THE SEASONAL AND VERTICAL DISTRIBUTION OF SUSPENDED PARTICULATE MATTER IN AN AREA OF THE NORTHEAST PACIFIC OCEAN[1]

Louis A. Hobson[2]
Department of Oceanography, University of Washington, Seattle 98105

ABSTRACT

Concentrations of the particulate matter, particulate organic carbon, and particulate carbohydrate were determined in an area of the northeast Pacific Ocean, at depths between the surface and 4,000 m, on six occasions in two years. Below 250 m, concentrations of particulate matter ranged from 30 to 1,000 mg/m^3, particulate organic carbon from 8 to 110 mg/m^3, and particulate carbohydrate from undetectable to 30 mg/m^3. There was more particulate matter in winter than in spring and summer. This temporal variation appeared to be related to variations in advection.

The particles making up about 90% of the mass of the particulate matter with diameters greater than about 2 μ ranged between 8- and 44-μ diameter. Sinking rates were calculated (0.1 to 10 m/day) and were slow compared with horizontal speeds. Thus, the influence of phytoplankton production in the area of the concentration of particles below 250 m in that area was of minor importance.

Below 250 m, the ratios of the variables and particle size showed no consistent changes with depth, suggesting that the particles were not rapidly oxidized while suspended in the water column.

INTRODUCTION

Concentrations of particulate matter in a given area of the ocean would be expected to vary seasonally if materials formed in the euphotic zone sink rapidly into deeper layers. The size and chemical composition of the sinking particles would decrease and change with depth if they were oxidized, dissolved, or both. Horizontal transport of water with varying concentrations of particulate matter through the area would be expected to produce temporal variations that might or might not be seasonal.

Riley, Van Hemert, and Wangersky (1965) surveyed the seasonal variation in the vertical distribution of particulate organic carbon in the Sargasso Sea. They found no consistent decrease of the carbon between 500 and 4,000 m, but seasonal variations were observed that could not be explained. Menzel and Goering (1966) found no vertical or seasonal variations of the particulate organic carbon below 250 m. They carried out decomposition experiments on particulate organic carbon taken from subsurface water of the Atlantic Ocean and concluded that the material was not rapidly oxidized. Menzel (1967) measured concentrations of particulate carbon in water off Peru and Ecuador and found homogeneous distributions from 100 to 5,000 m. However, Bogdanov (1965) examined, microscopically, suspended matter from the Pacific Ocean and concluded that the organic content of particles decreased slowly from 100 m to oceanic depths. Holm-Hansen, Strickland, and Williams (1966) found vertical variations of the particulate carbon at one station off southern California from 50 to 1,300 m, but no trends were apparent.

To obtain more information on the factors controlling the seasonal and vertical distribution of particles with diameters

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[2] Present address: Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543.

