551.464 : 546.21

A Study on the Dissolved Oxygen in the Ocean*

by

Y. Miyake and K. Saruhashi

Meteorological Research Institute, Tokyo

(Received February 13, 1967)

Abstract

According to the authors' calculation, the total amount of invasion of oxygen from the air into the sea is less than the amount of consumption by oxidation of the organic debris in the deep layer until the time when the invasion and the consumption reach the equilibrium. The rate of consumption of oxygen decreases exponentially with the depth. On the other hand, the oxygen which is supplied from the air enters into the deep layer according to the law of diffusion, decreasing rapidly with the depth. The combination of the above two makes the minimum layer of oxygen at a certain depth at the steady state.

However, in the oceans, there are currents and eddy diffusion in horizontal and vertical directions, and the pattern of oxygen distribution is decided as the superposition of biogeochemical processes and the dynamical motion of water. Using the equation given by Sverdrup concerning the change with time of the amount of dissolved oxygen in the sea, the distribution of oxygen in the western North Pacific is discussed. The results showed that at the steady state, the effect of horizontal advection is much larger than those of horizontal diffusion and biological consumption and the former seem to be in balance with vertical diffusion.

1. Why is the dissolved oxygen in the deep water unsaturated?

It is well known that the nitrogen dissolved in sea water is saturated in the surface as well as in the deeper layers of the ocean. However, the dissolved oxygen is nearly in saturation only at the surface and considerably unsaturated in the deeper layers. If there is no biological activity in the oceans, the dissolved oxygen should be saturated all the way from surface to bottom and the oxygen content should be smaller in the surface than in the deeper water, because the water temperature lowers with the depth.

However, owing to the biological activity in the ocean, the oxygen content is controlled not only by the exchange of oxygen through the air-sea interface and the mixing of water, but also by the photosynthesis, respiration and oxidation of organic matters (Miyake and Saruhashi, 1957). As a result of the dynamical balance in these changes, the dissolved oxygen in the surface layer becomes saturated or nearly saturated or sometimes slightly over-saturated.

---

* Presented at the XIth Pacific Science Congress, Tokyo, Aug. 1966.

In the deeper layer below the euphotic zone, the oxygen is mainly consumed by the oxidation of the organic debris, though its rate is much slower owing to the lower water temperature. The oxygen content in the deeper layer is also controlled by the slow exchange of oxygen associated with the exchange of water masses between deep and surface layers.

Now, we divide the ocean simply into two layers, the surface layer with 100 m thick and the deep layer with 3,900 m depth. At the steady state, the rate of exchange of water between the two layers is expressed as follows:

$$k_1 w_1 = k_2 w_2 \tag{1}$$

where, k_1 and k_2 are the velocity constants of exchange of water respectively from the surface into the deep and from the deep to the surface. The reciprocals of k_1 and k_2 are respectively the residence times of water in the surface and in the deep layer. w_1 and w_2 are respectively volumes of water in the surface and the deep layer (l/m^2). The change with time of the total amount of dissolved oxygen (mole/m^2) in the deep layer (O_2) is expressed as follows:

$$\frac{\partial O_2}{\partial t} = k_1 w_1 C_1 - k_2 w_2 C_2 - f_2 \tag{2}$$

in which C_1 and C_2 are respectively the concentrations of the oxygen (ml/l at STP) in the surface water and the deep water, f_2 is the oxidation rate of organic debris (mole/m^2, y) in the deep layer. In the steady state,

$$k_1 w_1 C_1 = k_2 w_2 C_2 + f_2 \tag{3}$$

As $k_1 w_1$ is equal to $k_2 w_2$ (Eq. 1) and f_2 is positive, C_1 must be larger than C_2 at the steady state.

The primary production rate is estimated to be 80 g C/m^2, y on an average. It is assumed that in 80 g C/m^2 of the organic carbon, 30, 40 and 50 g C/m^2 is oxidized in the deep layer into the carbon dioxide annually. In other words, 2.5, 3.3 and 4.2 moles of oxygen are consumed by the oxidation in the deep layer.

On the other hand, when the water temperature at the surface layer is 20°C, the dissolved oxygen content C_1 is 5.5 ml/l (or 550 l/m^2 or 25 moles O_2/m^2) under the saturation state. From the above equations (1) and (3), C_2 is obtained for the residence time (τ_1) of the surface water of five years and different values of f_2.

