On the Distribution and Variation of Nutrient Salts in the Adjacent Water to the Aleutian Islands in the North Pacific

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Introduction

Oceanographical observations in the salmon fishing ground have been carried out in the region adjacent to the Aleutian Islands on board R. V. "Tenyo-maru", covering over 80 days from May to July in 1952. The author has been engaged in these observations and had an opportunity of analysing a number of water samples on board the vessel. On the basis of the data obtained in the field as well as in the laboratory, the distribution and variation of nutrient salts in the waters of this region have been considered in the present paper.

Although the sea region under consideration has been regarded as one of the most important fishing grounds of the world together with the vicinity of Newfoundland and the North Sea, systematic investigations concerning chemical problems in this region have scarcely been reported except those carried out by Ratomanov (1936)[1] and Barnes and Thompson (1938)[2]. Even in the comprehensive investigation conducted by Barnes and Thompson, the regions mainly concerned were restricted to the eastern side of long. 180° while little information on the Eastern Hemisphere has been available up to now.

Some problems related to the consumption of nutrient salts by marine organisms will also be discussed here.

The Sea Region under Consideration

The region under study is located within the square enclosed by the longitudes of 170°E and 180° and the latitudes of 50°N and 55°N, extending over both sides of the Aleutian Ridge as it is indicated in Fig. 1 with oceanographical stations and bottom contours. As shown in the figure, the Bering Sea covers an area north of the ridge and the southern area is covered with a portion of the North Pacific. In this region, the Bering Sea forms a very deep basin, while in the east part off the region it becomes much shallower to form the continental shelf of Alaska.

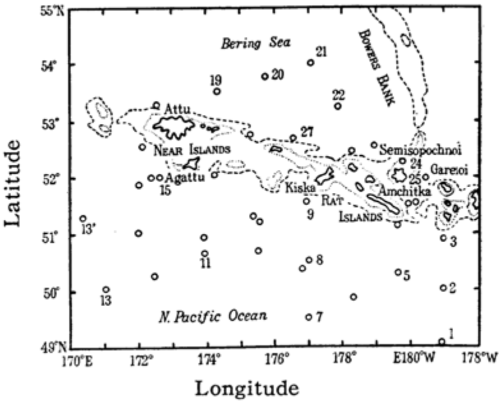

Fig. 1. Oceanographical Stations and Bottom topography near the Western Aleutian Islands. Dotted and broken lines indicate bottom contours of 200 m. and 500 m. depths, respectively.

Collection of Samples and Analytical Methods Adopted

Determinations of phosphate-phosphorus, silicate-silicon and dissolved oxygen were made on board ship as soon as possible after collection. Water samples for chlorine and nitrate-nitrogen determinations were brought to the author's laboratory

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* Contribution B-No. 137 from the Tokai Regional Fisheries Research Laboratory, Tokyo, Japan.

[1] C. E. Ratomanov, "Research of the Sea", Vol. 2, Moscow, 1936 (in Russian with English summary).

[2] C. A. Barnes and T. G. Thompson, University of Washington "Publications in Oceanography", Vol. 3, No. 2 (1938).

(Tokyo) and analysed. To the samples for nitrate determination mercuric chloride solution was added in order to avoid the change in concentration due to bacterial growth.

The improved method of Denigès-Atkins3) was adopted for the determination of phosphate-phosphorus. In this method color development was accomplished by the original procedure, but sea water free from phosphate was used as the media of diluted standards.

Silicate-silicon was estimated by means of Dienert-Wandenbulcke's method in which a buffered potassium chromate solution containing borax was adopted as the color standard. It was standardized against sodium silicate solution both with Beckman's spectrophotometer and by the visual method4). Color comparison aboard ship was performed by using improved Hehner tubes with the length of 25 cm.

Stock solutions of standards for phosphate and silicate determinations were prepared in duplicate, one of which served as reference and the other as the working standard, both being checked against each other from time to time. After the completion of the cruise it has been confirmed that the changes in concentration of the reference were negligibly small during the period.

Dissolved oxygen was determined by means of Winkler's iodometric titration5); and for chlorine determination the argentometric titration using uranine as the indicator6) was adopted.

