The Carbon Dioxide System in the Ocean

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Abstract

It is explained by the law of the ionic dissociation equilibrium that in the carbon dioxide system in sea water not only the bicarbonate ion content prevails among others ($>90\%$), but also it is nearly constant especially in deep layers (94%). In the next place, in order to clarify the carbon dioxide system in the ocean, taking into consideration the effects of biological production and decay as well as dissolution and precipitation of calcium carbonate, the theoretical relations between the carbon dioxide system and biological processes are deduced. As to the ratio between calcium content and carbonate alkalinity, it is concluded from the theoretical view point that it is not constant but varies widely.

The discussion is done by using the observed data obtained during the Antipode 15 Expedition and others. The results show that there is a good agreement between observation and theory.

1. Introduction

It is well known that the carbon dioxide system in the ocean consisting of free carbonic acid (H_2CO_3), bicarbonate ion (HCO_3^-) and carbonate ion (CO_3^{2-}) is mainly controlled by production and oxidative decomposition of organic matter, and formation and dissolution of solid carbonate represented by calcium carbonate. Among these processes, the relation between the total carbon dioxide content (ΣCO_2 or T) and regeneration of carbon dioxide through oxidation of organic matter was discussed by the present authors many years ago (MIYAKE and SARUHASHI, 1956). They showed that the greater part of increase in the total carbon dioxide content as well as the alkalinity in the deep layers of the ocean is caused mainly by the oxidation of organic matter rather than the

dissolution of calcium carbonate as previously suggested by MÖBERG and REVELLE (1937) and other investigators.

In this paper, the carbon dioxide system in the ocean is studied in more detail taking the effect of dissolution of calcium carbonate on the carbonate alkalinity into consideration.

2. The predominance and constancy of bicarbonate ion content in the carbon dioxide system in sea water

According to the observations up to the present, in the carbon dioxide system in sea water, not only the relative amount of bicarbonate ion is very much higher than others, but also it is nearly constant especially in deep waters. In this section, the reasons

for the predominance and constancy of the bicarbonate ion content in sea water are given.

There are the following well known equations concerning the electrolytic dissociation equilibrium of carbonic acid.

$$\frac{[H^+][HCO_3^-]}{[H_2CO_3]} = K_1 \quad (1)$$

$$\frac{[H^+][CO_3^{2-}]}{[HCO_3^-]} = K_2 \quad (2)$$

where $[H^+]$, $[H_2CO_3]$, $[HCO_3^-]$ and $[CO_3^{2-}]$ are the molar concentrations of respective chemical species, K_1 and K_2 are respectively the apparent first and second dissociation constant of carbonic acid. By combining the above two equations with the next equation which defines the total carbon dioxide content,

$$T = F + B + C \quad (3)$$

where $F = [H_2CO_3]$, $B = [HCO_3^-]$ and $C = [CO_3^{2-}]$, the following three equations are deduced.

$$F = \frac{T \cdot [H^+]^2}{\gamma} \quad (4)$$

$$B = \frac{T \cdot [H^+] K_1}{\gamma} \quad (5)$$

$$C = \frac{T \cdot K_1 K_2}{\gamma} \quad (6)$$

where

$$\gamma = [H^+]^2 + [H^+] K_1 + K_1 K_2 \quad (7)$$

In sea water, $[H^+] K_1$ is much larger than both $[H^+]^2$ and $K_1 K_2$. For example, in sea water with a temperature of 10°C, pH of 8.0 and a chlorinity of 19‰, the value of $[H^+] K_1$ is 8.1×10^{-15} , while those of $[H^+]^2$ and $K_1 K_2$ are much lower, respectively 1×10^{-16} and 4.1×10^{-16} . It may be said, therefore, that the main part of the total carbon dioxide content in sea water is bicarbonate ion. In other words, γ is approximately equal to $[H^+] K_1$. In fact, in the deep layers of the ocean where the temperature and pH are low and nearly constant, the percentage of bicarbonate ion in the total carbon dioxide content has a high and constant value of 94%.