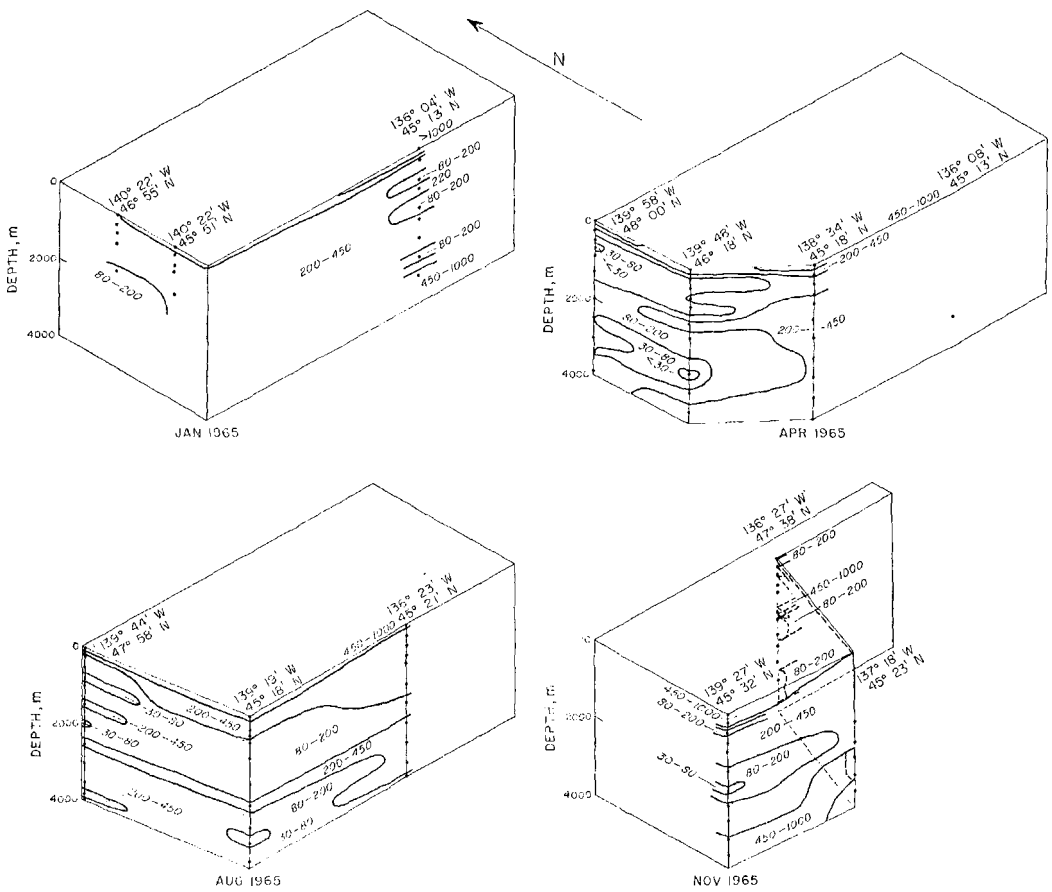

FIG. 1. Seasonal variation of the spatial distribution of particulate matter (mg/m³).

greater than 1 to 2 μ in the deep sea, measurements of the concentrations of particulate matter, particulate organic carbon, particulate carbohydrate, particle size, and current speed and direction were made in the northeast Pacific Ocean between 1964 and 1965.

METHODS AND MATERIALS

Cruises were made by the RV *Brown Bear* and CNAV *Oshawa* to an area bounded by 45° and 48° N lat, 135° and 140° W long, about 1,300 km off the coasts of Washington and Oregon, in August and October 1964, and in January, April, August, and November 1965. The area overlies the Tufts Abyssal Plain and has an average depth of about 4,500 m.

Samples were taken from the surface, at 250-m intervals to 1,000 m, and at 500-m intervals from 1,000 to 4,000 m at three stations within the area, with modified 6-liter Emsworth water bottles. The surface sample was made up of equal volumes of water from 1, 17, 34, and 50 m. Samples were drained into polyethylene containers and were usually subsampled about 30 min later. After agitation, subsamples of about 2 to 3 liters each were poured from the container into 4-liter polyethylene bottles. The subsamples were filtered through Gelman® type A (1–2-μ pore diam) glass-fiber filters, which were then placed in plastic petri dishes and dried at 60C for 24 hr and stored in a desiccator.

