

Relationship Between Dissolved Oxygen & Nutrients in the North-Western Indian Ocean

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Received 3 April 1976; revised received 13 August 1976

Oceanographic data obtained during the Indo-Soviet Monsoon Experiments (ISMEX) of 1973 and during the METEOR cruises of International Indian Ocean Expedition (IIOE) were used for calculating oxidative, reserved and organic fractions of nutrients in the North-western Indian Ocean. Distribution of σ_t values and the relationship between silicon and density were used for classifying water masses. Ratios were determined by atoms between apparent oxygen utilization (AOU), carbon, silicon, nitrogen and phosphorus. Consolidated ratio for AAOU: AC: ΔSi : AN: AP was found to be 280: 108: 40: 16: 1. On the basis of these calculations, a possible relationship indicating the chemical composition of planktonic algae has been suggested. Denitrification in this part of the Indian Ocean seems to take place at an intermediate layer extending from 24°N to 5°N.

ALTHOUGH a large volume of data on the distribution of nutrients in the Indian Ocean has been collected during the International Indian Ocean Expedition (1962-65), no assessment of nutrient fractions (oxidative, reserved and organic) has been made in any of the earlier studies. Such a study is important in understanding biochemical processes occurring in the oceans. In this communication, the chemical oceanographic data collected during the Indo-Soviet Monsoon Experiments (ISMEX) of 1973 and METEOR cruises of the IIOE (1965) have been utilized to identify the chemical characteristics of different water masses and to study the nutrient fractions in relation to oxidation of organic matter in the north-western Indian Ocean.

Materials and Methods

Physical and chemical parameters analysed were temperature, salinity, dissolved oxygen, inorganic phosphate, total phosphorus, nitrate-nitrogen, nitrite-nitrogen, ammonia-nitrogen, silicate-silicon, pH and total alkalinity. Sampling and analytical methods used have been given in the data-sheets of ISMEX and METEOR expedition reports¹.

Results and Discussion

General Hydrographic Features of the Area

Position of the stations covered during the 2 expeditions are shown in Fig. 1. Analysis of the data has been restricted to depths between 150 m and the depth of maximum apparent oxygen utilization (AOU). Seasonal variations caused by the monsoons rarely affect the water masses below 150-200 m, and at depths greater than about 1000 m, the variations are negligible. To test this hypothesis, longitudinal variations in temperature along 0°, 11° and 16°N lat. to a depth of 500 m observed during the ISMEX cruises have been plotted in Figs. 2-4. It can be seen from the

figures that the vertical movements of water masses below 150 m are not very pronounced. Observations made during SW monsoon, represented by the isotherms along 11° and 16°N latitudes (converging near the surface on the western sides of the sections), clearly indicate upwelling (Figs. 3 and 4). There is, however, a weak upsloping of the isotherms towards the eastern side of the section along 16°N.

According to Rochford², the water masses in the NW Indian Ocean consist of the following types: (i) Arabian Sea surface water originating in its NE part because in this region evaporation is greater than precipitation and runoff. (ii) Water

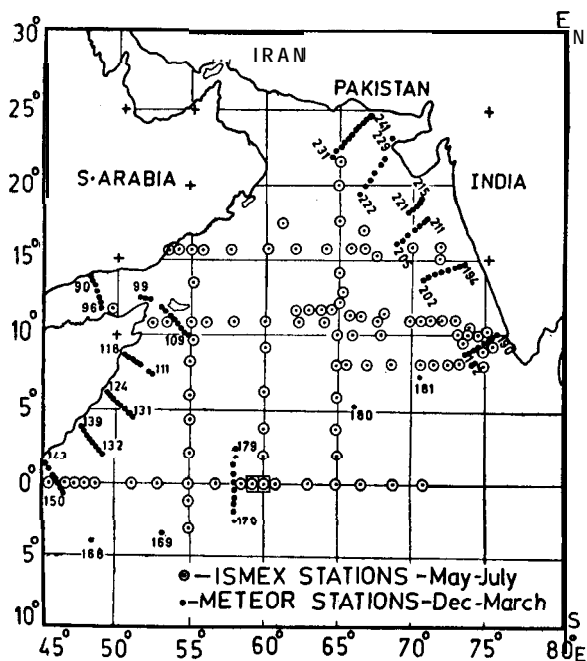
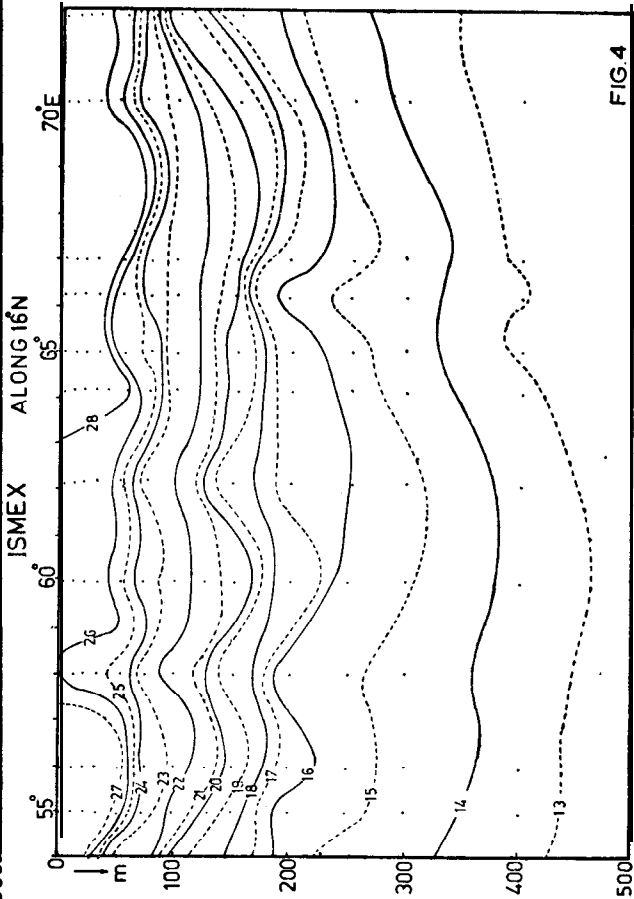
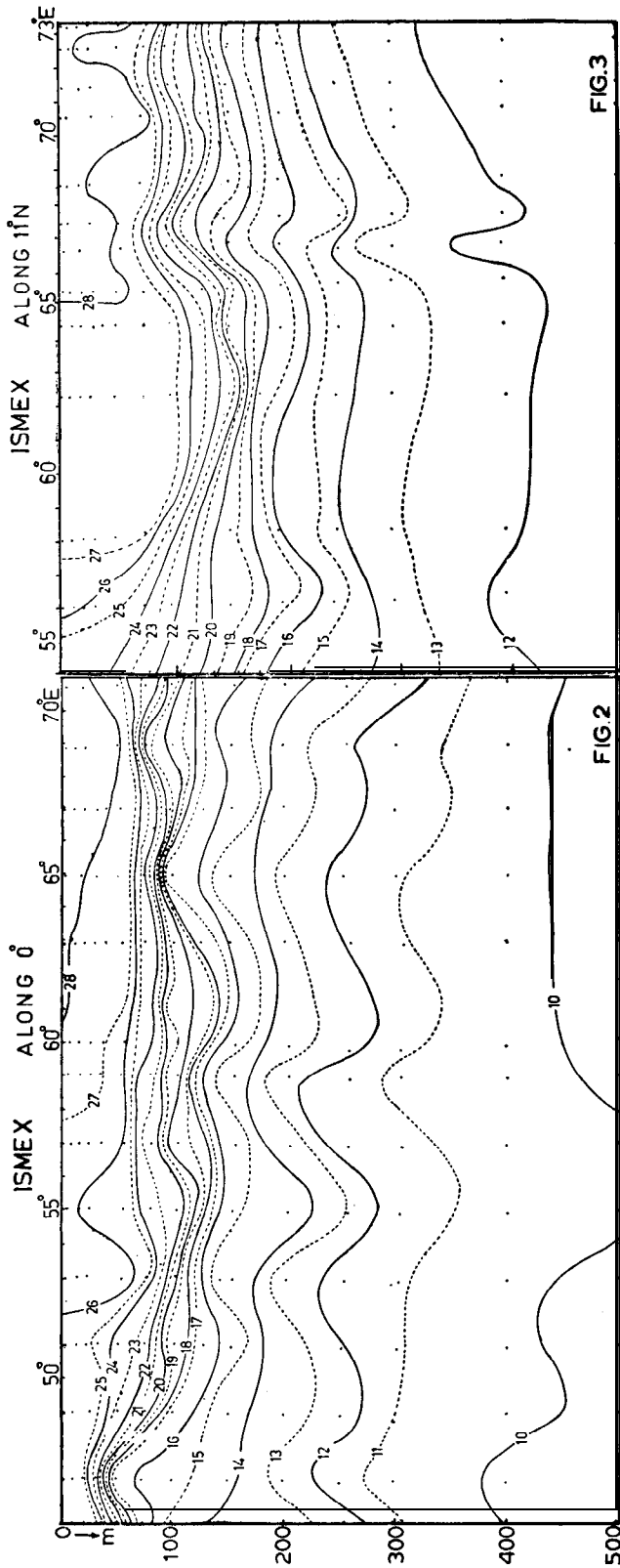