As regards the change in the fraction

of each component F, B and C in the total carbon dioxide content, a change of K_1 and K_2 with temperature, and a change of pH should be considered.

According to LYMAN (1957), by the change of temperature from 0°C to 20°C, K_1 changes from 6.9×10^{-7} to 9.3×10^{-7} , and K_2 changes from 3.8×10^{-10} to 6.5×10^{-10} . On the other hand, when pH changes from 8.2 to 7.4, the hydrogen ion concentration increases from 6.3×10^{-9} mole/l to 4.0×10^{-8} mole/l which is seven times higher than the former. Therefore, it is evident that a change in pH is much more effective on the variation of the carbon dioxide system than a change in water temperature.

However, it is to be noted that the influences associated with a change of pH are mainly on the relative abundance of free carbonic acid and carbonate ion, while little effect is brought about on the fraction of bicarbonate ion.

The tendency of the fraction of free carbonic acid and carbonate ion contents to be controlled considerably by the hydrogen ion concentration is clearly shown by the approximate equation of Eqs. 4 and 6 as follows,

$$\frac{F}{T} \div \frac{[H^+]}{K_1} \quad (8)$$

$$\frac{C}{T} \div \frac{K_2}{[H^+]} \quad (9)$$

For example, in sea water with a chlorinity of 19‰, F/T and C/T are respectively 0.009 and 0.09 at a temperature of 20°C and pH of 8.0, while they change to 0.043 and 0.017 at 4°C and pH 7.5. That is, under two different conditions F/T increases by five times, while C/T decreases to one fifth. On the contrary, B/T changes only from 0.90 to 0.94 by the same change in sea water conditions.

3. Two layer model of the carbon dioxide system in the ocean

In the previous section, the predominance and constancy of bicarbonate ion content in sea water are explained from the theoretical

view point. In this section, changes in the carbon dioxide system through biochemical processes are discussed in which production and oxidation of organic matter and dissolution of calcium carbonate are involved.

The change in the total carbon dioxide content is expressed as follows:

$$T = T_0 + \Delta T \quad (10)$$

where

$$T_0 = F_0 + B_0 + C_0 \quad (11)$$

$$\Delta T = \Delta F + \Delta B + \Delta C \quad (12)$$

where

$$\Delta F = F - F_0 \quad (13)$$

$$\Delta B = B - B_0 \quad (14)$$

$$\Delta C = C - C_0 \quad (15)$$

By the definition Δ values in the above equations can be either positive or negative.

The ocean can be divided into two layers with respect to the carbon dioxide system, *i. e.*, the first layer from the surface to about 1,000 m depth, and the second layer from 1,000 m depth to the bottom. In the first layer, production and oxidative decomposition of organic matter and formation and dissolution of calcium carbonate take place actively. On the other hand, in the second layer, only regeneration of carbon dioxide from organic matter and redissolution of a small amount of calcium carbonate go on very slowly.

Concerning T_0 in Eqs. 10 and 11, it is defined that in the first layer, T_0 is the total carbon dioxide content which should be present originally when there are no biochemical reactions, and in the second layer, T_0 is a part of the total carbon dioxide content which does not relate to the biochemical cycle. F_0 , B_0 and C_0 are the components of T_0 . ΔT is the amount of variation in the total carbon dioxide content, and ΔF , ΔB and ΔC are its components.

In the ocean, changes in the total carbon dioxide content are mainly caused by release or removal of free carbonic acid respectively through oxidation or production of organic matter, as well as by addition or deduction of carbonate ion respectively through dis-

solution or formation of solid calcium carbonate.