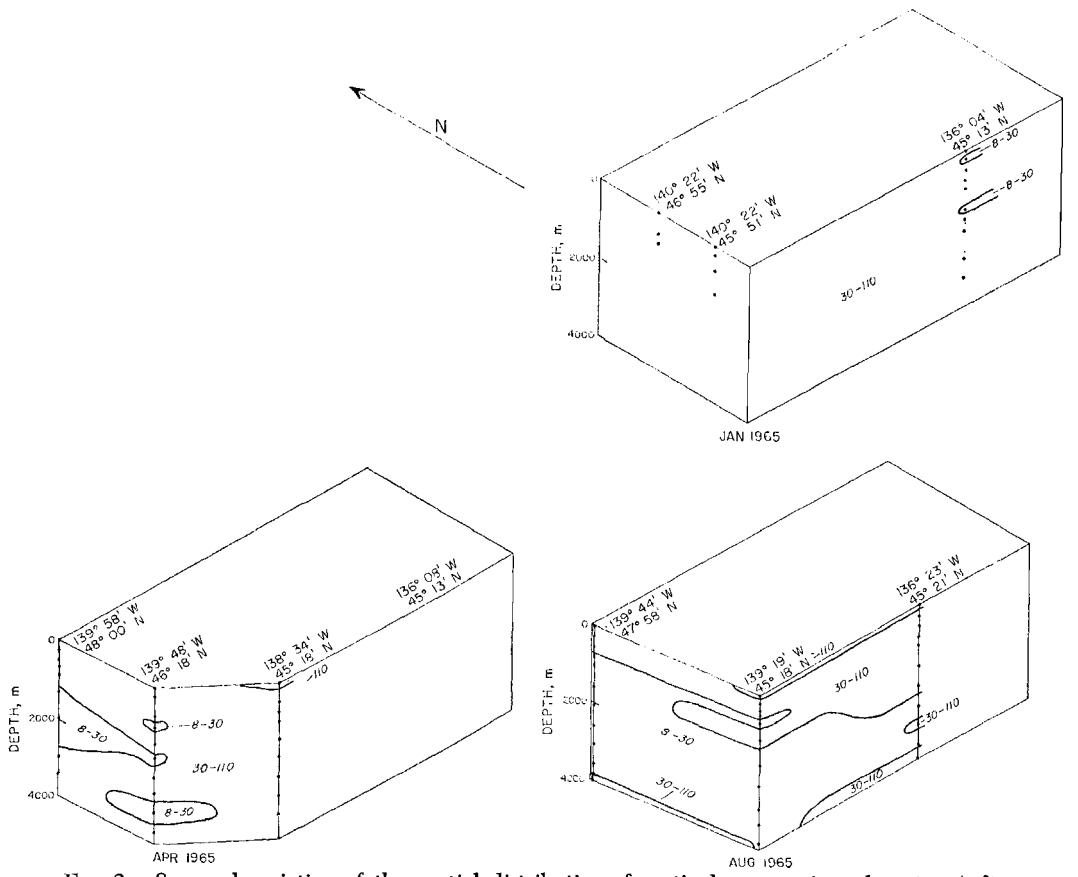

FIG. 2. Seasonal variation of the spatial distribution of particulate organic carbon (mg/m³).

The Emsworth bottles were rinsed with methanol and then with seawater that recently had been filtered through an HA Millipore® (0.45-μ pore diam) filter.

The volume and size of particles in 0.5-ml subsamples were determined on shipboard with a Coulter counter (model B, Coulter Electronics, St. Hialeah, Fla.). The counting stand was mounted on gimbals because it contains a manometer. A counting tube of 100-μ pore diameter was used and was standardized on ragweed pollen having a mean diameter of 19.5 μ. Counting tubes having pore diameters of 50, 100, and 200 μ were used during the first cruise and gave similar results for overlapping volume ranges. The 50- and 200-μ tubes were not used on later cruises because of the difficulty in changing tubes for each sample. Particle counts were corrected for background noise levels. Because of the difficulty in obtaining particle-free salt water to use as a standard, the subsample giving minimum particle numbers on each cruise was used as the blank for that cruise. The number of particles in given volume ranges from 7 μ^3 to 33 $\times$ 10^4 μ^3 were counted. All counts were made in triplicate. The volume of the particles was computed by multiplying the number of particles in a given volume range by the median volume of the range. The volume of particles was converted to mass assuming a density of 1 g/cm³.

Particulate organic carbon was converted to CO_2 using the wet combustion method of Oppenheimer, Corcoran, and Van Armen (1963). The volume of CO_2 produced was determined using a Scholander 0.5-cm³ gas analyzer (Scholander 1947).