Determination of nitrate-nitrogen was made by colorimetric methods using Harvey's reduced strychnine reagent; and as the artificial color standard the standardized safranine solution was used7).

Results and Discussion

1. Distribution of Water Temperature and Chlorinity.—As mentioned above, the region under consideration is topographically devided into two areas by the Aleutian Ridge running through the central part of the region. Therefore, it may be convenient to examine the distributions of water temperature, chlorinity and so on separately, by area. Data obtained from several stations within each area in the first decade of June were averaged and considered as representative values for each area.

Fig. 2 shows vertical distributions of water temperature and chlorinity. From the figure it is clear that distributions of water temperature are quite identical in both areas except for slight differences recognized beyond a depth of 200 m. A characteristic feature of the distribution of water temperature in this region is that the marked temperature minimum and the gentle maximum appear at depths of 100 m. and 400 m., respectively. Below the depth of 400 m. the water temperature falls gradually and the gradients of the fall are much gentler than those in other regions such as tropical waters.

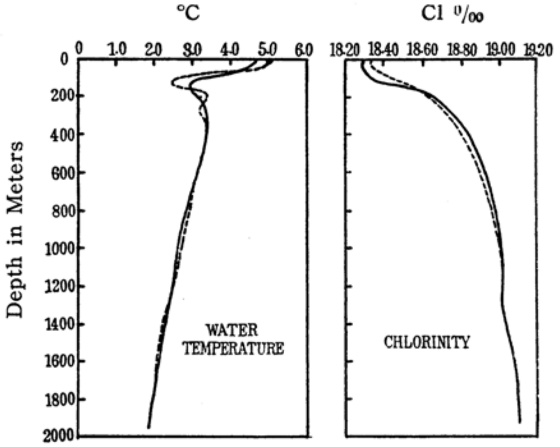

Fig. 2. Vertical distributions of water temperature and chlorinity. Solid lines represent the distributions in the Pacific side of the Aleutian Ridge, and broken lines those in the Bering Sea.

Distributions of chlorinity in these areas also are almost identical and chlorinity increases continuously with depth.

Close agreements in vertical distributions both of water temperature and of chlorinity between these areas suggest that horizontally uniform water masses may exist there. This type of distribution is in striking contrast to those in the Kuroshio or equatorial region.8)

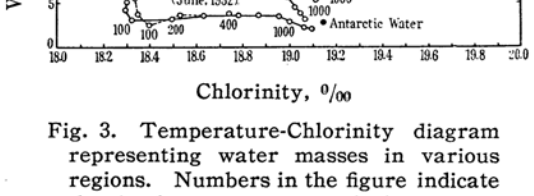

Fig. 3. Temperature-Chlorinity diagram representing water masses in various regions. Numbers in the figure indicate the depths in meters at which temperature and chlorinity for each point were obtained.

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3) R. J. Robinson, *J. Mar. Res.*, **7**, 33 (1948).

4) R. Fukai, *J. Oceanogr. Soc., Japan*, in press.

5) W. S. Wooster, "Technical report of the California Cooperative Sardine Program", No. 25, Scripps Inst. of Oceanogr. (1950).

6) Y. Miyake, This Bulletin, **14**, 29 (1939).

7) H. Wattenberg, *Rapp. et Proc.-Verb. des Reunions, Conseil permanent intern. pour l'explosation de la mer*, **103**, 19 (1937).

8) R. Fukai, This Bulletin, **26**, 485 (1953).

In Fig. 3, T–Cl curves which were previously obtained by the author are compared with those from the present data. It should be noticed that although T–Cl curves differ greatly from each other in the upper layers, they tend to converge on a point which represents water temperature and the chlorinity of a water mass having Antarctic origin.

2. Distribution of Dissolved Oxygen.—Vertical distributions of dissolved oxygen in these two areas are shown in Fig. 4 compared with those in the Kuroshio region. The distributions in the areas are in close agreement with each other as well as those of water temperature and chlorinity. As for characteristic features of the distribution, it may be pointed out that high contents of oxygen are encountered at and near the surface and they suddenly decrease in depths within 100–300m. forming a jumping layer. Oxygen at depths of 400–1000 m. is less than 1 cc. 0_2/l., being the minimum value among those oceanic waters of the North Pacific.