Fig. 1 — Area covered in the North-western Indian Ocean [Positions of stations during ISMEX and METEOR cruises have been shown by open circles and dots respectively]



Figs. 2 to 4 — Isotherms at stations along: 2 — the equator; 3 — 11°N latitude; and 4 — 16°N latitude (from ISMEX data)

having its origin in the surface layers of the Persian Gulf and flowing over the 50 m deep sill at the Hormuz Strait and reaching the Arabian Sea between depths of 100 and 300 m. This water can be identified at a depth of about 500 m in the equatorial region of the Indian Ocean. (iii) Water originating in the Red Sea and flowing over the 125 m deep sill at the Strait of Bab-el-Mandeb. This can be traced from its density between 400 and 900 m depths in the Arabian Sea and at a depth of 1000 m in the equatorial Indian Ocean. Wooster *et al.*³ characterized these 3 water masses by σ_t values of 25, 26.5 and 27.1 respectively. They further indicated that the water masses found below 1000 m in the northern Indian Ocean originate in the Antarctic circumpolar region and enter the North Indian Ocean from SW. These water masses penetrate north and reach both central and eastern basins, and have been identified in the present study by plotting the isopycnals along two meridional sections—one along 65°E long. from the equator up to 22°N lat. from ISMEX (Fig. 5) and the other along 58°E long., from 3°S to 2°N lat. from METEOR (Fig. 6). It can be seen from Figs. 5 and 6 that gradients and depth levels of the isopycnals 25, 26.5 and 27.1 are very similar. Further, using the terminology of Ivanenkov and Gubin⁴, the water masses between 1000 and 3000 m depth (Figs. 5 and 6) and having σ_t 27.6 could be termed as the North Indian Ocean Deep Water and those below 3000 m with σ_t 27.8 as the North Indian Ocean Bottom Water. These 2 water masses are formed as a result of mixing of the deep Antarctic and the bottom circumpolar water masses which are cold having low salinities. In addition to such a broad classification of water masses, several other types of water are formed due to the mixing of these water masses, but it was felt that a further classification would be beyond the scope of the present study.

In the Indian Ocean, because of high temperature in the surface layers, the concentration of oxygen is generally low. The water mass between 100 and 500 m, with its low concentration of oxygen of about 0.25 ml/litre, has been identified by Wooster *et al.*³. A layer of minimum oxygen concentration (~1.5 ml/litre) was observed at a depth of 1000-1500 m in the equatorial Indian Ocean. This water extends towards north and its oxygen concentration gradually gets depleted further to about 0.5 ml/litre and below (Fig. 7). Thus the Arabian Sea portion of the Indian Ocean has two oxygen minima; one between 100 and 500 m depth and the other between 1000 and 1500 m depth. This feature, however, seems to be absent south of the latitude 18°N⁵.

Photosynthetic productivity in the Arabian Sea is higher than that of the average of all other oceans⁶⁻⁸. This may often lead to a greater concentration of dead cells and detritus at the thermal discontinuity layer, which will consume oxygen during decomposition. Probably the first oxygen minimum in the shallow region of the Arabian Sea may be because of the oxidation of organic matter.

Taking into account the hydrographical features noted above, it is possible to divide the water

masses of the NW Indian Ocean for studying its chemical characteristics into the following 5 zones:

- (i) 0-60 m zone, which includes the uppermost mixed layer. This zone is subjected to intense seasonal variation and could be termed as the Arabian Sea Zone or the North Equatorial Surface Water Zone. It is marked by a maximum σ_t of 24.
- (ii) 60-500 m zone, having a mixture of waters from the Arabian Sea and the Persian Gulf with a maximum σ_t of 26.5.
- (iii) 500-1000 m zone with a water mass from the Red Sea having a maximum σ_t value of 27.1.
- (iv) 1000-3000 m zone, or the North Indian Ocean Deep Water mass probably originating in the deep waters of the Antarctic (circumpolar) marked by σ_t values lower than 27.8.
- (v) greater than 3000 m zone or the North Indian Ocean Bottom Water having its source in the Antarctic bottom water with σ_t value of 27.8 and above.

Nutrient-density relationships—Distinction between the water masses can also be made from the nutrient-density relationships. Stefánsson and Atkinson^{9,10} have found this relationship useful in studying the water masses, particularly when the temperature-salinity relationships of different water masses are almost similar to allow a clear distinction. Relation between silicate-silicon and σ_t using the data of both the cruises is shown in Fig. 8. Water from 0 to 200 m has σ_t between 22 and 26 with silicate concentration ranging from 0 to about 25 $\mu\text{g-at/litre}$. This largely includes the surface water of the Arabian Sea. Water from 201 to 500 m has σ_t between 26 and 27 and silicate concentration between 25 and 50 $\mu\text{g-at/litre}$. The cluster of points at lower silicate values probably indicates the Persian Gulf water. Similarly, the water between 501 and 1000 m having σ_t 27 and 27.3 and silicate concentration ranging from 50 to 70 $\mu\text{g-at/litre}$ is possibly the Red Sea water. Finally, the water below 1000 m with σ_t between 27.3 and 27.8 and with steeply increasing silicate concentration is probably the Antarctic circumpolar water which has been termed² as the North Indian Ocean Deep and Bottom Waters. Overlapping of values indicates mixing of water of different characteristics.

