SOME INFLUENCES OF THE COLUMBIA RIVER EFFLUENT ON MARINE PHYTOPLANKTON DURING JANUARY 1961[1]

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ABSTRACT

The distribution of the phytoplankton standing crop along the coasts of Oregon and Washington during January 1961 is described and attempts to evaluate the influences of freshwater runoff on the marine phytoplankton are made.

Marine diatoms and microflagellate concentrations are larger in the Columbia River plume than in the ambient water. Inshore, transition, and offshore species assemblages are present.

Silicate, nitrate, and phosphate concentrations are adequate to support phytoplankton growth in the three areas. Surface stability and critical-to-mixed-depth ratios are much larger in the plume than in the oceanic water. There is a correlation between the critical-to-mixed-depth ratios and the size of the phytoplankton standing crop. It is concluded that the freshwater runoff increases the area in which a neritic diatom flora could exist in winter.

INTRODUCTION

Standing crops of marine phytoplankton are frequently larger in zones where marine and river water mix than in purely marine zones. This feature has been observed in the Gulf of Maine (Bigelow 1924; Gran and Braarud 1935), Mediterranean Sea (Ghazzawi 1939; Halim 1960; Liebman 1940; Oren and Komarovsky 1961; Steuer 1935), and Bering Sea (Semina 1960). Riley (1937) studied the Mississippi River effluent in the Gulf of Mexico and showed that a zone of high chlorophyll content coincided with the plume water. Thomas and Simmons (1960) extended Riley's work, but were unable to show statistically a larger standing crop or photosynthetic rate of phytoplankton in the plume than in the ambient water, although they did not sample far enough from shore to obtain samples uncontaminated by river water (Anderson 1964).

Phytoplankton standing crops may increase in plume waters because of the effects of freshwater on the stability (Gran 1932; Gran and Braarud 1935; Semina 1960) and concentrations of nutrients in the marine water (Halim 1960; Liebman 1940; Riley 1937).

The conclusions of some of the studies are based on enumerations of algal cells concentrated with nets and centrifuges, techniques that are now known to be inadequate for measuring phytoplankton standing crops. Therefore, few quantitative data on the influences of freshwater runoff on standing crops and photosynthetic rates of phytoplankton in the oceans are available.

Workers from the Department of Oceanography, University of Washington, began a series of periodic surveys of the Columbia River effluent in January 1961. Budinger, Coachman, and Barnes (1963) described the physical aspects of the Columbia River plume. Stefánsson and Richards (1963) showed that the river water contained larger concentrations of nitrate and silicate than the ocean water and also increased the concentrations of nutrient salts in the surface water by entraining and mixing deeper water. Anderson (1964) examined the seasonal and geographic distribution of primary productivity and chlorophyll *a* in the plume area from January 1961 to June 1962. He concluded that low concentrations of nutrient salts

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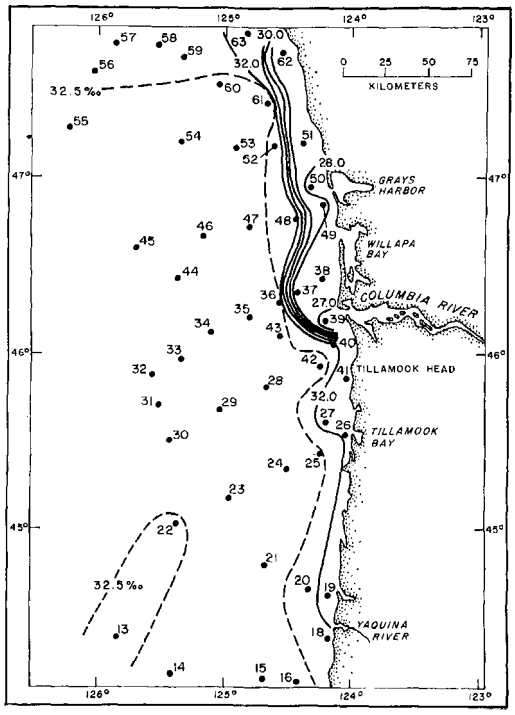

FIG. 1. Index map of *Brown Bear* Cruise 275 and surface salinity; January 1961.

and light intensities limit phytoplankton production in summer and winter, respectively.