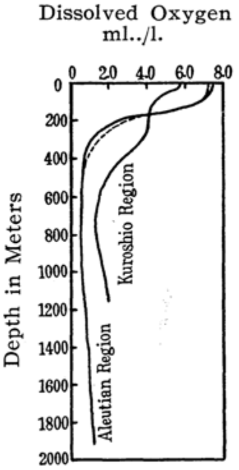

Fig. 4. Vertical distributions of dissolved oxygen. Solid lines: in the Pacific; broken line: in the Bering Sea.

As shown in Table I, a remakable fact is that the oxygen contents at the layers of 10 m. and 25 m. are higher than at the surface. This may probably result from photosynthesis by phytoplankton, since this type of distribution without biological support would be destroyed by the strong turbulence prevailing in the region.

TABLE I

AVERAGE CONTENTS OF DISSOLVED OXYGEN IN THE UPPER LAYERS

Depth m.	O_2 ml./l.		Saturation percentage
	obs.	calc.	
0	7.37	7.23	101.9
10	7.44	7.29	102.1
25	7.46	7.34	101.6
50	7.36	7·37	99.9
75	7.24	7.53	96.1
100*	6.99	7.62	91.7
150	4.94	7.50	65.9

* The layer of minimum water temperature.

The thickness of the euphotic layer may be estimated to be about 50 m. from the fact that the oxygen content at 50 m. layer is just saturated whereas the contents above this layer are supersaturated.

3. Distribution of Phosphate-phosphorus and Nitrate-nitrogen.—Vertical distributions of phosphate and nitrate are given in Fig. 5.

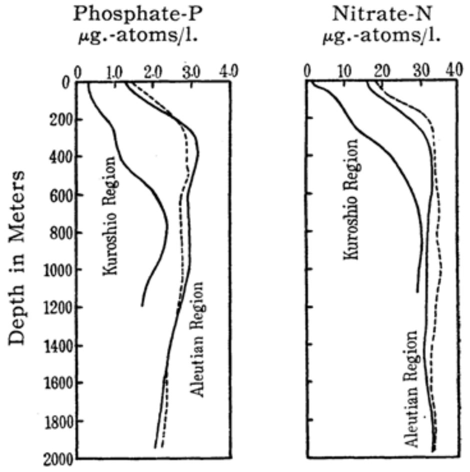

Fig. 5. Vertical distributions of phosphate-phosphorus and nitrate-nitrogen. Solid lines: in the Pacific; broken lines: in the Bering Sea.

The distributions of each of the constituents are almost the same in the two areas. The causes of slight differences recognized between the areas are not clear. Yet it may be remarkable that the phosphate contents at depths within 200–800 m. are lower in the waters of the Bering Sea than in the other area, while the contents of nitrate are higher in the former than in the latter.

Characteristics of the vertical distributions are that the high contents of both constituents are found at and near the surface and that the concentrations increase abruptly in a layer corresponding to the jumping layer of dissolved oxygen. The maximum amount of phosphate appears at a depth within 400–600 m., while the maximum of nitrate is not obvious. Attention is called to the fact that considerable amounts of both constituents (above 1.0 μg.-atoms PO_4-P/l. and 150 μg.-atoms NO_3-N/l.) were present in spite of the fact that abundant crops of phytoplankton existed there. The fact means that the nutrient salts in the upper layers have not been exhausted so that potential ability for organic production could still remain in the layers.

4. Distribution of Silicate-silicon.—Fig. 6 illustrates vertical distribution of silicate in the areas compared with those in the Kuroshio region and in the Northeast Pacific. As in cases of other constituents, considerable amounts of silicate are found at the surface and they further increase in the deeper layers. Referring to some differences in distributions between two areas, the contents are slightly lower on the side of the Bering Sea. It is conspicuous that the distributions differ greatly from those obtained by Thompson.