Nutrient Regeneration and Oxygen Utilization

Nutrients [expressions phosphate, silicate, nitrate, nitrite and ammonia in this paper stand for phosphate-phosphorus, silicate-silicon, nitrate-nitrogen, nitrite-nitrogen and ammonia-nitrogen respectively] in the subsurface layers normally include those which have been regenerated within the water column ('oxidative') and those which, due to vertical fluxes, have been transported upwards ('preformed')¹¹. Sugiyura¹² introduced the concept 'reserved', which he defined as that fraction of a nutrient obtained after subtracting the oxidative fraction from its total inorganic concentration.

Redfield *et al.*¹³ developed the relationship in atoms between carbon, nitrogen and phosphorus in the sea water as 106:16:1. Similarly, the relationship between oxygen utilization and carbon dioxide production was deduced by these authors as 276:106

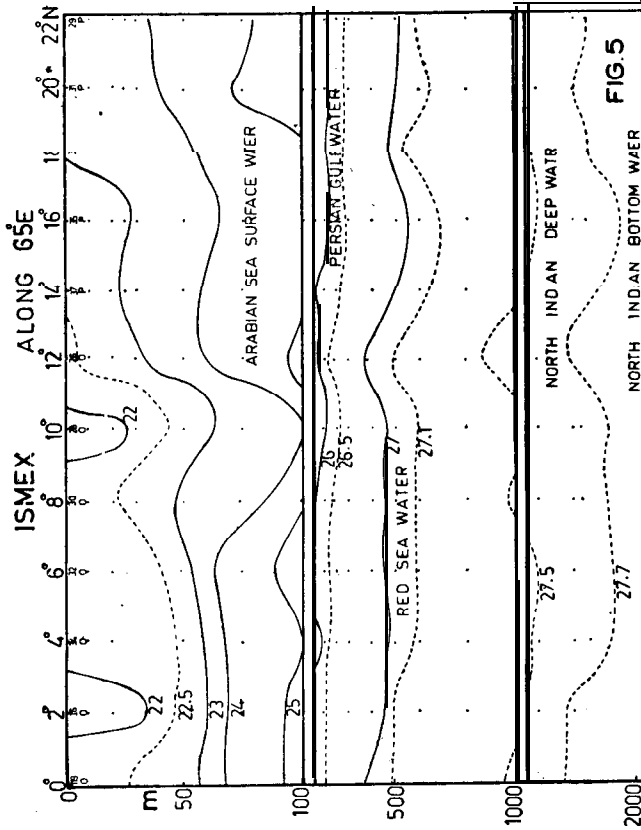


FIG.5

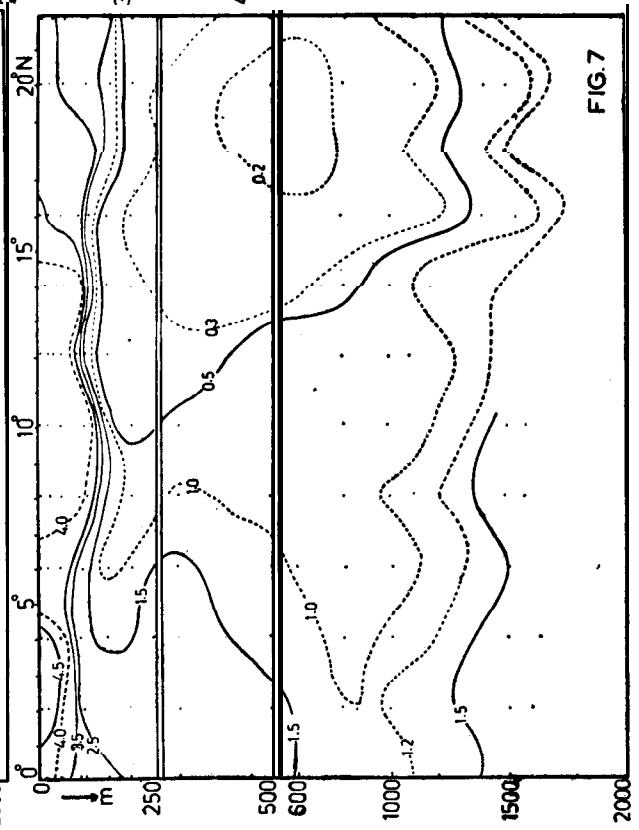


FIG.6

Fig. 5 — Isopycnals along 65°E longitude between the equator and 22°N latitude (from ISMEX data)

Fig. 6 — Isopycnals along 58°E longitude across the equator between 3°S and 2°N latitudes (from METEOR data)

Fig. 7 — Horizontal distribution of oxygen along 65°E longitude between the equator and 22°N latitudes (from ISMEX data)

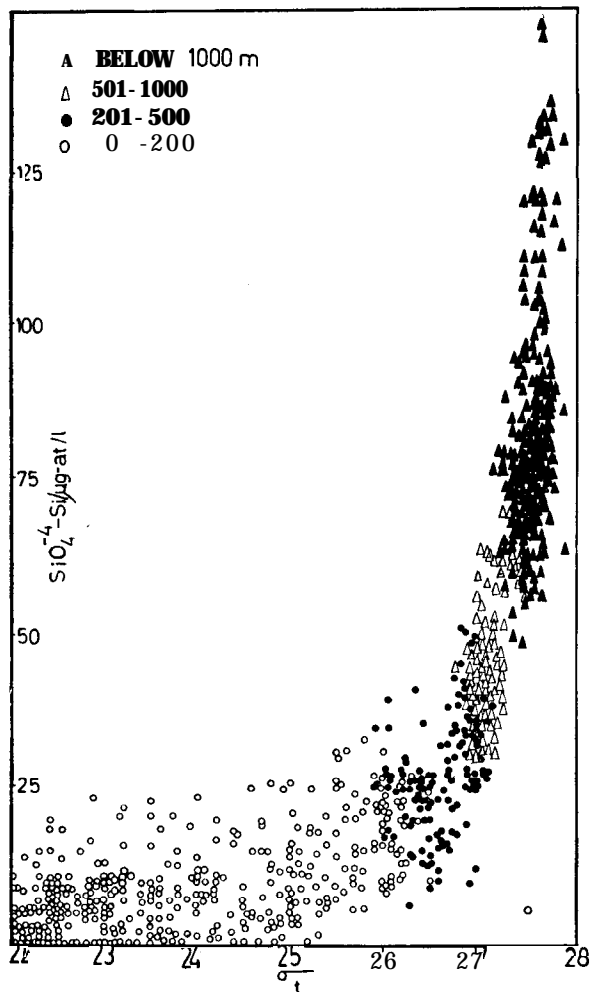


Fig. 8 — Silicate- σ_t relationships for different water masses in the North-western Indian Ocean

by atoms. This relationship was obtained from the composition of these elements in plankton, in sea water and from theoretical considerations. Stefáns-son¹⁴ obtained the atomic ratios of 276:14:3:16:1 between oxygen utilization, nitrogen, silicate and phosphorus for the waters of the Northern Irminger Sea. These ratios were found to be 270:16:16:1 in the western North Atlantic and Caribbean waters¹⁵. The ratios were calculated from the slopes of the regression lines between various nutrients and AOU, the latter being equal to $O_2' - O_2$, where O_2' is the concentration of dissolved oxygen in water with salinity and temperature in equilibrium with water-saturated atmosphere, and 0, is the observed concentration of oxygen. These ratios were similar to those occurring in plankton. From the relationships of this kind, Redfield¹¹ concluded that the changes occurring in the concentrations of carbon, nitrogen and phosphorus in water would be similar to ratios of these elements in plankton. In the present studies, depth of the maximum AOU has been assumed to be that at which the regenerative process is minimal. AOU values have been computed from the nomogram of Green and Carritt¹⁶.