Table 1. Calculation of oxygen concentration C_2 at deep layers. τ_1, 5 yrs.

C_1	k_1	f_2	C_2	
ml/l	1/y	mole/m^2, y	ml/l	Degree of saturation
5.5	1/5	2.5 (30 g C/m^2, y)	2.8	37%
5.5	1/5	3.3 (40 〃)	1.8	25
5.5	1/5	4.2 (50 〃)	0.9	12

As the mean temperature of the deep water is 3–4°C, under which the saturated amount of oxygen is 7.5 ml/l. Therefore, the degree of saturation corresponding to the calculated values of C_2 ranges from 12 to 37%, which is in good accordance with the observation. It is to be noticed that f_2 can not be greater than 60 g C/m² for 5 years of τ_1, or τ_1 can not be longer than 8 years for f_2 of 40 g C/m², y.

In the surface layer, the change with time in the total amount of the dissolved oxygen (O_1) is expressed as follows:

(4) $$\frac{\partial O_1}{\partial t} = -k_1 w_1 C_1 + k_2 w_2 C_2 + E + P - f_1$$

In the above equation E is the rate of entrance of the oxygen from the air (mole/m², y), P is the rate of formation of oxygen through photosynthesis (mole/m², y) and f_1 is the rate of consumption of oxygen through the respiration and oxidation of organic matters (mole/m², y).

At the steady state, the entrance rate of oxygen E is,

(5) $$E = k_1 w_1 C_1 - k_2 w_2 C_2 - P + f_1$$

From the equation (2) and the next condition (Eq. 6), the entrance rate should be zero, or

(6) $$f_1 + f_2 = P$$

there is no entrance through the air-sea interface at the steady state. However, as in the organic matter certain amounts of nitrogen and other oxidizable elements are contained, P is a little smaller than (f_1+f_2), *i. e.* by about 10%, which makes the entrance of oxygen from the air possible. In the equilibrium state, the amount of entrance of oxygen will be about 0.7 mole/m², y for the primary production of about 80 g C/m², y. In other words, even in the surface layer at the steady state, the dissolved oxygen has a tendency to become slightly unsaturated owing to the condition, $P < f_1 + f_2$.

In different parts of the oceans, there are always some fluctuations from the steady state in regard to oxygen, causing small differences in the partial pressure of oxygen between the ocean surface and the air above. Under such conditions, entrance or escape of a small amount of oxygen may take place.

In the surface layer in cold areas where photosynthesis exceeds respiration and oxidation in the spring and summer seasons, the supersaturation of oxygen occurs. However, the supersaturation has its physical meaning only at the interface between the air and the sea. Below the interface, for example, at the 10 m depth from the surface, the solubility of oxygen is twice as much as the surface value owing to the hydrostatic pressure (Henry's law). Therefore, there is no bubble formation of oxygen even when a high degree of "supersaturation" is observed (Miyake, 1951).

2. The rate of entrance of oxygen from the air

According to Adeney (1928), the invasion coefficient γ (ml/cm², min), or the rate of entrance of oxygen from the air to the sea surface can be expressed as follows:

$$\gamma = 9.6(t+36)(\alpha - C_1) \times 10^{-6} \tag{7}$$

where t is the water temperature, α is the concentration of the oxygen at the saturation at t°C (ml/l) and C_1 is the observed concentration of the dissolved oxygen at the surface.

Assuming that t is 20°C and α is 5.3 ml/l, the total amounts of entrance of oxygen from the air in a year for different values of C_1 are calculated as shown in Table 2.

Table 2. The rate of entrance of oxygen (E) from the air into the sea (20°C)

C_1	Degree of saturation	E	
ml/l	%	mole/m^2, y	ml/l, y
5.295	99.9	0.5	0.003
5.29	99.8	1.2	0.007
5.27	99.5	3	0.02
5.25	99.0	6	0.04

As shown in the above table, the annual rate of entrance of oxygen at the degree of saturation of 99.9 and 99.8% ranges from 0.5 to 1.2 mole/m^2, y which is in good agreement with the value (0.7 mole/m^2, y) obtained above on the basis of the balance of oxygen in sea water at the surface.