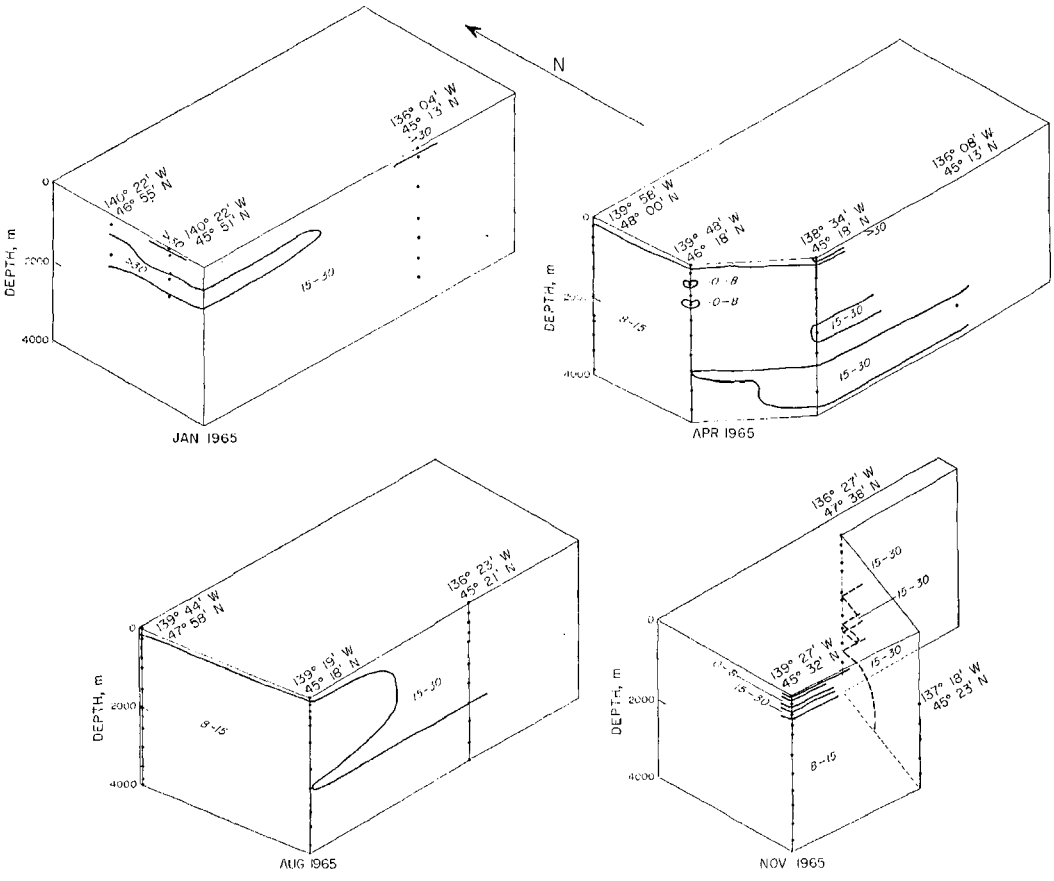

FIG. 3. Seasonal variation of the spatial distribution of particulate carbohydrate (mg/m³).

Particulate carbohydrate was measured using the colorimetric anthrone method standardized on glucose. The procedure of Antia and Lee (1963), developed for the quantitative determination of dissolved carbohydrate in seawater, was followed. However, the specified 5 ml of seawater was replaced by a glass filter with particulate matter and 5 ml of distilled water. After color development, the solutions were centrifuged at about 5,000 × g for 20 min. The supernatant was used to determine carbohydrate concentrations. Filter blanks were run with each batch of samples.

Two casts were made at one station in August 1965 and samples were considered to be duplicates. The variability of the duplicates was determined using a one-way analysis of variance model. The coefficients of variance of the measurement of particulate matter, carbon, and carbohydrate were 20, 56, and 31% at the 95% confidence level. These coefficients were used to calculate confidence intervals for the data.