Concentrations of chlorophyll *a* were much larger in the plume than in the oceanic water (Anderson 1964, Fig. 2) during January 1961. The object of the present research was to detemine the effects of river runoff on marine phytoplankton by making a detailed examination of the standing crops, species distributions, and photosynthetic rates of phytoplankton in the two areas.

I am indebted to Dr. G. C. Anderson for measurements of simulated *in situ* production, potential productivity (i.e., productivity measured at a constant light intensity), and chlorophyll *a*, and to Dr. F. A. Richards for data on concentrations of nutrient salts and salinity measurements. The work was supported in part by contracts with the Office of Naval Research and the U.S. Atomic Energy Commission (RLO-1725-50) and funds from the University of Washington and Washington State Initiative 171.

METHODS AND MATERIALS

The *RV Brown Bear* occupied 67 stations from 10 to 27 January 1961 (Fig. 1), to ascertain the distribution of the Columbia River plume. The 32.5‰ isopleth of salinity was used as an arbitrary division between ambient and plume water.

Salinity was measured with a conductivity bridge. Silicate, nitrate, and phosphate concentrations were measured using the methods of Mullin and Riley (1955*a*, *b*) and the molybdenum blue method (Barnes 1959), respectively.

The near-surface total sun and sky radiation was measured using a Kipp-Zonen solarimeter and taken from Weather Bureau records for Astoria, Oregon, and Seattle-Tacoma, Washington (U.S. Weather Bureau 1961).

Samples for phytoplankton, chlorophyll *a*, and productivity measurements were drawn from modified Emsworth bottles (Carruthers, Stubbings, and Lawford 1950) placed at selected depths of 100, 50, 10, and 1% of the surface light intensity.

Phytoplankton was preserved with neutralized formalin and Lugol's solution and concentrated by sedimentation. Counts of diatoms, silicoflagellates, and ciliates were made with a 25-ml counting chamber (Dawson 1960) and a Zeiss inverted microscope. Microflagellates were enumerated using a Palmer chamber (Palmer and Maloney 1954) and a compound microscope. Cell volumes and areas were calculated using formulas of volumes and areas of geometrical solids that approximated cell shapes. Weights (of counted forms) were calculated from volumes, assuming a specific gravity of 1.

The variability of phytoplankton standing crops over small distances (ca. 20 m) was examined to make generalizations about differences between measurements at different locations. The variability was estimated by examining numbers of cells collected simultaneously from the same

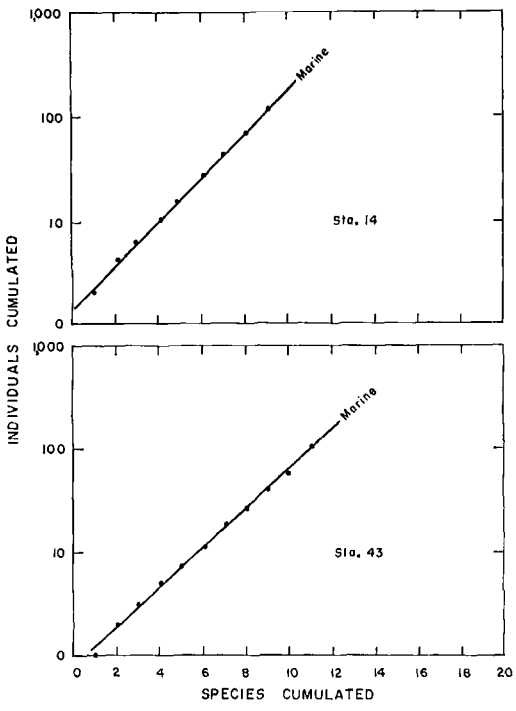

FIG. 2. Species cumulated vs. individuals cumulated.

depth at the stern and bow of the ship. The data were transformed to logarithms and square roots and examined with an analysis of variance model. Standard errors and contour intervals were calculated at the 95% confidence level after the method of Cushing (1953).

Diversity indices were calculated to give an objective description of species assemblages using a logarithmic equation (Odum, Cantlon, and Kornicker 1960):

$$D = (\ln I + C)/S,$$

where D is the diversity index, I is the number of individuals, S is the number of species in the sample, and C is the integration constant. Diatom species cumulated vs. the natural logarithms of individuals cumulated gave straight lines (e.g., Fig. 2) for all stations except one. Even though the indices are based on numbers, whereas the phytoplankton data are given as volumes, they help delineate the limits of the species assemblages of the phytoplankton.