Phosphate and oxygen utilization — Relationship between oxygen utilization and phosphate regeneration between 150 m and AOU maxima in the north-western Indian Ocean, based on ISMEX data, has been determined. The slope of the regression line gives the relation AAOU: AP as 280:1 by atoms with a correlation coefficient (r) as 0.8. To test the constancy and validity of this ratio, 'reserved phosphate' (P_r) values at all ISMEX stations along 0° and 16°N lat. and at a few deep METEOR stations, using the relation $PO_4^{3-}P-AOU/280$, were calculated. Fig. 9 shows the P_r values plotted against salinity. As is expected, P_r values increase with depth while the salinity variation is insignificant. The vertical nature of the distribution of points indicates that the $\Delta AOU: \Delta P$ ratio does not vary regionally and can be expected to be valid over the entire area of observation. We, therefore, treated together the data between 150 m and the maximum observed depth for the calculations of AOU and the oxidative ratios at all stations.

Nitrate and oxygen utilization — In the absence of any nitrate data from ISMEX, the relationship between nitrate and AOU between 150 m and AOU maxima in north-western Indian Ocean is based on METEOR data only. It has been observed⁵ that at an intermediate layer in the northern Arabian Sea, the process of denitrification causes nitrate values to decrease and this is associated with relatively higher values of AOU, such values have not been included in the calculation of the ratio. The slope of the regression line gave the relation between AAOU:AN as 17:1 by atoms, with r of 0.8.

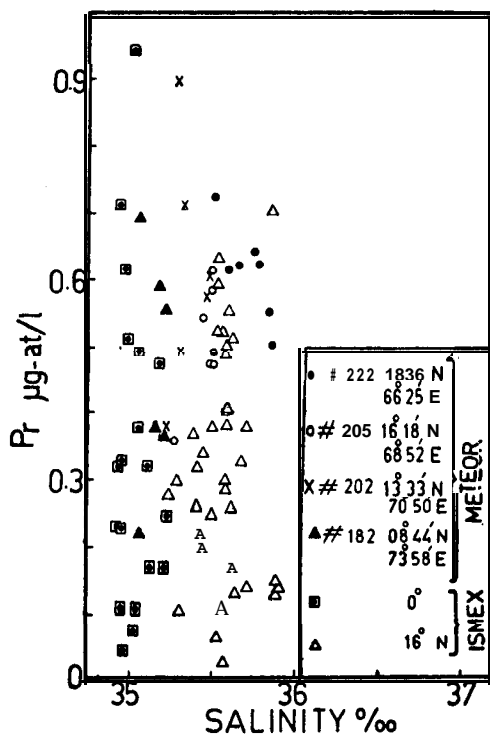


Fig. 9 — Relation between salinity and reserved phosphorus (P_r) between 150 m and depth of AOU maxima at selected stations and depths (from ISMEX data)

Nitrate-phosphate relationship — Relationship between nitrate and phosphate from 150 m to depths of AOU maxima in the north-western Indian Ocean has been determined using METEOR data. The slope of the regression line gives the ratio between AN: AP as 16:1 by atoms, with r of 0.73. The intercept on the phosphate axis at 0.41 $\mu\text{g-at/litre}$ shows that some phosphate is left in the water when the nitrate concentration approaches zero. This phosphate concentration includes both oxidative and reserved fractions. The intercept on the phosphate axis, during the calculation of phosphate-oxygen utilization relationship, at 0.12 $\mu\text{g-at/litre}$ indicates the reserved fraction of phosphate as it corresponds with the zero value of AOU. The balance of 0.29 $\mu\text{g-at/litre}$ of phosphate is left in the surface water when nitrate concentration approaches zero. This would also mean that nitrate would act as a limiting factor for the production of phytoplankton.

Silicate-oxygen utilization — Following method has been used to study the relationship between silicate and AOU in the Indian Ocean (ISMEX data). Silicate values were pooled first into each 5 $\mu\text{g-at/litre}$ intervals up to a concentration of 10 $\mu\text{g-at/litre}$ and then into each 10 $\mu\text{g-at/litre}$ intervals. The corresponding values of AOU up to 150 $\mu\text{g-at/litre}$ silicate concentrations were also pooled accordingly. These points, plotted in Fig. 10, show a non-linear relationship for the entire range. A second order relationship between AOU and silicate was determined, taking AOU as a non-variant. The curve representing AOU as a function of silicate is concave in the direction of the AOU axis at low silicate concentrations and convex at high silicate concentrations. A relationship, therefore, corresponding to such a situation, would be

$$\text{AOU} = (\text{AOU})_0 + \frac{\text{Si}^2}{a_0 + a_1\text{Si} + a_2\text{Si}^2} \quad \dots(1)$$

Averaging all the AOU values at zero silicate and putting this as $(\text{AOU})_0$, we find the best fit to be

$$\text{AOU} = 32 + \frac{\text{Si}^2}{0.12065 + 0.01025\text{Si} + 0.00197\text{Si}^2} \quad \dots(2)$$

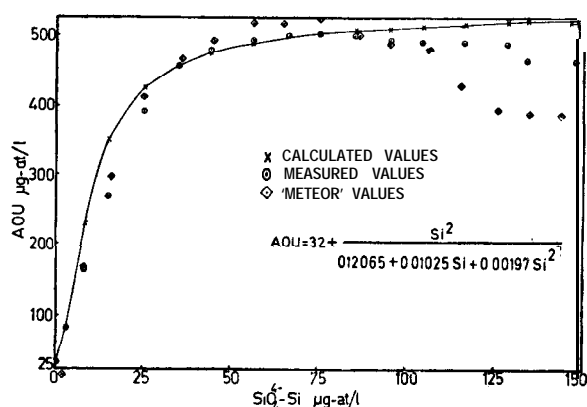


Fig. 10 — Silicate-apparent oxygen utilization relationship in the North-western Indian Ocean [Silicate values have been pooled into each 5 $\mu\text{g-at/litre}$ interval up to 10 $\mu\text{g-at/litre}$ and above that into each 10 $\mu\text{g-at/litre}$ interval along with the corresponding AOU values]

From Fig. 10 it can be seen that the AOU approaches an asymptotic value at silicate concentrations greater than 135 $\mu\text{g-at/litre}$.