The change in the total carbon dioxide content (mM/kg) through various biochemical processes in the first and the second layers can be expressed as follows.

$$\Delta T_1 = \Delta O_1 + \Delta D'_1 - \Delta b_1 \quad (16)$$

(The first layer)

$$\Delta T_2 = \Delta O_2 + \Delta D_2 \quad (17)$$

(The second layer)

The suffixes 1 and 2 represent respectively the first and the second layer. ΔO is the amount of carbon dioxide released through oxidation of organic matter, Δb is the amount of carbon dioxide which is converted to organic matter through photosynthesis, $\Delta D'$ is the difference of the amounts of carbon dioxide released by the dissolution (ΔD), and lost by the formation of calcium carbonate. In the second layer, it is considered that the effects of formation of calcium carbonate and production of organic matter are negligible. No quantity in the above equations is constant, but varies with location and depth in each layer.

Among the above quantities, ΔO is obtained by the apparent oxygen utilization (AOU), *i. e.*, the difference of the saturated concentration of dissolved oxygen and the observed concentration *in situ*. It is assumed that 80% of AOU is used for oxidation of organic carbon. To estimate values of ΔD and $\Delta D'$, a value of $[Ca]_0$ must be known, which is the concentration of non-cyclic calcium in the second layer with a total carbon dioxide of T_0 . A probable value of $[Ca]_0$ which is consistent with every other factor can be estimated by the method of trial and error to be described later.

In principle, Δb_1 should be equal to the concentration of carbon in surface sea water remaining as organic compounds both in dissolved and particulate forms including living matter. However, a greater part of the organic carbon settles down to the deep as organic debris sooner or later after it has been produced in the surface layer. Therefore, the actual concentration of or-

ganic carbon in the surface layer would be much smaller than Δb_1 . Judging from the vertical distribution of the organic carbon in the ocean, the organic carbon concentration remaining in the surface layer is approximately only a half of Δb_1 . At any rate, since Δb_1 can not be obtained directly from the observation, it must be calculated by using Eq. 16 as follows.

$$\Delta b_1 = -\Delta T_1 + \Delta O_1 + \Delta D_1' \quad (18)$$

However, in order to estimate the value of Δb_1 , ΔT_1 or T_0 in the first layer must be known. It is assumed here that at the same station, T_0 has the same value both in the first and the second layer. In the second layer, T_0 can be easily obtained by Eq. 17.

Thus, the total carbon dioxide content in sea water in both layers can be written as follows.

$$T_1 = T_0 + \Delta O_1 + \Delta D_1' - \Delta b_1 \quad (19)$$

(The first layer)

$$T_2 = T_0 + \Delta O_1 + \Delta D_2 \quad (20)$$

(The second layer)

In the same way, using the relation

$$\Delta B = \Delta T - (\Delta F + \Delta C) \quad (21)$$

the bicarbonate ion contents in the first and the second layer at the same station can be expressed as follows.

$$B_1 = B_0 - \Delta F_1 - \Delta C_1 + \Delta O_1 + \Delta D_1' - \Delta b_1 \quad (22)$$

(The first layer)

$$B_2 = B_0 - \Delta F_2 - \Delta C_2 + \Delta O_2 + \Delta D_2 \quad (23)$$

(The second layer)

As in the case of T_0 , it is assumed that a value of B_0 is the same in both layers at the same station.

With respect to the carbonate alkalinity (CA, meq/kg), using the relation

$$\Delta CA = \Delta B + 2\Delta C, \quad (24)$$

the following equations are deduced.

$$CA_1 = CA_0 - \Delta F_1 + \Delta C_1 + \Delta O_1 + \Delta D_1' - \Delta b_1 \quad (25)$$

(The first layer)

$$CA_2 = CA_0 - \Delta F_2 + \Delta C_2 + \Delta O_2 + \Delta D_2 \quad (26)$$

(The second layer)

It is also assumed here that a value of CA_0 is the same in both layers at the same station.