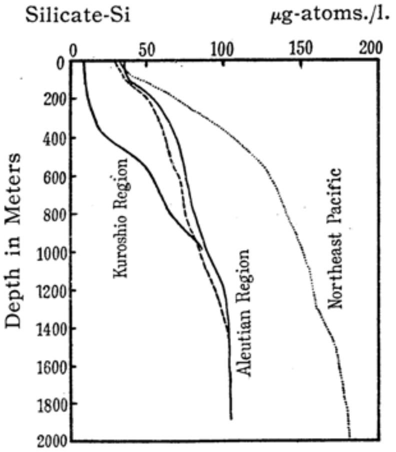

Fig. 6. Vertical distributions of silicate-silicon. Solid lines: in the Pacific; broken line: in the Bering Sea; dotted line: in the Northeast Pacific obtained by Thompson (1938).

5. Relationship between Distributions of Nutrient Salts.—As described above, the prevailing features of the nutrient salt distribution are summarized as follows:

(i) Distributions are horizontally uniform except those in limited areas such as the vicinity of islands,

(ii) concentrations are high even in the surface layer,

(iii) and increase further with maximum gradients in depths within 100–300 m.

From the type of distributions, it is expected that parallel correlation may exist between concentrations of these constituents. From Fig. 7 which shows the correlation between phosphate and nitrate, it is concluded that the average atomic ratio of N : P is 12, although points plotted in the figure are somewhat scattered. This value is lower than the normal ratio of 15 proposed by Cooper⁹⁾. As the author has recently pointed out¹⁰⁾, the ratios in the waters below subsurface layers in the Kuroshio region coincide with the normal ratio. So far it has not been conclusive, however, whether the deviation from the normal ratio in the Aleutian region is attributed to local differences or related to the rate of regeneration of these constituents.

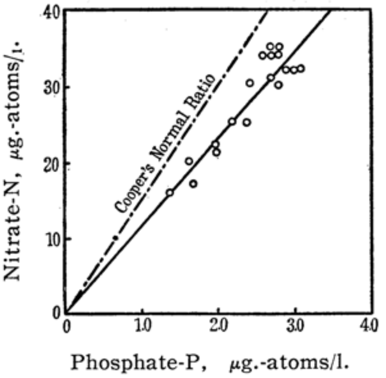

Fig. 7. Relationship between nitrate-nitrogen and phosphate-phosphorus in the adjacent region to the Aleutian Islands.

In case of the regeneration of these constituents, in general, dissolved oxygen would be consumed. The relationship between phosphate contents and oxygen depletion (the difference between the saturation value and observed value) is shown in Fig. 8. Oxygen depletion may serve as a measure of oxygen consumption.

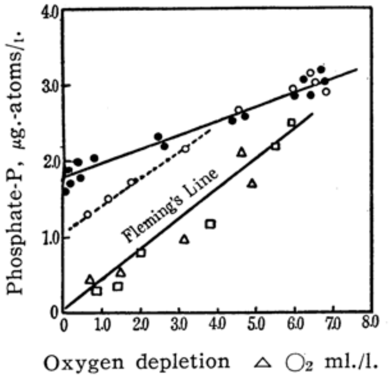

Fig. 8. Relationship between phosphate-phosphorus and oxygen depletion in various regions. Dots designate points for the Aleutian Region in 1st decade of June; circles for those at the end of June. Squares: for the Kuroshio Region; triangles: for the Equatorial Region.

In the figure, was added a line which was proposed by Fleming¹¹⁾ on the basis of the proportion between liberated oxygen and as-

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9) L. H. N. Cooper, *J. Mar. Biol. Assoc., United Kingdom*, **22**, 177 (1938).

10) R. Fukai, This Bulletin, **25**, 323 (1952).

11) R. H. Fleming, "Proc. the 6th Pacific Science Congress", Vol. 3 (1939).

similated phosphorus, both due to photosynthesis. It can be stated that points plotted for the Kuroshio and Equatorial regions are in close agreement with Fleming's line, while the slope of the line derived from the points for the Aleutian region differs greatly from that of Fleming's line. In addition, the slope had been altered in the course of time and it came to coincide with that of Fleming's line after about a month. This indicates that a constant ratio between phosphate and oxygen depletion has not been maintained during the period and that the decrease in dissolved oxygen has taken place in association with the decrease in phosphate contents in the subsurface layer. Although the mechanism of this decrease in dissolved oxygen may be complicated, it may relate to the decomposition processes in the layer in question. The deficiency of dissolved oxygen in the subsurface layer should be emphasized as a feature in the Aleutian region together with the deviation of N-P ratios from the normal ratio.