To compute current velocities, geopotential anomalies were calculated, using the equation of geostrophic motion (Sverdrup, Johnson, and Fleming 1942) with the data from these cruises. A reference level of 3,000 m was used. Geopotential anomalies were calculated for the 3,000- to 4,000-m interval whenever possible. Usually there was no slope between the two levels and use of the 3,000-m level was justified.

RESULTS

In January 1965, the concentrations of particulate matter at depths greater than 250 m varied between 80 and 1,000 mg/m³

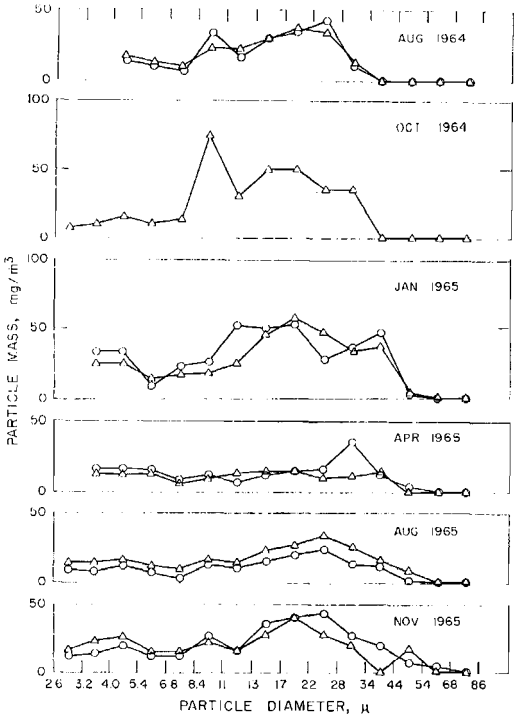

FIG. 4. The relationship of particle mass to particle diameter. Triangles—mean of observations in the 250- to 2,000-m layer; circles—mean of observations in the 2,000- to 4,000-m layer.

(Fig. 1). In April, less than 30 to 450 mg/m³ were present at the northwestern and southwestern stations at depths greater than 250 m. Lower values were observed in August 1965 at the southeastern station, when the concentrations ranged between 80 and 200 mg/m³ at 2,000 and 4,000 m. There were between 200 and 1,000 mg/m³ at depths between 2,000 and 3,500 m at the southwestern and southeastern stations in November 1965. Concentrations were usually between 450 and 1,000 mg/m³ in the upper 50 m. These are minimal values because a density of 1 g/cm³ was used to convert particle volume to mass.

In January, at depths greater than 250 m, the concentrations of particulate organic carbon ranged between 8 and 110 mg/m³ (Fig. 2) and in April, they were between 8 and 30 mg/m³ at 1,200 and 2,200 m at the northwestern and southwestern stations. Concentrations of 8 to 30 mg/m³ also were present at the southeastern station in August. In the upper 50 m, concentrations were usually between 30 and 110 mg/m³, but in April and August the concentrations increased to greater than 110 mg/m³ at the southeastern station.

In January, concentrations of particulate carbohydrate ranged between 15 and 30 mg/m³, to greater than 30 mg/m³ at depths greater than 250 m at all stations (Fig. 3). In April, they were between undetectable and 15 mg/m³ at the northwestern and southwestern stations and remained about the same from April to November 1965. Concentrations in the upper 50 m were greater than 30 mg/m³ in January and April and decreased to 15 to 30 mg/m³ in August and November.

Generally, the concentrations of particulate matter, particulate organic carbon, and particulate carbohydrate at depths deeper than 250 m, decreased from January 1965 to April 1965, with low concentrations first appearing in the western area and later in the eastern area. The distribution did not change through November, although a high concentration of particulate matter occurred in November at depths greater than 2,000 m in the southern regions.