4. Relation between calcium content and carbonate alkalinity in sea water

Up to now, many researchers (TSUNOGAI *et al.*, 1973, HORIBE *et al.*, 1974, BREWER *et al.*, 1975) have considered that the dissolution of n mole of calcium carbonate in sea water should bring about the increase of $2n$ equivalents in the carbonate alkalinity, because carbonate ion is divalent. From this view, they have tried to find out the 1:2 relationship between a change in calcium ion content (in mole) and that in the carbonate alkalinity (in equivalent) in sea water.

But this is not the case, because change in the carbonate alkalinity is controlled not only by the dissolution of carbonate, but also by other biochemical processes as shown in Eqs. 25 and 26. Since, as will be shown later, both the calcium content $[Ca]$ and the carbonate alkalinity CA are smallest at the surface of the ocean, the ratio between each change in the two quantities can be obtained by taking a surface value of each component as a respective standard. Thus, the relation between changes of $[Ca]$ and CA are derived from Eqs. 25 and 26 as follows, in which $\Delta D'$ or ΔD is replaced by $\Delta[Ca]$.

$$\frac{\delta[Ca]}{\delta CA} = 1 - \frac{\beta}{\delta CA} \quad (28)$$

where

$$\delta[Ca] = [Ca] - [Ca]_s \quad (29)$$

$$\delta CA = CA - CA_s \quad (30)$$

$$\beta = -(F - F_s) + (C - C_s) + (O - O_s) - (\Delta b - \Delta b_s)$$

and, s denotes a surface value. It is assumed that $[Ca]_0$ is the same in both layers at the same station.

The relation between calcium content and carbonate alkalinity is complicated and the ratio also changes widely as shown later in Table 4.

5. Discussion

In order to prove the above views on the carbon dioxide system in the ocean, the total carbon dioxide content, the dissolved oxygen content, water temperature and salinity of sea water collected at the stations in the tropical area in the South Pacific Ocean covering the area of about 15°–17°S and 170°–173°W during the cruise of the Antipode 15 Expedition by the Scripps Institution of Oceanography and the observed values of the calcium content (HORIBE *et al.*, 1974). Unfortunately, as pH values are not available in the above observations, those obtained in the nearby stations of the Southern Cross Expedition conducted by the Ocean Research Institute of the University of Tokyo are used (HORIBE *et al.*, 1970).

Δb_1 is calculated by using Eq. 18. The results of calculation show that Δb_1 is 140–160 $\mu\text{M/kg}$ which is about two times the surface concentration of organic carbon in the equatorial western Pacific (about 70–80

$\mu\text{M/kg}$). This ratio between Δb_1 and the organic carbon concentration in the surface agrees very well with the above estimation given by the present authors. It is also reasonable to see that Δb_1 tends to diminish with increasing depth, approaching zero at about 500 m below the surface which coincides with the depth of the bottom of euphotic zone.

The fraction of each component (F, B and C) is obtained from the observed values of the total carbon dioxide content (T) by referring to the tables which were previously compiled by one of the present authors for different chlorinity, temperature and pH (SARUHASHI, 1955).

The carbonate alkalinity is obtained by using the calculated values of B and C. The concentration of every chemical species is normalized to the salinity of 35‰ (Cl; 19.374 ‰). $[\text{Ca}]_0$, the noncyclic calcium content in the second layer is determined to be 10.38 mM/kg by applying the trial and error method. In Figs. 1a to 1d are shown the

Fig. 1. Vertical distribution of components of carbon dioxide system.

Unit; mM/kg. CA, m eq/kg

a. Station 2 b. Station 6 c. Station 10 d. Station 11

Table 1. Vertical distribution of ΔO_2 , ΔD_2 , B_0 , T_0 and CA_0 in the second layer.

