of anoxia, which means the lowest DO level under given conditions. The time scale for anoxia, $t^*$, is defined by

$$\frac{C_L(t^*) - C_L(\infty)}{C_L(0) - C_L(\infty)} = e^{-1}. \quad (10)$$

This time scale means the time during which the sum of the time varying terms (the first

![Figure 5](image1.png)

Fig. 5. $C_M(t)$ and $C_L(t)$ for average diffusivities and consumption rates.

![Figure 6](image2.png)

Fig. 6. (a) $C_L(\infty)$ as a function of $K_2$ for various $K_1$ (in 0.02 cm$^2$ s$^{-1}$ interval) for average consumption rates. Open circle denotes the plot for the average diffusivities in our observations. (b) Same as (a) but for twice the average consumption rate.

![Figure 7](image3.png)

Fig. 7. (a) $C_L(\infty)$ as a function of $R_L$ for various $R_M$ for average diffusivities. Open circle denotes the plot for the average consumption rates in our observations. (b) Same as (a) but for halved diffusivities.
and second terms) in the right-hand side of Eq. (8) reduces to $e^{-1}$ times the initial value.

Figure 6a shows $C_L(\infty)$ as a function of $K_2$ for various values of $K_1$ with the average consumption rates as constants. $C_L(\infty)$ generally decreases with increases of $K_1$ and $K_2$. For $K_2$ smaller than the average, $C_L(\infty)$ is less sensitive to $K_2$, while, for $K_2$ larger than the average, $C_L(\infty)$ is less sensitive to $K_2$. This show that the second thermocline can be an effective barrier causing oxygen depletion in the bottom water, because $K_2$ smaller than the average often appears. Figure 6b shows $C_L(\infty)$ which is the same as shown in Fig. 6a except that the consumption rates are twice the average ones; such consumption rates can sometimes appear under the present conditions as shown in Fig. 4. $C_L(\infty)$ is generally smaller than that in the previous case, but the characteristics are still almost the same. Figure 7a shows $C_L(\infty)$ as a function of $\bar{R}_L$ for various $\bar{R}_M$ with the average diffusivities as constants. $C_L(\infty)$ generally decreases with increases of $\bar{R}_M$ and $\bar{R}_L$, however serious anoxia such that DO decreases to well below 1 mg l$^{-1}$ does not occur for even an order of magnitude larger value of $\bar{R}_L$ than the average. Figure 7b shows $C_L(\infty)$ as in Fig. 7a but for half diffusivities; such diffusivities can appear sometimes as shown in Fig. 4. In this case, serious anoxia can occur when $\bar{R}_L$ is a few times larger than average.

Figure 8a shows $t^*$ as a function of $K_2$ for various $K_1$ with the average consumption rates as constants, and Fig. 8b shows the same but for consumption rates that are doubled. In this case, $t^*$ is generally smaller than one month, and it is not so sensitive to the diffusivities. For average diffusivities and consumption rates, $t^*$ is about two weeks. Figure 9a shows $t^*$ as a function of $\bar{R}_L$ for various $\bar{R}_M$ with the average diffusivities as constants, and Fig. 9b shows the

![Graphs showing $t^*$ as a function of $K_2$ and $\bar{R}_L$ for various $\bar{R}_M$ with average diffusivities as constants.](image)

Fig. 8. $t^*$ as a function of $K_2$ for various $K_1$ for average consumption rates. Open circle denotes the plot for the average diffusivities in our observations. (b) Same as (a) but for twice the average consumption rate.

![Graphs showing $t^*$ as a function of $\bar{R}_L$ for various $\bar{R}_M$ with average diffusivities as constants.](image)

Fig. 9. (a) $t^*$ as a function of $\bar{R}_L$ for various $\bar{R}_M$ for average diffusivities. Open circle denotes the plot for the average consumption rates in our observations. (b) Same as (a) but for half diffusivities.
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same but for half diffusivities. In these cases, \( t^* \) is also smaller than one month except for small \( \overline{R_L} \) in the latter case. \( t^* \) sensitively decreases with increase of \( \overline{R_L} \), but it is not sensitive to \( \overline{R_M} \). For \( \overline{R_L} \) larger than about \( 10 \times 10^{-6} \text{mg l}^{-1} \), \( t^* \) is almost the same in both cases, and it attains a fairly small value of about a week or less.