The fractions of organic carbon in the particulate matter were usually between 0.20 and 0.30 (Table 1). These ratios may be high because of the assumption of a particle density of 1 g/cm³. If the density of 2.6 g/cm³ is used, assuming the particles are mainly silicate, the ratios are about 0.08 to 0.12. The ratio was the same in the two layers, except in April 1965 at the northwestern station, where the ratio was higher in the 250- to 2,000-m layer.

The fraction of particulate carbohydrate-carbon in the particulate organic carbon was generally in the range of 0.10 to 0.20. The ratio was the same in the two layers, except at the southwestern station in August 1965, when the ratio was higher in the deeper layer.

Most of the particles were 8- to 44-μ diameter (Fig. 4). The size of particles was about the same at depths greater than 250 m during all cruises.

In January 1965, the water transport

TABLE 1. *Seasonal variation of ratios of particulate organic carbon to particulate matter in the 250- to 2,000-m and 2,000- to 4,000-m layers**

Date	Particulate organic carbon : Particulate matter		
	Southeast	Southwest	Northwest
1964			
Oct	0.26 ± 0.09 (3)		
1965			
Jan	0.20 ± 0.05 (6) 0.22 ± 0.07 (3)	0.12 ± 0.05 (2)	0.14 ± 0.06 (2)
Apr		0.19 ± 0.05 (5)	0.45 ± 0.12 (5)
	0.33 ± 0.19 (1)	0.20 ± 0.07 (3)	0.26 ± 0.09 (3) 0.70 ± 0.20 (4) 0.28 ± 0.10 (3)
Aug	0.20 ± 0.05 (5) 0.20 ± 0.05 (5)	0.22 ± 0.06 (5) 0.22 ± 0.06 (4)	0.20 ± 0.05 (5) 0.22 ± 0.05 (6)

* The upper number is the mean of observations in the 250- to 2,000-m layer and the lower is the mean of observations in the 2,000- to 4,000-m layer ± the variability at the 95% confidence level; the number of observations is in parentheses.

between 500 and 2,000 m was offshore. Current speeds varied between 17 cm/sec at 500 m and 3 cm/sec at 2,000 m. The transport shifted to onshore in April, with current speeds between 15 cm/sec at 500 m and 3 cm/sec at 2,000 m and did not change in August 1965. However, in November 1965, the transport was to the north with current speeds of 10 cm/sec at 500 m and 5 cm/sec at 2,000 m.

DISCUSSION

These data indicate that most of the particulate organic carbon contained in particles with diameters greater than 1 to 2 μ below 250 m in the open sea is bound in small, probably nonliving particles, 8 to 44 μ in diameter. Mullin (1965) concentrated particulate matter with diameters between 1 and 350 μ from surface seawater and showed that about 88% of the oxidizable fraction had diameters of 1 to 95 μ. The sinking rates of these small particles through a homogeneous, nonturbulent liquid can be calculated using Wadell's sedimentation formula (Krumbein and Pettijohn 1938):

$$V = \frac{r^2 g}{7\eta}(\rho - \rho_o),$$

where V is the velocity in cm/sec, r is the particle radius in cm, g is the acceleration due to gravity (980 cm/sec^2), ρ is the density of the particle (g/cm^3), ρ_o is the density of seawater at about 1,000 m (1.027 g/cm^3), and η is the viscosity of seawater with a salinity of 33‰ and temperature of 5C (0.016 g cm^{-1} sec^{-1}, Sverdrup et al. 1942). Radii of 10 and 5 μ and approximate densities of 1.1 g/cm^3 for organic particles and 2.6 g/cm^3 for inorganic particles were used, and the probable range of sinking rates was computed. The maximum and minimum sinking rates were 12 and 0.14 m/day for the more dense 10-μ particles and less dense 5-μ particles. Arrhenius (1963) gives a sinking rate of 2,900 m in less than 100 years for inorganic particles with diameters greater than 0.5 μ, or greater than 0.08 m/day. Riley et al. (1965) derived a rate of 2 m/day from theoretical considerations of consumption rates of the particles at depth.