Depth m	ΔO_2 mM/kg	ΔD_2 mM/kg	B_0 mM/kg	T_0 mM/kg	CA_0 meq/kg
a. Station 2 (15°22'S, 172°05'W)					
1,000	0.14	0.0	2.01	2.14	2.20
2,000	0.16	0.02	2.02	2.15	2.19
3,000	0.16	0.04	2.03	2.16	2.20
4,000	0.12	0.02	2.03	2.16	2.21
5,000	0.11	0.02	2.02	2.16	2.21
b. Station 6 (16°40'S, 172°10'W)					
1,000	0.13	0.01	2.02	2.15	2.21
2,000	0.15	0.02	2.02	2.16	2.20
3,000	0.15	0.03	2.03	2.16	2.20
4,000	0.11	0.02	2.02	2.15	2.20
5,000	0.11	0.02	2.01	2.15	2.21
c. Station 10 (17°58'S, 172°01'W)					
1,000	0.14	-0.02	2.01	2.15	2.20
2,000	0.16	0.02	2.02	2.15	2.20
3,000	0.16	0.02	2.03	2.16	2.21
4,000	0.12	0.01	2.03	2.16	2.21
5,000	0.11	0.01	2.02	2.16	2.21
d. Station 11 (20°32'S, 172°47.5'W)					
1,000	0.12	-0.01	2.01	2.15	2.20
2,000	0.16	0.02	2.01	2.15	2.20
3,000	0.15	0.02	2.02	2.16	2.21
4,000	0.11	0.01	2.02	2.15	2.20
5,000	0.12	0.0	2.02	2.15	2.21

vertical profiles of T , F , B , C , CA , ΔO and the calcium content from the surface to the bottom at Stns. 2, 6, 10 and 11.

In Tables 1a to 1d, the calculated values by using Eqs. 20, 23 and 26 of ΔO , ΔD , B_0 , T_0 and CA_0 in the second layer at the same stations as above are given.

In the upper part of Figs. 2a to 2d are shown the vertical profiles in the second layer of T_2 , B_2 etc. In the lower part, the calculated values of T_0 , B_0 and CA_0 are shown. It is of interest that the values of T_0 , B_0 and CA_0 are the same at the four station, *i. e.*, T_0 is 2.15 mM/kg, B_0 is 2.02 mM/kg and CA_0 is 2.20 meq/kg. By using these values F_0 and C_0 are obtained to be 0.04 mM/kg and 0.09 mM/kg.

In Tables 2a to 2d the calculated values of ΔO_1 , $\Delta D_1'$ and Δb_1 in the first layer are

Table 2. Vertical distribution of ΔO_1 , $\Delta D_1'$ and Δb_1 in the first layer.

Depth m	ΔO_1 mM/kg	$\Delta D_1'$ mM/kg	Δb_1 mM/kg
a. Station 2 (15°22'S, 172°05'W)			
0	0.0	-0.09	0.16
100	0.01	-0.09	0.16
200	0.02	-0.07	0.12
300	0.05	-0.06	0.09
500	0.08	-0.05	0.02
750	0.13	-0.03	0.0
1000	0.14	0.0	0.0
b. Station 6 (16°40'S, 172°10'W)			
0	0.0	-0.08	0.15
100	0.01	-0.08	0.12
200	0.04	-0.08	0.10
300	0.05	-0.08	0.08
500	0.08	-0.07	0.02
750	0.11	-0.02	0.0
1000	0.13	0.01	0.0
c. Station 10 (17°58'S, 172°01'W)			
0	0.0	-0.07	0.16
100	0.01	-0.07	0.16
200	0.04	-0.07	0.15
300	0.05	-0.07	0.09
500	0.06	-0.05	0.02
750	0.10	-0.03	0.0
1000	0.14	-0.02	0.0
d. Station 11 (20°32'S, 172°47.5'W)			
0	0.0	-0.08	0.15
100	0.02	-0.08	0.13
200	0.03	-0.07	0.11
300	0.05	-0.06	0.08
500	0.07	-0.05	0.02
750	0.10	-0.03	0.0
1000	0.12	-0.01	0.0

given at Stns. 2, 6, 10 and 11. In Tables 3a to 3d the observed and the calculated values are compared with respect to B , T and CA at the same stations. As described above it is assumed here that T_0 etc., are the same in both the first and second layer at the same station.