As shown in Table 2, the averaged amount of entrance of oxygen from the air into the sea reaches 3 mole/m^2,y when the degree of saturation is 99.5%. On the other hand, in the deep layer the rate of consumption of oxygen by the oxidation of organic matter is about 3 mole/m^2,y when 40 g C/m^2 is oxidized annually (Tab. 1). At the time when the degree of saturation reaches 99.5%, the rate of entrance of the atmospheric oxygen increases to the same level as the rate of consumption of oxygen by oxidation which leads to the equilibrium with respect to the oxygen in the ocean. In other words, before reaching the equilibrium, the rate of entrance of oxygen is less than that of oxidation, which results in the deficit of oxygen in the deep layer.

3. The occurrence of the oxygen minimum layer

As stated in a preceding chapter, the rate of entrance of oxygen is less than that of oxidation of organic debris in the deep layer until the time when the entrance and the consumption reach the equilibrium. At the equilibrium, the degree of saturation of oxygen in the surface layer will be about 99.5% and the rate of oxidation will be about 3 mole C/m^2, y. It is known that the rate of consumption of oxygen decreases exponentially from the bottom of the thermocline. On the other hand, the oxygen which enters from the air is transferred to the deep by turbulent diffusion, with a rate of diffusion decreasing rapidly with depth. If there is no biological consumption, the dissolved oxygen content should increase with increasing depth. However, there are the entrance of oxygen from the air and the consumption of oxygen by oxidation, in which the rate of entrance is slower than the latter at the beginning. Therefore the oxygen gradually decreases in the deep. The combination of the rate of entrance and the vertical change of rates of turbulent diffusion and oxidative consumption produces the oxygen minimum layer at a certain depth. The occurrence of the oxygen minimum layer is qualitatively illustrated in Fig. 1.

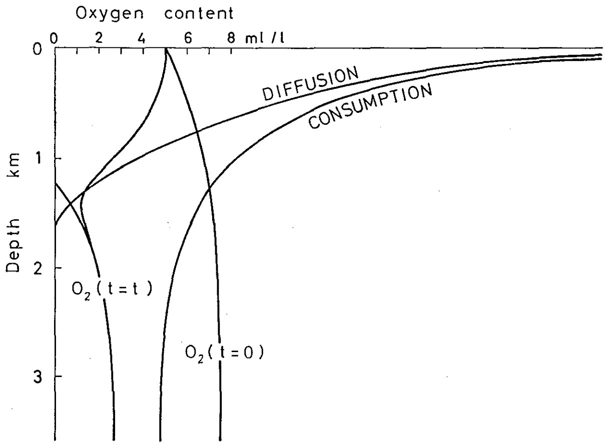

Fig. 1. Schematic explanation of occurrence of O_2 minimum layer.

4. Dynamical motion of sea water and the distribution of the dissolved oxygen

As discussed above, the primary pattern of the distribution of the dissolved oxygen in the ocean is determined by the biogeochemical balance of oxygen in the ocean. However, in the oceans, there are advection and eddy diffusion of water both in the horizontal and the vertical directions, and the final distribution of oxygen is controlled by the superposition of the biogeochemical processes and the dynamical motion of water.

According to SVERDRUP (1938), the change of the dissolved oxygen concentration (O) in the deeper layer with time is given by the following differential equation:

$$\frac{\partial O}{\partial t}=D_h\frac{\partial^2 O}{\partial x^2}+D_h\frac{\partial^2 O}{\partial y^2}+D_z\frac{\partial^2 O}{\partial z^2}-u\frac{\partial O}{\partial x}-v\frac{\partial O}{\partial y}-w\frac{\partial O}{\partial z}-f \tag{8}$$

where D_h and D_z are the eddy diffusion coefficients respectively in the horizontal and the vertical directions, u, v and w are current velocities on each direction, f is the rate of oxidative consumption of oxygen by organic matter. At the steady state, neglecting the vertical flow, the equation (8) is rewritten as follows:

$$D_z\frac{\partial^2 O}{\partial z^2}=\left(u\frac{\partial O}{\partial x}+v\frac{\partial O}{\partial y}\right)-D_h\left(\frac{\partial^2 O}{\partial x^2}+\frac{\partial^2 O}{\partial y^2}\right)+f \tag{9}$$