Assuming that sinking rates at 2,000 m are probably between 0.1 and 10 m/day for most of the suspended particles, the horizontal movement would be about 2.6 km while sinking 0.1 to 10 m. Thus, their vertical and horizontal distribution must be controlled primarily by advection. The particles must be transported large distances from their point of origin before

TABLE 2. *Seasonal variation of ratios of particulate carbohydrate-carbon to particulate organic carbon in the 250- to 2,000-m and 2,000- to 4,000-m layers**

Date	Particulate carbohydrate-carbon : Particulate organic carbon		
	Southeast	Southwest	Northwest
1965			
Jan	0.16 ± 0.06 (3) 0.18 ± 0.07 (1)	0.19 ± 0.08 (3)	
Apr		0.14 ± 0.04 (5)	0.13 ± 0.04 (5)
	0.14 ± 0.09 (1)	0.13 ± 0.05 (3)	0.14 ± 0.04 (6) 0.14 ± 0.04 (5) 0.14 ± 0.04 (4)
Aug	0.15 ± 0.04 (5) 0.20 ± 0.06 (4)	0.10 ± 0.03 (6) 0.28 ± 0.09 (4)	0.15 ± 0.04 (5) 0.14 ± 0.04 (6)

* The upper number is the mean of observations in the 250- to 2,000-m layer and the lower is the mean of observations in the 2,000- to 4,000-m layer ± the variability at the 95% confidence level; the number of observations is in parentheses.

settling onto the bottom. However, seasonal and vertical variations in particle concentrations can occur. The variations may be the result of differences in production of particles in the euphotic zone and their subsequent sinking and horizontal transport. Jerlov (1959) has described these processes. The observed temporal changes of particulate matter suggest that water with a lower particle content began moving through the area from west to east in April 1965. If the decrease in the concentrations of the particulate matter is assumed to arise from the eastward advection of water with a low particle content, a current speed can be derived that should be about the same as the computed value. At 2,000 m, water was moving eastward at about 3 cm/sec (2.6 km/day) from April 1965 to August 1965. The low concentration appeared in the western region in April and was observed about 450 km to the east approximately 120 days later, giving a current speed of 3.8 km/day. The speeds derived from the independent calculations are in reasonable agreement. Dodimead, Favorite, and Hirano (1963) indicated that the currents shifted in the area from easterly to northerly between summer and winter at 200 and 500 m. Thus, it is postulated that a vernal shift in current direction from northerly to easterly accounts for the temporal variation of the concentrations of particulate matter observed in the northeast Pacific Ocean.

The particle content of water moving offshore or to the north may be increased relative to water moving eastward because of higher primary production in the coastal water (Anderson 1964) and influx of terrestrial particles. However, the primary production of the phytoplankton in the surface water of the study area has little or no immediate effect on the distribution of particles below about 100 m.

This research supports the conclusion that there are vertical variations of the concentrations of particulate matter below the surface layer (Dal Pont and Newell 1963; Holm-Hansen et al. 1966), but this conclusion is not supported by the observations of Menzel and Goering (1966) and Menzel (1967), which indicate a homogeneous distribution of particles. No explanation for this difference is apparent.

No change of the ratios of the variables nor particle size with depth was observed, indicating that the chemical composition of the particles is not altered greatly during the transit below 250 m. Menzel (1964) and Menzel and Goering (1966) drew similar conclusions. This conclusion is supported by ratios of particulate organic nitrogen to particulate organic carbon calculated using data from the literature (Table 3). Most of the ratios were in the range of 0.3 to 0.5, although the samples were taken in the northeast and southwest Pacific and northwest Atlantic Oceans. However, ratios of Holm-Hansen et al.