In the upper part of Figs. 3a to 3d the vertical profiles of B_1 , T_1 , CA_1 etc., in the first layer at Stns. 2, 6, 10 and 11 are shown. In the lower part of Figs. 3a to 3d are given

Fig. 2. Vertical distribution of components of carbon dioxide system in the second layer. Unit; mM/kg. CA, m eq/kg
a. Station 2 b. Station 6 c. Station 10 d. Station 11

Fig. 3. Vertical distribution of components of carbon dioxide system in the first layer. Unit; mM/kg. CA, m eq/kg

a. Station 2 b. Station 6 c. Station 10 d. Station 11

Table 3. Vertical distribution of B, T and CA.

Depth m	B (mM/kg)		T (mM/kg)		CA (meq/kg)	
	Calc.	Obs.	Calc.	Obs.	Calc.	Obs.
a. Station 2 (15°22'S, 172°05'W)						
0	1.56	1.56	1.90	1.90	2.22	2.22
100	1.58	1.58	1.92	1.92	2.24	2.24
200	1.69	1.69	1.99	1.99	2.26	2.26
300	1.78	1.78	2.05	2.05	2.28	2.28
500	1.96	1.97	2.16	2.15	2.29	2.29
750	2.10	2.10	2.25	2.25	2.33	2.33
1,000	2.15	2.15	2.29	2.29	2.37	2.36
2,000	2.19	2.19	2.33	2.33	2.37	2.37
3,000	2.21	2.21	2.35	2.35	2.38	2.39
4,000	2.15	2.15	2.29	2.29	2.33	2.34
5,000	2.13	2.14	2.28	2.28	2.34	2.34
b. Station 6 (16°40'S, 172°10'W)						
0	1.59	1.59	1.92	1.92	2.22	2.22
100	1.65	1.65	1.96	1.96	2.25	2.25
200	1.73	1.73	2.01	2.01	2.27	2.27
300	1.79	1.80	2.04	2.05	2.26	2.26
500	1.96	1.96	2.14	2.14	2.29	2.29
750	2.09	2.09	2.24	2.24	2.32	2.32
1,000	2.16	2.15	2.29	2.29	2.34	2.35
2,000	2.19	2.19	2.32	2.33	2.37	2.37
3,000	2.20	2.20	2.33	2.34	2.38	2.38
4,000	2.15	2.14	2.28	2.28	2.33	2.34
5,000	2.15	2.14	2.28	2.28	2.33	2.34
c. Station 10 (17°58'S, 172°01'W)						
0	1.60	1.60	1.92	1.92	2.22	2.22
100	1.61	1.60	1.93	1.93	2.24	2.24
200	1.70	1.69	1.98	1.98	2.25	2.25
300	1.78	1.78	2.04	2.04	2.27	2.27
500	1.95	1.95	2.14	2.14	2.29	2.29
750	2.07	2.07	2.22	2.22	2.30	2.29
1,000	2.12	2.12	2.27	2.27	2.32	2.32
2,000	2.20	2.19	2.33	2.33	2.38	2.38
3,000	2.20	2.20	2.33	2.33	2.38	2.39
4,000	2.15	2.15	2.28	2.28	2.33	2.33
5,000	2.14	2.14	2.28	2.28	2.32	2.32
d. Station 11 (20°32'S, 172°47.5'W)						
0	1.61	1.62	1.92	1.92	2.21	2.22
100	1.66	1.66	1.96	1.97	2.24	2.24
200	1.73	1.72	2.01	2.01	2.26	2.26
300	1.79	1.79	2.05	2.05	2.28	2.28
500	1.97	1.97	2.15	2.15	2.29	2.29
750	2.08	2.09	2.22	2.22	2.30	2.31
1,000	2.13	2.13	2.26	2.26	2.31	2.31
2,000	2.19	2.19	2.32	2.32	2.37	2.37
3,000	2.19	2.19	2.32	2.33	2.37	2.37
4,000	2.14	2.14	2.27	2.27	2.32	2.32
5,000	2.14	2.15	2.27	2.28	2.32	2.33

Table 4. The ratio of $\delta[\text{Ca}]$ and $\delta[\text{CA}]$.