Chlorophyll *a* concentrations were determined using the method of Creitz and Richards (1955) with the equations of Richards with Thompson (1952). A reading at 750 mμ was made and subtracted from readings at all wavelengths to correct for turbidity.

Measurements of simulated *in situ* productivity were made each day from local noon to sunset with the ^{14}C method, using a deck incubator with Wratten neutral density and gelatin filters to simulate energy available to the phytoplankton at the sampled depths. Productivity indices (Strickland 1960) were estimated by illuminating water samples for 3 hr in an incubator with "cool white" fluorescent lights giving an energy flux of about 3 cal cm^{-2} hr^{-1}. All data are reported as per unit of phytoplankton standing crop.

Critical depths were calculated with the equation of Sverdrup (1953):

$$D_{cr} = \bar{I}_e/I_c k,$$

where D_{cr} is the approximate critical depth (m), $\bar{I}_e$ is the "effective" energy passing into the sea during a 24-hr period (cal cm^{-2} hr^{-1}), I_c is the approximate compensation intensity (cal cm^{-2} hr^{-1}, 24-hr mean) of the phytoplankton populations, and k is an approximation of the extinction coefficient (m^{-1}) of the water determined by the relationship:

$$k = 1.7/D,$$

where D is the depth at which a Secchi disc disappears from view. The effective energy ($\bar{I}_e$) of Sverdrup was 0.2 of the total sun and sky radiation; 0.5 of the total radiation was used in this study. An average compensation intensity was calculated from data in the literature (Table 1).

Depths of the surface mixed layer were estimated from stabilities of water columns using the equation (Sverdrup, Johnson, and Fleming 1942):

$$E' = 10^{-3}\, d\sigma t\, dz^{-1},$$

where E' is a measure of the stability in the upper 100 m. Stability was considered positive when E' exceeded $10^{-4}\, dz^{-1}$ (Strickland 1960).

TABLE 1. *Compensation intensities (24-hr means) from various studies*

Compensation intensity	General information
0.087 cal cm^{-2} hr^{-1}*	Cultures of *Coscinodiscus excentricus* suspended in English Channel; Jenkin (1937). [Corrected by Anderson and Banse (1963)]
0.14	Mixed population with zooplankton; Pettersson, Hoglund, and Landberg (1934)
0.18	Revision of 0.14 value; Pettersson (1938)
0.42	Cultures from lakes; Schomer and Juday (1935)
$\bar{x}$ = 0.21 cal cm^{-2} hr^{-1}	From Strickland (1958)

* Jenkin measured the compensation depth of a *C. excentricus* culture in an experiment of about 24 hr. The light intensity at that depth was about 9 joules. Therefore, the 24-hr mean compensation intensity is about 2.09 cal cm^{-2} (24 hr)$^{-1}$ or 0.087 cal cm^{-2} hr^{-1}.

RESULTS

Salinities were low in the river mouth, increasing to the north along the coast with horizontal gradients paralleling the shore (Fig. 1). Vertical distributions of salinity, temperature, and density (Fig. 3) were representative of offshore water, indifferently stable to about 80 m, and there was an inshore area with a large decrease of the density of the surface water due to influx of river water.

Nitrate and phosphate concentrations in the euphotic zone were uniform at 5–8 and 0.3–1 μg-at./liter, respectively, in the sampled area, while silicate concentrations increased from less than 10 to greater than 30 μg-at./liter from offshore to areas