6. Quantitative Consideration on the Rate of Organic Production by Phytoplankton.—In the above it has been concluded that the potential ability for organic production still remained in this region at the beginning of June. As the duration of this condition depends upon the rate of organic production, it is desirable to find out the production rate.

Oceanographical observations were repeatedly carried out at sea around 150 nautical miles S. of Attu Island on June 5–6 and 29–30. Table II has been made by averaging a number of data obtained from several stations occupied there. On these materials the following computations have been based.

TABLE II

DATA USED FOR THE ESTIMATION OF THE PRODUCTION RATE

Water layer m.	June 5–6		June 29–30	
	Water temp. °C	PO_4-P μg-at./l.	Water temp. °C	PO_4-P μg.-at./l.
0–25	4.50	1.33	6.08	0.93
25–50	4.29	1.47	5.12	1.19
50–75	4.00	1.60	4.03	1.41

At first, the rise in water temperature may be expressed by

$$\frac{\partial T}{\partial t}=\frac{A_z}{\delta}\cdot\frac{\partial}{\partial z}\left(\frac{\partial T}{\partial z}\right)-V_x\cdot\frac{\partial T}{\partial x}\,, \qquad (1)$$

where, T is water temperature, A_z, coefficient of eddy diffusivity, δ, specific gravity of sea water, and V_x, current velocity component along x-axis.

In the equation, we may conveniently take x-axis from the west to the east and z-axis from the surface to the bottom. In equation 1, the lateral mixing of water masses was ignored because the horizontal gradients of water temperature were so small; and current velocity components except that along x-axis were of no account.

Let us rewrite equation 1 as

$$A_z=\delta\left(\frac{\partial T}{\partial t}+V_x\cdot\frac{\partial T}{\partial x}\right)\Big/\frac{\partial^2 T}{\partial z^2}\,. \qquad (2)$$

Since gradients of temperature distribution, current velocity component and specific gravity of sea water are known, we can obtain the value of A_z from the equation 2. The calculated values of A_z are shown in the first column in Table III.

TABLE III

COMPUTED VALUES FOR NET PRODUCTION RATE

Water layer m.	A_z	R PO_4-P μg.-at./l./sec.	Net production rate mg.C/m³./day
0–25	(10)	-5.1×10^{-7}	56
25–50	10	-1.0×10^{-7}	11

On the other hand, the decrease in phosphate contents during the period may be expressed by

$$\frac{\partial C}{\partial t}=R+\frac{A_z}{\delta}\cdot\frac{\partial}{\partial z}\left(\frac{\partial C}{\partial z}\right), \qquad (3)$$

where C is concentration of phosphate R, biological rate of change (rate of net consumption).

In equation 3, the horizontal eddy diffusion and advection were ignored since the horizontal distribution of phosphate was uniform as previously stated. From Eq. 3, we may obtain

$$R=\frac{\partial C}{\partial t}-\frac{A_z}{\delta}\cdot\frac{\partial^2 C}{\partial z^2}\,. \qquad (4)$$

Then, on the basis of Eq. 4, the value of R can be calculated by introducing into the equation the values of A_z, which have been obtained from Eq. 2, and gradients in phosphate distribution. The values of R thus obtained for each layer are shown in the second column in Table III.

Since photosynthesis by phytoplankton is usually accompanied by the consumption of phosphate, the rate of carbon assimilation can be computed as in the third column of Table III from the values of R, using the proportion given by Fleming.

Few data have been available for comparing these values, except those which were derived from Reiley's data concerning the annual variations of plankton carbon on Georges Bank[12] (Table IV). The values for the Aleutian region agree well with the value for the spring burst of phytoplankton given by Riley.

TABLE IV

NET PRODUCTION RATES COMPUTED FROM THE DATA OBTAINED BY RILEY ON GEORGES BANK (1947)

Period	Net production rate mg.C/m³./day
Feb.–Mar.	4
Mar.–Apr.	20
Apr.–May	50

Most recently, Nielsen[13] has pointed out on the basis of the results obtained from the determinations using radiocarbon C^{14} that the production rates hitherto estimated were too high, especially in the tropical regions, criticizing the experiments carried out by Riley[14] in the Sargasso Sea. However, Nielsen himself has admitted that Riley's values are reliable so far as the waters on the coastal bank are concerned.