If the curve is examined point by point, the differences between the measured and the calculated values of AOU appear to be significant up to 25 $\mu\text{g-at/litre}$ silicate. This range is found up to 200 m depth. The measured values were generally lower than the calculated values. Since the process of oxidation of organic matter starts just below the mixed layer, a considerable amount of nutrients is released during the oxidation process. However, since silicate in sea water can also originate from processes other than oxidation, low values of AOU in relation to silicate is either due to the utilization of oxygen during the oxidation of organic matter or because of a greater dissolution of diatom frustules to increase the silicate concentration. The measured AOU values deviate again at concentrations greater than 85 $\mu\text{g-at/litre}$ of silicate. These concentrations normally occur at depths ranging from 1000 to 1500 m where the oxygen progressively increases resulting in lower values of AOU. At levels greater than 135 $\mu\text{g-at/litre}$ of silicate, AOU approaches an asymptotic value for which both calculated and observed values agree. This indicates that the water masses having such silicate and oxygen concentrations originate from a similar source.

To test the applicability of Eq. (2), METEOR data were also processed in the same fashion. At lower concentrations of silicates, METEOR values agreed well with the ISMEX values. At higher levels, METEOR values also started deviating almost at the same point as ISMEX values and became asymptotic at a similar concentration of silicate. However, the deviation in the METEOR values was greater probably because the samples came from greater depths and the analytical methods used were different. During ISMEX cruises, the maximum depth from which samples came was 2500 m whereas METEOR sampled up to 5000 m. At the latter depth the oxygen concentration in the water was greater resulting in lower values of AOU. However, the possibility of the differences being actual cannot be ignored.

Silicate-phosphate relationship — A linear relationship between the two, at selected depths, has been reported earlier^{14,15}. However, as the concentrations of both silicate and phosphate increased with depth, $\Delta\text{Si} : \Delta\text{P}$ ratios did not remain constant. The departure from a linear relationship may be due to a number of factors : (a) seasonal and regional variations in the composition of plankton, (b) differences in the rates of regeneration of silicate and phosphate, and (c) dissolution of silica from the frustules of diatoms rejected by herbivores which takes place at a depth greater than where the regeneration of phosphate and nitrate largely occurs as a result of decomposition of organic matter¹³.

Higher silicate concentration may also be due to the transport of silicate-rich water from the Antarctic into deeper waters of the Indian Ocean. Another reason for the increase of $\Delta\text{Si} : \text{AP}$ ratio with depth may be that phosphate goes into the sediment whereas silicate largely remains in the column of water.

Relationship between silicate and phosphate values between 150 m and AOU maxima, based on ISMEX data, was worked out. The slope of the line gave a ratio for $\Delta\text{Si} : \text{AP}$ as 40:1 by atoms with r of 0.67.

Consolidated ratios- Thus the ratios by atoms from ISMEX and METEOR data would be:

ISMEX

$$\text{AAOU} : \text{AP} = 280:1 \quad \dots(3)$$

$$\Delta\text{Si} : \text{AP} = 40:1 \quad \dots(4)$$

Combining these two

$$\text{AAOU} : \Delta\text{Si} = 7:1 \quad \dots(5)$$

Although a linear relation between AOU and silicate does not exist for the entire range of concentration, the ratio indicated in Eq. (5) is the average of all the available values which have been used to approximate the reserved and oxidative fractions of silicate, irrespective of depth and area of observation.

METEOR

$$\text{AAOU} : \text{AN} = 17:1 \quad \dots(6)$$

$$\text{AN} : \text{AP} = 16:1 \quad \dots(7)$$

Combining these two

$$\text{AAOU} : \text{AP} = 272:1 \quad \dots(8)$$

Nutrient Fractions

Using consolidated ratios given above, different fractions of phosphorus, nitrogen and silicon were calculated and these are presented in Table 1.

ISMEX and METEOR data on nutrients were used for calculating different fractions (oxidative, reserved and organic) grouping on a latitudinal and meridional basis (Table 2).

It is evident from Table 2 that if all the nutrients were to be released as a result of oxidation of organic matter, then the oxygen concentration and oxygen saturation would have been far lower than the value given in the table. The oxidative fraction of silicate increased with depth up to 1500 m after which it tended to decrease (Fig. 11). The reserved fraction, on the other hand, increased progressively with depth (Fig. 11). The latitudinal differences were not very well marked in both phosphorus and silicate.

An interesting feature in the reserved fraction of silicate was the negative values during the METEOR cruises. These values came from the well-mixed surface water. During ISMEX cruises, negative

values were absent in the surface layers (Fig. 11). During both METEOR and ISMEX cruises, negative value of silicate was also recorded at intermediate depths (Fig. 11).

The oxidative fraction of phosphorus was found to increase progressively up to 1000 m depth during METEOR and up to 1500 m during ISMEX. After these depths, it decreased. This condition of phosphorus seems similar to that of silicate. The reserved fraction of phosphate also increases with depth, but it varies in different regions (Fig. 11). Near the equator, in deeper waters, the values of

TABLE 2 COMPUTED VALUES OF OXYGEN AND NUTRIENT FRACTIONS FROM METEOR DATA ALONG 58°E LONG. IN THE DEPTH RANGE 1000-1500 m

[Values expressed in $\mu\text{g-at/litre}$]

OXYGEN			
Oxygen saturation (from $t^\circ\text{C}$ and $\text{S}_{\text{‰}}$)	O_2'		638
Oxygen concentration average	O_2		175
Apparent oxygen utilization	$\text{O}' - \text{O}_2$		463
Oxygen saturation			27%
PHOSPHORUS			
Inorganic	PO_4^{3-}P		2.57
Equivalent oxygen utilization	$280 \times \text{PO}_4^{3-}\text{P}$		720
P of oxidative origin	$\text{P}_{\text{ox}} = \text{AOU}/280$		1.65
Reserved phosphorus	$\text{P}_r = \text{PO}_4^{3-}\text{P} - \text{P}_{\text{ox}}$		0.92
Excess O, 0, saturation	$100\% \text{ O}_2 - 280 \times \text{PO}_4^{3-}\text{P}$ $(-82/638) \times 100$		-8.2 -13%
SILICON			
Reactive silicate	$\text{SiO}_4^{4-}\text{Si}$		92
Equivalent oxygen utilization	$7 \times \text{SiO}_4^{4-}\text{Si}$		644
Si of oxidative origin	$\text{Si}_{\text{ox}} = \text{AOU}/7$		66
Reserved silicate	$\text{Si}_r = \text{SiO}_4^{4-}\text{Si} - \text{Si}_{\text{ox}}$		26
Excess O, 0, Saturation	$100\% \text{ O}_2 - 7 \times \text{Si}$ $(-6/638) \times 100$		-6 -1%
NITROGEN			
Nitrate	NO_3^-N		37.53
Equivalent oxygen utilization	$17 \times \text{NO}_3^-\text{N}$		638
NO ₃ of oxidative origin	$\text{N}_{\text{ox}} = \text{AOU}/17$		27.23
Reserved nitrate	$\text{N}_r = \text{NO}_3^-\text{N} - \text{N}_{\text{ox}}$		10.3
Excess O, 0, saturation	$100\% \text{ O}_2 - 17 \times \text{NO}_3^-\text{N}$		0 0%