5. Discussion

From the results of the preceding sections, let us consider the conditions which lead to the serious anoxia in Hiuchi-Nada. Serious anoxia occurred frequently in the 1960's and 1970's, but the anoxia was not so serious during our observations except for one case on 2 September during S2. Since physical properties of the water column should be fairly stable over rather a long time scale such as a few years or more, the diffusivities in the past can be assumed to be almost the same level as those estimated from our observations. Thus, average diffusivities would usually appear and half diffusivities would occasionally appear in the past as at present. In the former case, as shown in Fig. 7a, the degree of anoxia can be below \( 2 \text{mg l}^{-1} \) for \( \overline{R_L} \) larger than about \( 10 \times 10^{-6} \text{mg l}^{-1} \) which is a few times the average \( \overline{R_L} \) in our observations. Hence it is supposed that frequent anoxia occurred when consumption rates were a few times or more larger than average and when diffusivities were, perhaps, a few tens of per cent or more smaller than average. Evidence for such large consumption rates is provided by the fact that the loads of organisms and nutrients were drastically cut down in the 1970's following the several laws for preservation of water quality which came into effect during this period; for example, the COD load from the paper making factories in Iyomishima and Kawanohe was about 30 t day\(^{-1}\) at the end of 1970's, while in 1970 it was as much as 300 t day\(^{-1}\). For such large consumption rates, the time scale for anoxia to develop is about a week or less as seen from Fig. 9. Hence diffusivities small enough for the anoxia to occur can be realized for such short periods during normal variations in diffusivity. Thus we can say that an anoxic water mass is generated when both consumption rates are a few times larger than the average at present and small diffusivities appear during the variations in diffusivity which are usual in summer. Also we can say that the time scale for anoxia is about a week or less. From this result, it can be concluded that serious anoxia will rarely occur under the present conditions where consumption rates are fairly small. However, considering that the time scale for anoxia is very small, we cannot deny the possibility of generation of serious anoxia such as observed on 2 September during S2. Specialized conditions may be able to appear in such a short time scale.

It should be noted that both an increase in consumption rate and a decrease in diffusivity are necessary for anoxia on such a short time scale. From Fig. 6a, very small diffusivities of the order of 0.01 cm\(^2\) sec\(^{-1}\) seem to be able to cause serious anoxia without a significant increase in consumption rates. But the time scale for anoxia in the case is about a month as can be seen from Fig. 8a, and such small diffusivities can hardly be maintained for a month. Thus, the time scale for anoxia is a useful parameter to consider when determining the mechanism of generation of the anoxic water mass.

The serious anoxia on 2 September during S2 (Fig. 2) seems to be an unusual phenomenon, when we consider the unusual fluctuations of the consumption rates during that summer. It is apparent that small diffusivities and large consumption rates between 18 and 26 August caused this anoxia. A possible explanation for the mechanism which caused the large consumption rates is as follows. We notice large diffusivities between 9 and 18 August about a week before the occurrence of the large consumption rates. These diffusivities are caused by the destruction of the thermocline as shown in Fig. 2; thermocline destruction is probably due to the combined effect of an increase in wind speed and a decrease in the hours of sunshine, as stated before. Under such diffusivities, nutrient in the bottom water, which have been supplied by degradation of organisms and release from the sediment and stored below the second thermocline, are resupplied to the upper euphotic zone leading to a bloom of phytoplankton and of zooplankton which grazes on them. After the bloom, detritus and fecal pellets settle down to the bottom water with the recovery of the
stratification and cause a large oxygen demand there. The peak in diffusivities followed by a peak in consumption rates as shown in Fig. 4 suggest such a process. However, data on the vertical distribution of nutrients and organisms or their vertical fluxes are insufficient to examine this process, and further investigations are necessary in this respect. The reason for the small diffusivities between 18 and 26 August is not clear. Since the above process is triggered by the destruction of the thermoclines, investigations are also required to determine the cause of short-term variation in the thermoclines.

We should further mention the relation between the time scale for anoxia and the vertical scale. It is fairly complicated to examine this problem using Eq. (10), because the time scale depends on too many factors. Moreover, a three-layer situation may not be so common. So we consider this problem using a simple two-layer model where upper water of constant DO, \( C_0 \), overlies a lower layer of thickness \( H_L \) and variable DO, \( C_L \). In this case, an equation similar to Eq. (6) is set up and the solution includes only one time-varying exponential term. Then the time scale for anoxia is written as

\[
t^* = \left( \frac{K}{hH_L + \frac{R_L}{C_0}} \right)^{-1},
\]

where \( h \) is the thickness of the thermocline between the two layers and \( K \) the vertical diffusivities there. Equation (11) shows that the short time scale for anoxia in Hiuchi-Nada is caused by the short vertical scale. Hence, in deeper water, the time scale for anoxia will be larger than in our case, and long-term variations of conditions will be the major concern in generation of the anoxic water mass. For example, Falkowski et al. (1980) shows that the time scale for anoxia in New York Bight Appendix, the depth of which is about twice that of our case, is about one month for the case of small diffusivity, and that the anoxic water in 1976 was influenced by meteorological conditions in the preceding winter (their definition of the time scale is different from ours, but, even if our model and definition are applied, the time scale of almost the same order of magnitude will be provided). Thus the dependence of the time scale for anoxia on the depth scale is important when considering the mechanism of generation of the anoxic water mass.

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References
新しい文字列を提供する必要がある。