Thus, if we assume that the organic production continues at the rate obtained above, and that the nutrient supply from the substratum is prevented by the development of stratification, the potential ability for organic production is reckoned to last for about 20 days more. Consequently, the production may actually continue till the end of summer without deficiency in nutrient salts.

7. Estimation of the Production Rate based upon the Diurnal Variations of Dissolved Oxygen.—Anchored observations on the diurnal variations of oxygen throughout 24 hours were carried out at Station 24, situated north of Semisopochnoi Island, in the last decade of May. Results obtained are shown in Fig. 9. Values plotted for dissolved oxygen in the figure represent integral mean concentrations from the surface to a depth of 50 m. Although the water was shifted continuously by tidal current during the period, the temperature and chlorinity of water were kept strictly constant. For this reason, it can be assumed that the changes in dissolved oxygen were caused by biological activity in a water mass.

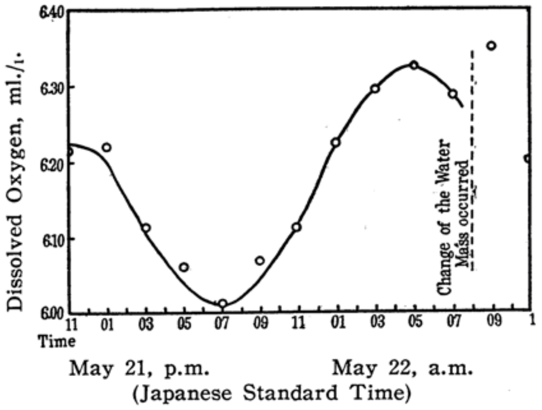

Fig. 9. Diurnal variation of dissolved oxygen at St. 24, off Semisopochnoi Island.

According to the figure, the net increase in the oxygen content amounting to 0.3 ml/1. took place in 10 hours from 7:00 P. M. to 5:00 A. M. (Japanese Standard Time). When this amount of oxygen is converted into the amount of assimilated carbon, we may obtain 165 mg.C/m³.

On the other hand, the author's experiment[15] showed that in case of the carbon assimilation by phytoplankton, 30–50% of assimilated carbon was simultaneously consumed through the respiration processes. Consequently, an estimate of 85 mg.C/m³/day for the net production rate may be obtained by subtracting the quantity for respiration from the net quantity for assimilation during 10 hours.

This value is considered to represent the upper limit for the assimilation rate, since it was estimated for the area in the vicinity of an island, and since carbon was also consumed by zooplankton possessing no assimilating activity. With these views in mind, the values based upon the phosphate consumption seem to be reliable.

Summary

The author was engaged in the oceanographical observations carried out in a region adjacent to the Aleutian Islands in 1952 and obtained a number of data, on which the present discussions are based.

As the results, slight differences in distributions of nitrate-nitrogen, phosphate-phosphorus and silicate-silicon were found between the northern and southern areas separated by the Aleutian Ridge, although distributions are almost the same in the two areas.

Characteristic features in distributions of these nutrient salts are that the high concentrations were found even in the surface layer, increasing further with maximum gradients in depths within 100–300 m.

The ratios of N : P in the region under

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[12] G. A. Riley, *J. Mar. Res.*, **6**, 104 (1947).

[13] E. S. Nielsen, *J. Couseil. perm. intern. pour l'exploration de la mer*, **18**, 117 (1952).

[14] G. A. Riley, *J. Mar. Res.*, **2**, 145 (1939).

[15] R. Fukai and K. Okubo, not yet published.

study are lower than the normal ratio given by Cooper; and deficiencies in dissolved oxygen were recognized in the subsurface layers. These facts seem to be related to the characteristics of the decomposition processes in the Aleutian region.

On the basis of the rate of phosphate consumption in the upper layers, the net production rate has been computed by introducing some simplifying assumptions; and has obtained the value of 56 mg. C/m^3/day. This value is considered to be reliable, since it coincides with that derived from Riley's data and with that calculated from the data concerning the diurnal variations of dissolved oxygen.

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