TABLE 1 -CALCULATED FRACTIONS OF PHOSPHORUS, NITROGEN AND SILICON

Fraction	Phosphorus	Nitrogen	Silicon
Total	Analysis after oxidation (Pt)	Analysis after oxidation (Nt)	—
Inorganic	Direct analysis	Direct analysis for $\text{NO}_3^- + \text{NO}_2^- + \text{NH}_3$	Direct analysis for $\text{SiO}_4^{4-}\text{Si}$ (reactive)
Oxidation	$\text{P}_{\text{ox}} = \text{AOU}/280$	$\text{N}_{\text{ox}} = \text{AOU}/17$	$\text{Si}_{\text{ox}} = \text{AOU}/7$
Reserved	$\text{P}_r = \text{PO}_4^{3-}\text{P} - \text{P}_{\text{ox}}$	$\text{N}_r = \text{NO}_3^-\text{N} - \text{N}_{\text{ox}}$	$\text{Si}_r = \text{SiO}_4^{4-}\text{Si} - \text{Si}_{\text{ox}}$
Organic + particulate	$\text{P}_t = \text{PO}_4^{3-}\text{P}$	$\text{N}_t = (\text{NO}_3^- + \text{NO}_2^- + \text{NH}_3)$	—

reserved fraction ranged between 40 and 50% of the inorganic phosphorus concentration. The fraction gradually decreases towards the north reaching 32% along the latitude 16°N.

In deep waters, the percentage of reserved silicate has been found to be higher than that of the reserved phosphorus. The reserved fraction of both phosphorus and silicate in the surface layers are

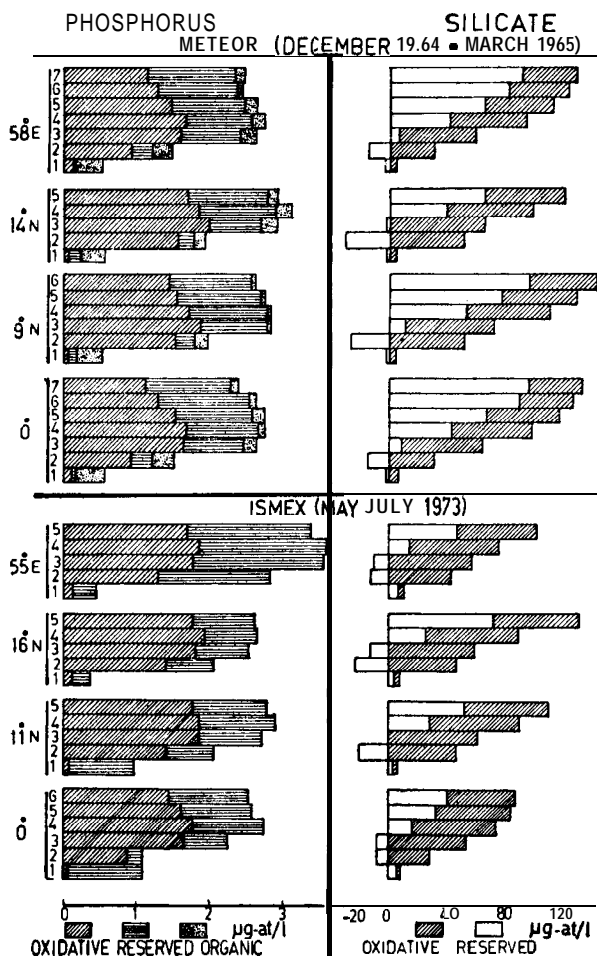


Fig. 11 --- Distribution of different fractions of phosphorus and silicate in relation to latitudes of the North-western Indian Ocean [Fractions of phosphorus and silicate refer to different depth (m) levels: (1) 0-60; (2) 60-500; (3) 500-1000; (4) 1000-1500; (5) 1500-2000; (6) 2000-3000; and (7) 3000 and below]

greater during SW monsoon as compared to NE monsoon (Fig. 11). Upwelling of nutrient-rich water has been reported along the coast north of the equator during SW monsoon¹⁷. In the area studied, the mean resultant surface wind which blows onshore is predominantly north-easterly from December to March, but from May to July, the wind north of the equator is mainly south-westerly veering offshore from the western part of the Arabian Sea³. Thus the nutrient-rich upwelled water can easily be driven offshore resulting in the increase of the reserved fractions of the nutrients as observed with ISMEX data.

Table 3 gives the fractions of nitrate according to depth in different regions. Like the silicate and phosphate, the oxidative fractions of nitrate also increase up to about 1500 m and then decline. The reserved fractions, on the other hand, increase progressively with depth. However, unlike silicate and phosphate, the fractions of nitrate are greatly influenced by processes like nitrification and denitrification. The negative values in the surface mixed layer (Table 3) probably indicate a deficit of nitrate.

Nitrate Deficits

Earlier investigations in the northern Arabian Sea have shown that the reduction of nitrate to nitrite and presumably to free nitrogen, takes place in this region⁵. Negative values of N_r in Table 3 point out that this process may extend southwards, probably close to the equator. We have attempted to estimate the rates of these processes and the amount of nitrate lost.

As an initial step we have estimated the amount of nitrate reduction from the following equation, deduced by Cline and Richards¹⁸.

$$\delta N = (NO_3)_{exp} - (NO_3)_{obs} - (NO_2)_{obs};$$

exp = experimental; obs = observed ... (9)

where

$$(NO_3)_{exp} = (NO_3)_{ox} \pm (NO_3)_r; \text{ ox = oxidative; } r = \text{reserved} \quad \dots (10)$$

Ammonia nitrogen was not included in the mass balance because of its low concentration (av. 1.5 µg-at/litre) in the water column.

Since the calculated oxidative ratios are valid throughout the area of observation in the depth region from 150 m to where AOU is maximum, by applying these ratios, P_r^* and N_r^* values in this depth range can be calculated. The straight line,

TABLE 3 -COMPUTED VALUES OF NITRATE FRACTIONS IN THE NW INDIAN OCEAN

Section of observations (av. values in µg-at/litre)

Depth range m	Along 0°		Along 9°N		Along 14°N		Along 58°E	
	N_{ox}	N_r	N_{ox}	N_r	N_{ox}	N_r	N_{ox}	N_r
0-60	2.56	-1.44	1.37	-0.84	1.62	-0.87	1.94	-1.62
60-500	16.06	2.52	26.75	-6.46	27.75	-6.95	16.69	1.5
500-1000	29.19	6.53	32.81	1.77	34.56	0.03	28.75	7.63
1000-1500	29.56	8.59	30.44	5.73	32.37	5.45	28.94	8.59
1500-2000	26.5	11.33	27.69	7.23	29.50	7.83	25.25	11.17
2000-3000	22.81	14.21	25.31	9.64	—	—	22.62	13.42
3000-over	20.19	16.11	—	—	—	—	19.81	16.51

deduced by the least squares method, is described by the equation:

$$N_r = 12.2P_r - 1.7 \quad \dots(n)$$

The slope of this line is similar to the value of 12.5 used by Fiadeiro and Strickland¹⁹ for the water off Peru and 13.1 deduced by Cline and Richards¹⁸ for the eastern tropical Pacific.

