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The Geochemical Balance of Nutrient Matters in the Oceans*

by

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Abstract

The geochemical balance and cycles of P, Si and N in the oceans are discussed taking the following items into consideration: concentration in sea water of each nutrient matter in oxidative, preformed and organic form, input from rivers, biological production and decomposition, deposition to the sea bottom and transfer between the surface and deep layers.

Results show that the remarkable difference in concentrations in nutrient matters between the Pacific-Indian and the Atlantic Ocean is mainly due to difference in the residence time of waters in deep layer in each ocean.

The residence time of deep water which is estimated on the basis of the geochemical cycles of nutrient matters is 160～270 y and 90～130 y respectively for the Pacific-Indian and the Atlantic.

To compare the biological activities on nutrient matter, a new concept, Biological Activity Index, β is introduced.

$$\beta=\frac{\text{Biological decomposition}}{\text{Input}}\div\frac{\text{Content in the euphotic zone}}{\text{Biological up-take}}$$

In the oceanic environments, β is estimated to be 0.015 for C, 60 for Si, 180 for P and the highest value of about 330 for N.

1. The cycle of nutrient matter in the oceans

The distribution of nutrient matters in the oceans is complicated both in the horizontal and vertical directions. Generally, the concentration of nutrients in sea water is higher at the higher latitudes, as well as in the deep layer. It is also known that, nutrient concentration is much higher in the Indo-Pacific Ocean than in the Atlantic.

Table 1 shows the phosphorus content in the Indo-Pacific and the Atlantic Ocean, The average concentration of the inorganic phosphorus is 2.5 μg atom/l in the Indo-Pacific while in the Atlantic it is only 1.7 μg atom/l. It is to be noticed that the concentration of preformed phosphorus is the same in both oceans (1.2 μg atom/l).

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Table 1. Phosphorus content in Indo-Pacific and Atlantic Oceans (μg atom/1)

	Indo-Pacific	Atlantic
Inorganic	2.5 (surface 0.5)	1.7 (surface 0.3)
Oxidative	1.3	0.5
Preformed	1.2	1.2
Organic	0.5	0.3
Total	3.0	2.0

Table 2. Silicon content in Indo-Pacific and Atlantic Oceans (μg atom/1)

	Indo-Pacific	Atlantic
Inorganic	110 (surface 10)	35 (surface 3)
Oxidative	40	15
Preformed	70	20

Table 2 shows the concentration of silicon in the Indo-Pacific and Atlantic Oceans. The difference in Si concentration is remarkable between the Indo-Pacific and the Atlantic. In the Indo-Pacific, it is 110 μg atom/l on an average, while it is only 35 μg atom/l in the Atlantic. The content of preformed silicon is also much different between the two oceans.

To explain the difference in concentration of nutrients in different oceans, the cycle of nutrient matters is considered.

Table 3. Cycle of phosphorus and silicon in the sea (μg atom/cm^2, y)

	Indo-Pacific		Atlantic	
	P	Si	P	Si
Primary production	6	180	6	180
Deposition	0.03	4	0.15	20
River	0.03	4	0.15	20

Table 3 shows the cycles of nutrients in the oceans. Primary production represents the rate of change of inorganic nutrients into organic form. It is assumed that the mean rate of organic production is 8 mg C/cm^2, y in both oceans. Corresponding values for phosphorus and silicon are respectively 6 μg atom and 180 μg atom/cm^2, y.

The deposition rates of phosphorus and silicon are calculated by using the average contents in marine sediments, and assumed deposition rates of bottom sediments of 2 mm/10^3 y and 10 mm/10^3 y respectively in the Indo-Pacific and the Atlantic. The rate of discharge from river waters is estimated by average contents of the elements