By using the observed values of the vertical distribution of dissolved oxygen at 38°N, 148°E and the horizontal distribution on the iso-sigma-t plane respectively at σ_t, 25.0, 25.5, 26.0, 26.5, 27.0, 27.5 in the western North Pacific Ocean (Figs. 2–4) (Kawamoto,

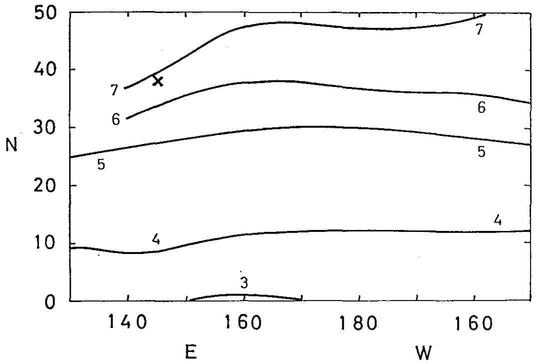

Fig. 2. Horizontal distribution of oxygen (σ_t, 25.0) unit: ml/l

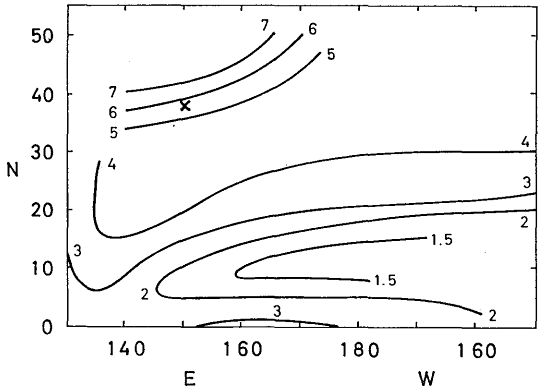

Fig. 3. Horizontal distribution of oxygen (σ_t, 26.5) unit: ml/l

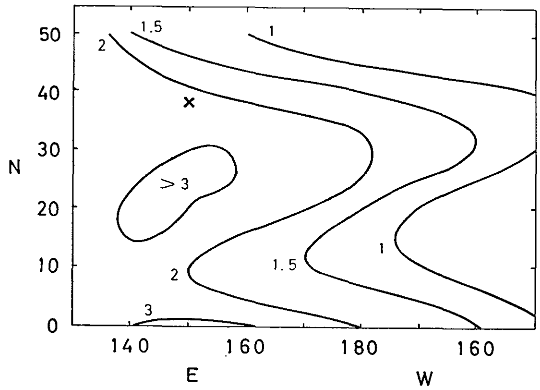

Fig. 4. Horizontal distribution of oxygen (σ_t, 27.0) unit: ml/l

Table 3. Calculation of horizontal advection of oxygen (38°N, 148°E)

Depth m	Flow rate cm/sec	u, v cm/sec	$\frac{\partial O}{\partial x}$ ml/l/10^8 cm	$\frac{\partial O}{\partial y}$ ml/l/10^8 cm	$u\frac{\partial O}{\partial x}$, m$l$/$l$/$10^8$ sec	$v\frac{\partial O}{\partial y}$ ml/l/10^8 sec	Sum
300	30	21(NW)	−0.5	1.0	−10	21	11
400	25	17	−0.1	−1.2	−1.7	20	18
500	20	−14(SW)	−0.1	−1.2	1.4	17	18
600	18	−13	−0.1	−1.1	1.3	14	15
800	15	−10	−0.1	−1.1	1.0	11	12
1,000	13	− 9	−0.1	−1.0	0.9	9	10
1,100	12	− 8	−0.1	−0.9	0.8	7	8
1,500	10	− 7	−0.1	−0.9	0.7	6	7

Table 4. Calculation of horizontal diffusion of oxygen (38°N, 148°E)
(D_h, 5×10^8 cm^2/sec)