Depth m	Ratio	
	Calc.	Obs.
a. Station 2 (15°22'S, 172°05'W)		
300	0.3	0.5
500	0.7	0.6
750	0.7	0.6
1,000	0.7	0.6
2,000	0.7	0.7
3,000	0.7	0.8
4,000	0.9	1.0
5,000	0.9	0.9
b. Station 6 (16°40'S, 172°10'W)		
300	0.4	0.1
500	0.3	0.2
750	0.7	0.6
1,000	0.8	0.7
2,000	0.7	0.7
3,000	0.8	0.7
4,000	0.9	0.9
5,000	0.9	0.9
c. Station 10 (17°58'S, 172°01'W)		
300	0.1	0.1
500	0.3	0.3
750	0.6	0.6
1,000	0.5	0.6
2,000	0.6	0.6
3,000	0.6	0.5
4,000	0.8	0.7
5,000	0.8	0.8
d. Station 11 (20°32'S, 172°47.5'W)		
300	0.4	0.3
500	0.3	0.4
750	0.6	0.6
1,000	0.7	0.7
2,000	0.6	0.6
3,000	0.6	0.6
4,000	0.8	0.9
5,000	0.7	0.7

the schematical representations of Eqs. 19, 22 and 25 which are used for calculation of B_1 , T_1 and CA_1 . In these figures the calculated values of B_1 , T_1 and CA_1 are represented by thick lines and the observed values by solid circles. Tables 3a to 3d and Figs. 3a to 3d show a good agreement between calculation and observation of B_1 , T_1 and CA_1 .

In Table 4 are shown the observed and calculated values of the ratio of change with depth in the calcium content $\delta[\text{Ca}]$ in mole and that in the carbonate alkalinity δCA in equivalent at Stns. 2, 6, 10 and 11. Calculated values are obtained by Eq. 28. As seen in Table 4, there is a good agreement between the observed and calculated values of $\delta[\text{Ca}]/\delta\text{CA}$ showing that the ratio is not a constant value of 0.5, but varies widely ranging from 0.1 to 1.0.

These agreements suggest that the above consideration by the present authors on the carbon dioxide system in the ocean is right and appropriate. However, since the above discussions are mainly based on observations carried out in the tropical areas in the western part of the South Pacific, further studies in other areas in the world oceans are necessary.

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海洋における二酸化炭素系について

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海洋中の二酸化炭素系は、イオンの解離平衡の法則によれば、重炭酸イオンが最も多く存在し、全炭酸の90%以上をしめる。重炭酸の含量は高いのみならず、特に深海においては、94%の一定値をしめす。この理由から、少量の炭酸イオン、または遊離炭酸が加えられた時には、これらの大部分は直ちに、重炭酸イオンに転換する。

次に、全炭酸量(T)、重炭酸イオン含量(B)および炭酸アルカリ度(CA)を説明するために、理論式をみちびいた。それは有機炭素の生産と分解、および固体炭酸カルシウムの溶解と生成を考慮に入れたものである。また海水中のカルシウム含量と炭酸アルカリ度の変化率の関係につき、理論的に考察した結果、両者の間には簡単な関係がないことを結論した。スクリップス海洋研究所がおこった Antipode 15 Expedition の間に得られた生化学的過程に関する測定値を用いて、上記のT, B, CAを定量的に求めた。計算の結果は、測定値と非常に一致をしめした。