TABLE 3. *Vertical variations of the ratios of particulate organic nitrogen (N) to particulate organic carbon (POC)**

Area	N : POC	Reference
Northeast Pacific	0.46 (2) 0.32 (1) 0.29 (2) 0.073 (1)	Parsons and Strickland (1962)
Southwest Pacific	0.28 (8) 0.53 (5)	Dal Pont and Newell (1963)
Northwest Atlantic	0.38 (4) 0.40 (2) 0.34 (2) 0.36 (2)	Menzel and Ryther (1964)

* The upper number is the mean of observations in the 250- to 2,000-m layer and the lower is the mean of observations in the 2,000- to 4,000-m layer; the number of observations is in parentheses.

(1966) computed from the analyses of samples collected between 50 and 1,300 m in the subtropical eastern Pacific were lower, ranging between 0.07 and 0.11.

REFERENCES

ANDERSON, G. C. 1964. The seasonal and geographic distribution of primary productivity off the Washington and Oregon coasts. Limnol. Oceanog., **9**: 284–302.

ANTIA, N. J., AND C. Y. LEE. 1963. Studies on the determination and differential analysis of dissolved carbohydrate in seawater. Fisheries Res. Board Can., Manuscript Rept. Ser., No. 168, p. 1–75.

ARRHENIUS, G. 1963. Pelagic sediments, p. 655–727. *In* M. N. Hill [ed.], The sea, v. 3. Interscience, New York and London.

BOGDANOV, YU. A. 1965. Suspended organic matter in the Pacific. Okeanologiya, **5**: 77–85.

DAL PONT, G., AND B. NEWELL. 1963. Suspended organic matter in the Tasman Sea. Australian J. Marine Freshwater Res., **14**: 155–165.

DODIMEAD, A. J., F. FAVORITE, AND T. HIRANO. 1963. Salmon of the North Pacific Ocean. II. Review of the oceanography of the subarctic Pacific region. Bull. Intern. North Pacific Fisheries Comm., **13**: 1–195.

HOLM-HANSEN, O., J. D. H. STRICKLAND, AND P. M. WILLIAMS. 1966. A detailed analysis of biologically important substances in a profile off southern California. Limnol. Oceanog., **11**: 548–561.

JERLOV, N. G. 1959. Maxima in the vertical distribution of particles in the sea. Deep-Sea Res., **5**: 173–184.

KRUMBEIN, W. C., AND F. J. PETTIJOHN. 1938. Manual of sedimentary petrography. Appleton-Century-Crofts, New York. 549 p.

MENZEL, D. W. 1964. The distribution of dissolved organic carbon in the western Indian Ocean. Deep-Sea Res., **11**: 757–766.

———. 1967. Particulate organic carbon in the deep sea. Deep-Sea Res., **14**: 229–238.

———, AND J. J. GOERING. 1966. The distribution of organic detritus in the ocean. Limnol. Oceanog., **11**: 333–337.

———, AND J. H. RYTHER. 1964. The composition of particulate organic matter in the western North Atlantic. Limnol. Oceanog., **9**: 179–186.

MULLIN, M. M. 1965. Size fractionation of particulate organic carbon in the surface waters of the western Indian Ocean. Limnol. Oceanog., **10**: 459–462.

OPPENHEIMER, C. H., E. F. CORCORAN, AND J. VAN ARMEN. 1963. Method for the determination of organic carbon in seawater. Limnol. Oceanog., **8**: 487–488.

PARSONS, T. R., AND J. D. H. STRICKLAND. 1962. Oceanic detritus. Science, **136**: 313–314.

RILEY, G. A., D. VAN HEMERT, AND P. J. WANGERSKY. 1965. Organic aggregates in surface and deep waters of the Sargasso Sea. Limnol. Oceanog., **10**: 354–363.

SCHOLANDER, P. F. 1947. Analyzer for accurate estimation of respiratory gases in one-half cubic centimeter samples. J. Biol. Chem., **167**: 235–250.

SVERDRUP, H. U., M. W. JOHNSON, AND R. H. FLEMING. 1942. The oceans. Prentice-Hall, Englewood Cliffs, New Jersey. 1087 p.