Depth m	$\frac{\partial^2 O}{\partial x^2}$	$\frac{\partial^2 O}{\partial y^2}$	$D_h\left(\frac{\partial^2 O}{\partial x^2}+\frac{\partial^2 O}{\partial y^2}\right)$
	ml/l/10^{16} cm^2		ml/l/10^8 sec
300	0	1.5	7.5
400	−0.1	−0.2	−1.5
500	−0.1	−0.2	−1.5
600	−0.1	−0.2	−1.5
800	−0.1	−0.2	−1.5
1,000	−0.1	−0.1	−1.0
1,100	−0.1	−0.1	−1.0
1,500	−0.1	−0.1	−1.0

Table 5. Vertical distribution and vertical eddy diffusion of oxygen (38°N, 148°E)
(D_z, 50 cm^2/sec)

Depth m	σ_t	O_2 ml/l	$\frac{\partial O}{\partial z}$ ml/l/10^4 cm	$\frac{\partial^2 O}{\partial z^2}$ ml/l/10^8 cm^2	$D_z\frac{\partial^2 O}{\partial z^2}$ ml/l/10^8 sec
300	26.75	4.2	−1.4	0.1	5
400	26.9	2.8	−1.0	0.4	20
500	27.1	1.9	−0.7	0.3	15
600	27.2	1.6	−0.4	0.3	15
800	27.35	1.1	−0.1	0.2	10
1,000	27.4	1.0	0	0.1	5
1,100	27.5	1.0	+0.1	0.1	5
1,500	27.6	1.3	+0.2	0.1	7

Table 6. Comparison of advection, diffusion and biological effects on dissolved oxygen.
(unit, ml/l/10^8 sec)

Depth m	Advection	Horiz. diffn.	Biol. consmptn.	Total $(A-H+B)$	Vert. diffn.
300	11	7.5	0.4	4	5
400	18	−1.5	0.3	19	20
500	18	−1.5	0.25	19	15
600	15	−1.5	0.20	16	15
800	12	−1.5	0.13	13	15
1,000	10	−1.0	0.07	11	10
1,100	8	−0.5	0.07	9	5
1,500	7	−0.3	0.05	7	5

1957), the horizontal and vertical gradients of dissolved oxygen and their secondary differentials were calculated. The mean speed and direction of water current at different depths are assumed as given in Table 3. The horizontal and vertical eddy diffusion coefficients are assumed to be respectively $5\times10^8\,cm^2/sec$ and $50\,cm^2/sec$. The rates of oxygen consumption by organic matter are respectively 2 ml/l, y and 0.2 ml/l, y at the depths of 100 m and 1,000 m for the decomposition rate of the organic matter of 40 g C/m^2, y.

As given in Table 6, it is concluded that the effect of horizontal advection on the distribution of dissolved oxygen is much larger than those of horizontal diffusion and biological consumption and the former is mainly conpensated for by vertical diffusion.

References

ADENEY, W. E., 1928: The dilution method of sewage disposal. Cambridge.

KAWAMOTO, T., 1956: On the distribution of the dissolved oxygen in the Pacific Ocean. Part 2. On the $\sigma-O_2$ diagram in the equatorial region of the North Pacific Ocean. Umi to Sora (Sea and Sky) 32, 92-98.

MIYAKE, Y., 1951: The possibility and allowable limit of formation of air bubbles in the sea. Pap. Met. Geophys., 2, 95-101.

MIYAKE, Y. and K. SARUHASHI, 1956: On the vertical distribution of the dissolved oxygen in the ocean. Deep-Sea Res., 3, 242-247.

SVERDRUP, H. U., 1938: On the explanation of the oxygen minima and maxima in the oceans. J. de Conseil, 13, 163-172.

海洋中の溶在酸素に関する研究

三宅　泰雄・猿橋　勝子

海水中の酸素の減少は有機物の酸化（呼吸）によるものとし，有機物の分布，水の拡散などを考慮に入れて，酸素極小層の出現を考察した。

海洋においては，海流，水平および鉛直方向の拡散があるので，酸素の分布は生物地球化学的な過程と，海水の動的な運動の二つの重なり合いによって決定されると考えられる。

著者らは，溶在酸素の時間的変化に関する Sverdrup の方程式を用いて，北太平洋西部海域における酸素の分布を考察した。

計算の結果は，定常状態においては，水平方向の移流は，水平方向の拡散や生物による消費にくらべてかなり大きく，水平方向の移流が，鉛直方向の拡散とほぼつりあっていることが分った。