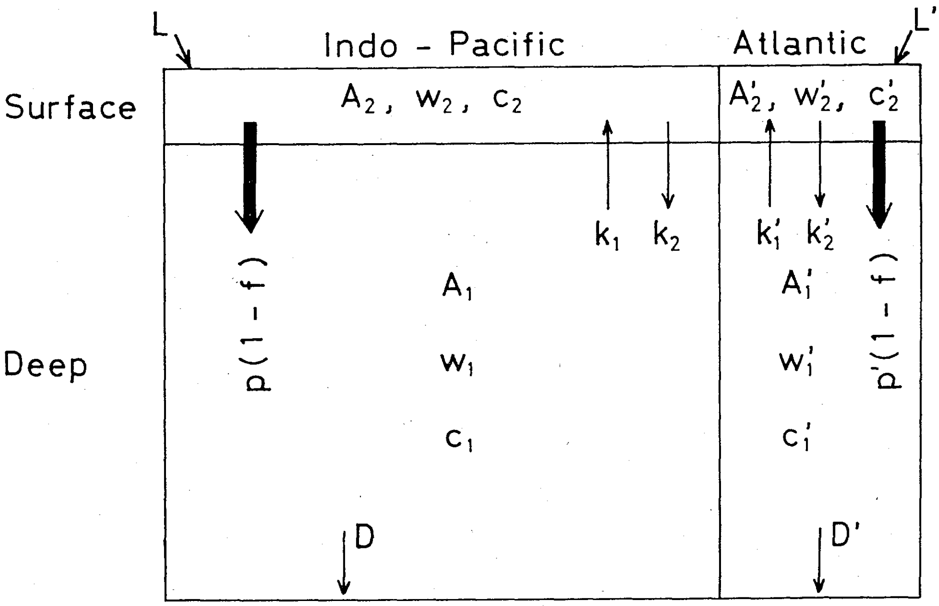

Fig. 1. Cycle of nutrients in the oceans.

in river waters and the mean rate of discharge of river water of 8 ml/cm^2, y in the oceans. It is also assumed that the relative amount of discharge of river waters is larger in the Atlantic than in the Indo-Pacific. As shown in Table 3, for both elements, deposition and discharge from rivers compensate for each other and the biological effect is exceedingly higher than others effects.

Fig. 1 shows a simple scheme of the cycle of nutrients in the oceans. The world ocean is simply divided into two, the Indo-Pacific and the Atlantic. In the vertical direction, only the surface and deep layers are considered. A is the content of a nutrient (μg atom/cm^2), w is the amount of water (g/cm^2), and c is the concentration of nutrient (μg atom/l). L is the rate of discharge of nutrients from the land (μg atom/cm^2, y). D is the rate of deposition of nutrients to sea-floor (μg atom/cm^2, y), p is the primary production rate of nutrient (μg atom/cm^2, y) and f is the regeneration factor of nutrients in the euphotic zone. $p(1-f)$ means the rate of transfer of organic nutrients from surface to deep layer which return to inorganic form in the latter. k is the rate of transfer of water between the two layers (g/cm^2, y). The numerical figures 1 and 2 denote respectively the surface and the deep layer and a prime indicates the Atlantic Ocean.

In this simple model, only the transfer of nutrients in the vertical direction is considered for first approximation, because the lateral transfer of water between the Indo-Pacific and the Atlantic takes place through the Antarctic Ocean in which there is little gradient in nutrient concentration in the latitudinal direction.

At the steady state, the amount of a nutrient A_1 is expressed as follows:

$$A_1=\frac{k_2A_2+p(1-f)-D}{k_1} \tag{1}$$

f is the regeneration factor which is assumed to be 0.2 to 0.3. In addition, there are relations between A_1, w_1 and c_1 or A_2, w_2 and c_2 as given in equations (2) and (3). There is also an equation for the conservation of water in the vertical transfer (Eq. 4).

$$k_1A_1=k_1w_1c_1 \tag{2}$$

$$k_2A_2=k_2w_2c_2 \tag{3}$$

$$k_1w_1=k_2w_2 \tag{4}$$

From the above equations, equation (5) can be deduced:

$$c_1-c_2=\frac{(1-f)p-D}{k_2w_2} \tag{5}$$

Here, c_1-c_2 represents the difference in concentration of a nutrient between the deep layer and the surface layer. Similar equations to the above hold for the Atlantic.

By putting the observed or assumed values in the equations, k_1 and k_2 can be calculated. The reciprocals of k_1 and k_2 are τ_1 and τ_2 which are the residence time of water respectively in the deep and the surface layer in the Indo-Pacific Ocean. In the same way, τ_1' and τ_2' in the Atlantic can be calculated.

The results are given in Table 4. The estimated residence time of water in the surface layer in the Indo-Pacific Ocean is 4 to 5 years by using the phosphorus and 6—7 years by the silicon cycle. The corresponding values in the Atlantic are a little smaller than those in the Indo-Pacific which are respectively 3 years and 2.5 years.