Using Eqs. (9)-(11) it is possible to reconstruct the depth profiles of nitrate anomalies through the oxygen minimum zone for METEOR stations 222-227 along with the relative positions of the secondary nitrite maximum in Fig. 12. Nearly a perfect matching of the maximum values of δN and nitrite suggests that this procedure of calculation gave a reasonable estimate of the amount of nitrate lost by denitrification. The process involved appears to be denitrification, for at this depth range the consumption of nitrogen in any form can be ruled out. Fig. 12 also suggests that the intensity of the process increases as we move offshore towards the open ocean.

To study the spatial variation of nitrate deficits, δN values from selected stations have been plotted against depth from 19°N to 4°S lat. (Fig. 13). Positive values of δN are generally found at depths where there is a sharp decrease in oxygen concentration. The values become negative at depths where the oxygen concentration is greater than 0.3 ml/litre. Fig. 13 also suggests that the depth of nitrate loss lies between 150 and 1000 m and its lower limit decreases southwards. At stations

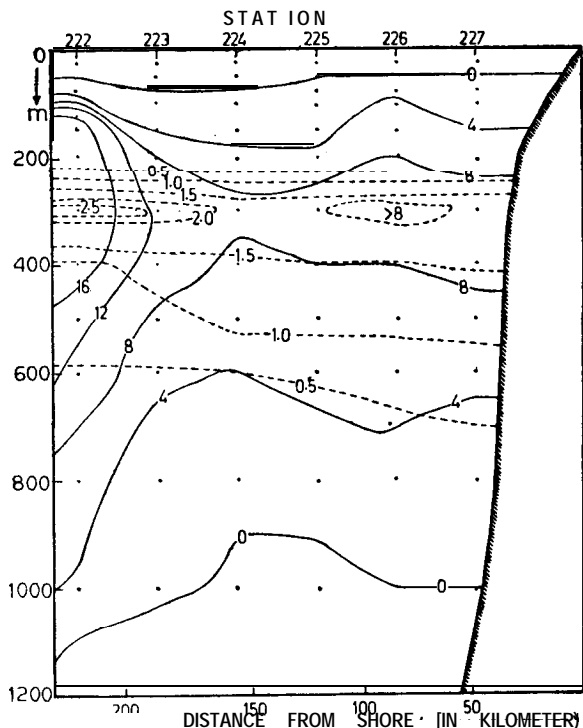


Fig. 12 -Calculated nitrate anomaly and nitrite distributions for METEOR stations 222-227 [Nitrate anomaly (continuous lines) and dissolved nitrite (broken lines) concentrations are given in $\mu\text{g-atoms/litre}$]

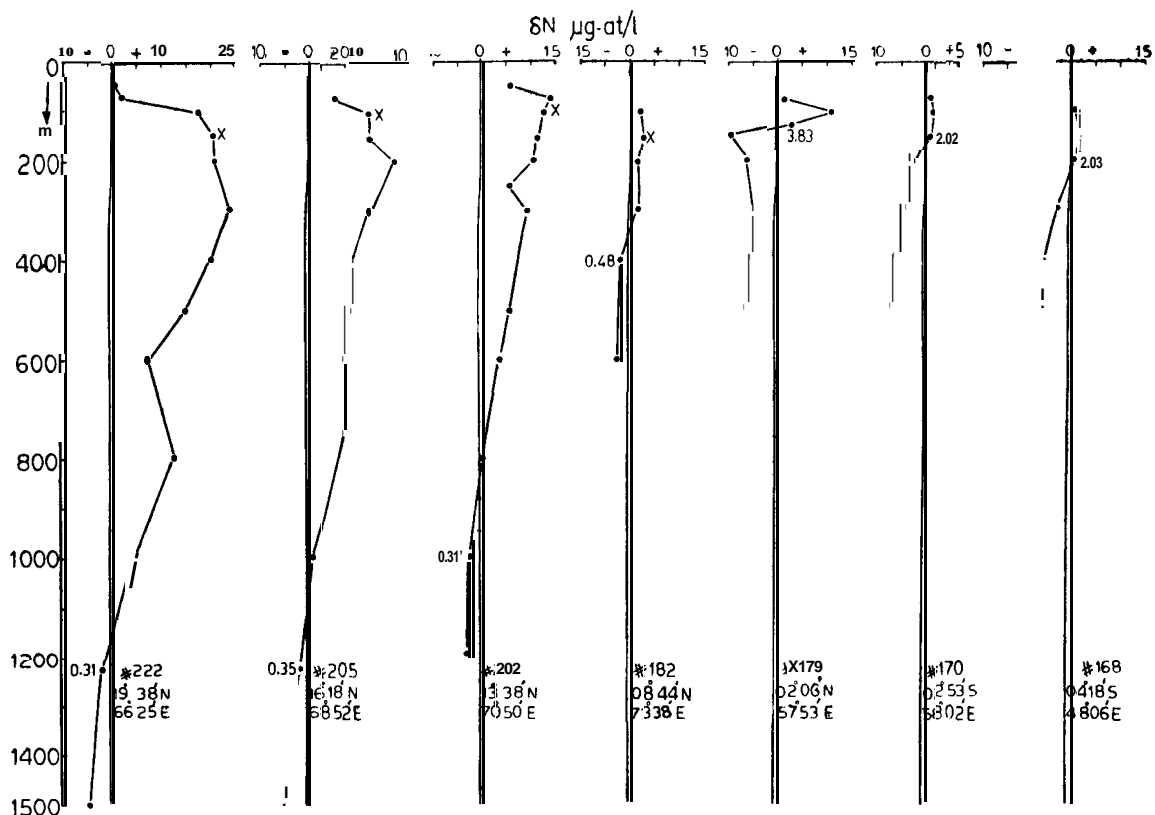


Fig. 13 — Reconstructed nitrate anomaly profile at selected METEOR stations between 19°38'N and 04°18'S latitude ^s [Cross signs at the first 4 stations indicate the depth of sharp decrease in oxygen concentration. Numbers denote oxygen concentrations in millilitre/litre. Procedure used in the reconstruction is given in the text]

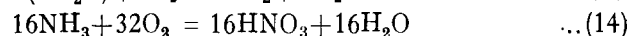
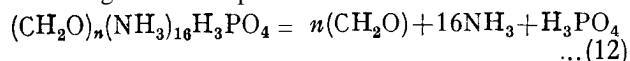
south of 2°N, nitrate values show anomalies even in the presence of a considerable amount of oxygen. This suggests that the processes in these layers is related to biological activity and the loss of nitrate due to denitrification ceases somewhere north of 2°N. From the interpolation of the values between 9° and 2°N (Table 3), the process appears to end at approximately 4°N latitude.

Stoichiometric Relationships

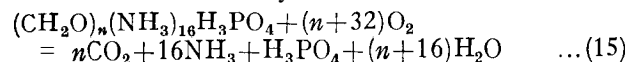
Extensive literature is available on C: N: P ratios in sea water and marine organisms, especially phytoplankton^{5,13,20,21}. For the northern and eastern basins of the Arabian Sea, the C: N: P ratio in plankton has been suggested as 105:15:1 by atoms⁵.