The residence time in the deep layer in the Indo-Pacific is 160～250 years from the phosphorus cycle and 230 to 270 years from the silicon cycle. The residence time in the Atlantic is 90～130 years.

Table 4. Residence time of water in surface and deep layers in the oceans (years)

	Surface	Deep
Indo-Pacific	4−5 (P) 6−7 (Si)	160−200 (P) 230−270 (Si)
Atlantic	3−3.3 (P) 2.3−2.6 (Si)	120−130 (P) 90−100 (Si)

It is of interest to note that, from the above equations, the following approximate equation can be deduced:

$$c_1/c_1'=\tau_1/\tau_1' \tag{6}$$

The concentration of nutrient in the oceans is controlled mainly by two factors, organic production rate and vertical exchange rate of water. Since the mean organic production rate is nearly the same in both oceans, the concentration depends on the exchange rate of water between the surface and the deep layer or its reciprocal, the residence time. As a result, the ratio of concentration of nutrient in deep layers in the two oceans is approximately equal to the ratio of residence time.

2. Biogeochemical balance of inorganic nutrients in the ocean

The biogeochemical balance of inorganic nutrients in the ocean can be expressed generally as follows:

$$L+B+E=D+P+S, \tag{7}$$

where L is the rate of supply from the land through rivers, B is the rate of supply through the decomposition of organic matter, E is the rate of entry from the air. On the right side of the equation, D is the deposition rate, assuming 5 mm/10^3 y of sedimentation rate. P is the organic production rate and S is the escape rate to the air. Among them, B and P should be equal when the oceans as a whole are in a steady state with respect to living matters.

The estimated values of the above terms in equation (7) and the contents (a) of various nutrients in the euphotic zone are given in Table 5.

Table 5. Cycle of nutrients in the world oceans (μg atom/cm^2, y)

Element	River L	From air E	To air S	Primary production or biological decay P or B	Deposition D	Surface content (100 m) μg atom/cm^2 a
C	20	1, 500	1, 500	670	2	20, 000
Si	5	0	0	180	5	100
P	0. 04	0	0	6	0. 04	5
N	0. 3	0. 7 (rain)	1 (ammonia)	100	0. 04	30

In order to compare the effect of biological activity on the nutrient in the ocean, the following equation is proposed, in which β is called the biological activity index of a nutrient element.

$$\beta=\frac{\text{Biological decomposition}}{\text{Input}}\div\frac{\text{content in the euphotic zone}}{\text{Biological up-take}} \tag{8}$$

The meaning of β is as follows. The greater the ratio of biological decomposition rate to the input rate from land and atmosphere, the greater is the biological effect on the nutrient. On the other hand, the biological effect is greater when the ratio of content of the element in the euphotic zone to the biological up-take rate is smaller and *vice versa.* The combination of the above two makes the biological activity index β.

The results of calculation of β for the oceans as a whole are shown in Table 6. As shown in the table the nutrient with the highest value of β is nitrogen and the second is phosphorus.

Table 6. Biological activity index of nutrients.

Element	β
C	0.015
N	330
Si	60
P	180

海洋中の栄養塩の地球化学的収支

三宅泰雄・猿橋勝子

海洋中のリン，ケイ素および窒素の地球化学的収支とサイクルを次のことがらを考慮して論ずる。すなわち，それぞれの栄養物質の酸化性，保存性および有機性のものの濃度，河川からの流入量，生物学的生産と分解，海底への沈積および表層と深層水の相互移行を考慮する。その結果は，太平洋・インド洋と大西洋の栄養物質濃度の大きい差異は，それぞれの層の水の滞留時間の差によることがしめされる。

栄養物質の地球化学的サイクルにもとづいて算定される深層水の滞留時間は，太平洋・インド洋では 160 年から 270 年，大西洋では 90 年から 130 年となる。

栄養物質に対する生物活動の度合を比較するために生物活動度インデックス (β) という新らしい概念を導入した。

$$\beta=\frac{\text{生物の分解量}}{\text{流入量}}\div\frac{\text{表層の栄養塩含量}}{\text{生物による摂取量}}$$

海洋においては，生物活動度インデックス (β) は，炭素について 0.015，ケイ素について 60，リンについて 180，窒素では最高値の 330 となる。