Probable chemical composition of planktonic algae — Ratio between oxygen utilization and phosphorus regeneration is 280:1 by atoms. The ratio between AAOU: AN is 17:1 by atoms. A combination of these 2 gives the relation between AN: AP as 16:1. This agrees well with the observed values. From this relationship, we have attempted to deduce a model for the planktonic algae in the Indian Ocean, using plankton data obtained earlier⁵.

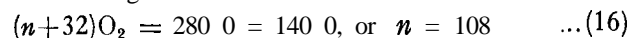
The data suggest that the organisms probably have the composition $(\text{CH}_2\text{O})_n(\text{NH}_3)_{16}\text{H}_3\text{PO}_4$. Applying the assumptions suggested by Richards²², the different stages in the process would be:



The overall reaction by summation will be



Since the AAOU: AP ratio is 280:1 by atoms, it would give



Relation between carbon dioxide and oxidation equivalents was studied. Values of carbon dioxide were computed from salinity, temperature, pH and total alkalinity using the nomogram of Buch²³. To cover higher chlorinity range, the nomogram was extended²⁴. The slope of the regression line is 308/280 ($\Delta\Sigma\text{CO}_2/\Delta\text{ox. equiv.}$) by atoms with a correlation (r) of 76%, the value calculated from Eq. (16) is 108/280 ($\Delta\text{CO}_2 \text{ biogenic}/\Delta\text{ox. equiv.}$) by atoms.

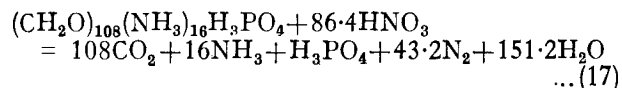
In the oceans, the ideal conditions for the lime-secreting organisms occur at mid-depth²⁵, while the dissolution of calcium carbonate from planktonic Foraminifera probably takes place near the bottom. Borate ions also influence the alkalinity of the sea water and form complexes with organic decomposition products²⁶. Gieskes²⁷ has reviewed the total alkalinity-CO₂ system in sea water and has indicated the sources of error that may be involved in the calculations. The low value obtained from Eq. (16) may probably be due to these errors.

Thus the organisms in the NW Indian Ocean seem to have a composition very close to $(\text{CH}_2\text{O})_{108}(\text{NH}_3)_{16}\text{H}_3\text{PO}_4$. The ratio between oxygen consump-

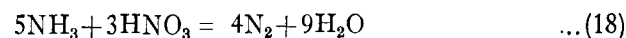
tion and carbon production (280/108) works out to be 2.6. This agrees well with the values obtained from the other oceans and indicates that a complete oxidation of organic matter having one atom of phosphorus would require 280 atoms of oxygen. Simultaneously, it would release into the water one phosphate ion, 16 nitrate ions and 108 molecules of carbon dioxide.

Denitrification — The process of denitrification involves the use of nitrate ions as the next source of free energy when practically all the oxygen from the system has been utilized. During this process, nitrite ions are formed as an intermediate product and gaseous nitrogen as an end product. Since at an intermediate depth of the NW Indian Ocean, oxygen concentration is very often lower than 0.1 ml/litre and has been found to be associated with nitrite with an average value of 0.1 µg-at/litre, probably the occurrence of denitrification is the usual feature at this depth-range leading to the loss of inorganic nitrogen compounds to gaseous nitrogen. Calculations of nitrate anomalies confirm the occurrence of this process.

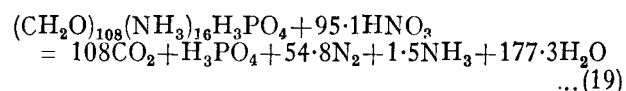
Using the stoichiometric relation deduced above, the process of denitrification can be written as



The average concentration of ammonia in the depth range of denitrification has been observed to be about 1.5 µg-at/litre. This means that 14.5 µg-at/litre of the ammonia released is oxidized to nitrogen gas. Using the fundamental equation for the oxidation of ammonia, which is



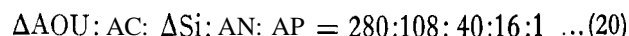
the overall reaction becomes



The observed concentration of nitrate in this layer is about 20.5 µg-at/litre. This would mean that approximately 78% of the available nitrate would be reduced during denitrification. This agrees with the earlier observation that in the northern and eastern basins of the Arabian Sea, about 70% of nitrate is lost by denitrification at an intermediate layer⁵. Thus, it can be concluded that about 2/3rd of nitrate is lost by denitrification in those layers of the NW Indian Ocean where the concentration of oxygen does not exceed 0.3 ml/litre and this process may extend southwards up to about 5°N lat. This water has its origin in the Red Sea and the Persian Gulf where excess evaporation reduces its oxygen content, which is further depleted because intense denitrification takes place in it throughout its flow until it loses its identity through mixing when it reaches close to the equator.

General Remarks

The following oxidative ratios by atoms for the NW Indian Ocean seem appropriate:



Similar ratios for the other regions are:

$$\text{AAOU: } \Delta\text{Si: AN: AP} = 276:16:14:3:1 \quad \dots (21)$$

by atoms for the Northern Irminger Sea¹⁴, and

$$\text{AAOU: } \Delta\text{Si: AN: } \Delta\text{P} = 270:16:16:1 \quad \dots (22)$$

by atoms for the western North Atlantic and the Caribbean Sea¹⁵.

From Eq. (20) it is clear that silicate concentration in the Indian Ocean is higher than in the Atlantic and, except for the $\Delta\text{Si: AP}$ ratio, the difference in the other ratios is only marginal.

The ratio of carbon, nitrogen and phosphorus (C: N: P) in the phytoplankton organisms has been suggested to be 105:15:1 by atoms for the northern Arabian Sea⁵. The present study shows the ratio as 108:16:1 by atoms. The widely accepted ratios for oceanic phytoplankton is 106:16:1 by atoms. Thus the plankton organisms in the Indian Ocean do not seem to differ significantly in composition from those of the other regions.

However, while calculating the ratio by the method of least square regression, it was assumed that the variables are linearly related. This assumption has certain limitations as the linear regression line may not always be the ideal fit through the points. Moreover, the components for which the oxidation equivalents were determined have been assumed to be non-variant. The reverse would probably be true if the relation is somewhat different. Tests have, however, shown that even if there is a reverse relationship it would remain within the errors of the analytical and statistical methods. The coefficients of correlation, though somewhat low, are all within the limits of accepted values (~ 0.7).

The stoichiometric relationship developed here gives an approximation of the conditions leading to the decomposition of organic matter in the NW Indian Ocean. Because of the similarity of this model with that of the other oceanic areas, it is thought that the model might remain valid for the entire Indian Ocean.

Acknowledgement

The authors are grateful to Dr P. Koteswaram, the former Director General of Observatories and Dr P. K. Das, Deputy Director General of Observatories, India Meteorological Department, for making available ISMEX data. Thanks are due to Prof. Dr Klaus Grasshoff of the Institut für Meeres-

kunde, Kiel, West Germany, for making available METEOR data, and to Dr (Miss) Aditi Pant of NIO for calculation of oxidation equivalents.

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