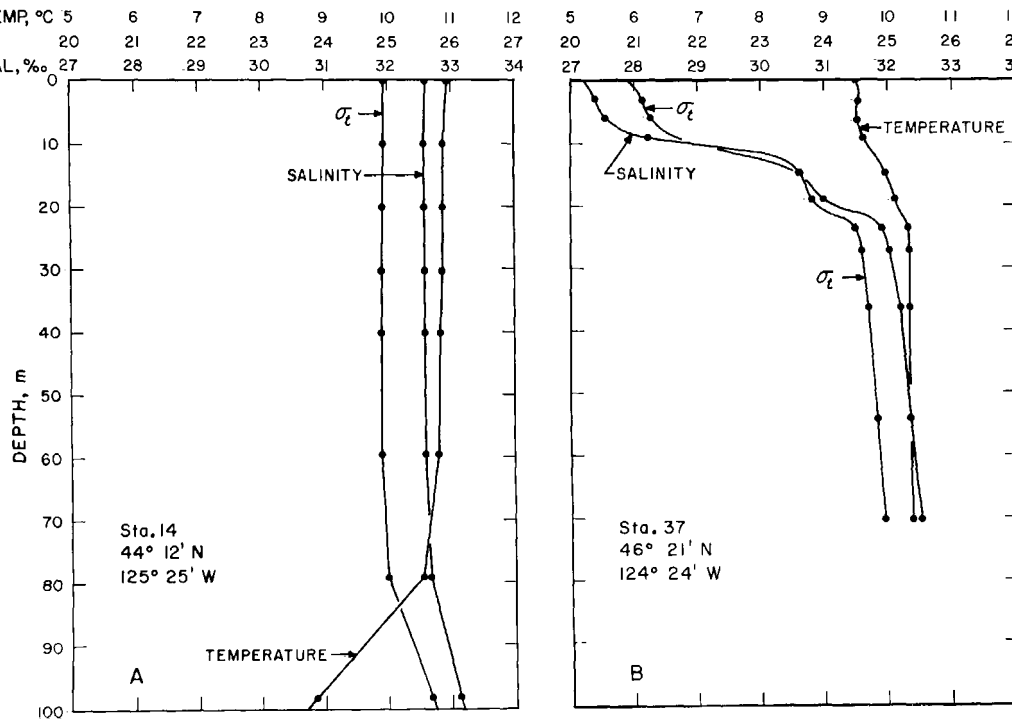

FIG. 3. Vertical distribution of temperature, salinity, and sigma-*t*. A) Offshore. B) Inshore, just off river mouth.

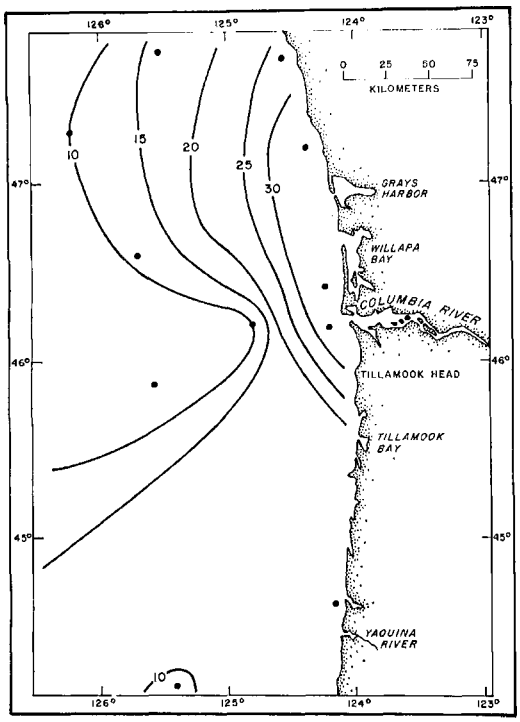

FIG. 4. Inorganic dissolved silicate (μg-at./liter), average over four light depths.

influenced by the plume water (Fig. 4).

The average surface light intensity increased during the cruise from about 36 to 165 cal cm^{-2} day^{-1} and was probably uniform over the sampling area (Fig. 5).

Standing crops of marine diatoms (including silicoflagellates) were equal to or less than 3 mg/m^3 (mean of four light depths in the euphotic zone) at offshore stations, increasing to 10–35 mg/m^3 in coastal water, and to about 40 mg/m^3 off the mouth of Grays Harbor (Fig. 6). Diatoms were homogeneously distributed with depth at all stations in the ambient water, but their distribution varied in the plume water. Freshwater diatoms were present in small numbers from the mouth of the Columbia River to the north along the coast. Diversity indices indicated the presence of three species assemblages (Fig. 7, Table 2): 1) an offshore group; 2) an inshore group in water of reduced salinity and also containing small volumes of the freshwater diatoms, *Fragilaria capucina* Desmazieres, *F. crotonensis* Kitton, *Melosira granulata* (Ehrbg.) Ralfs, and

TABLE 2. *Diatom species and average volume (1×10^{-8} μ^3/m^3) in three species assemblages*

Inshore stations:	20	37	38	39	40	49	50	51	62
Biddulphia aurita	0	*T**	25	4	0	24	33	120	0
Bacteriastrum hyalinum	*T*	3	13	*T*	4	*T*	*T*	*T*	12
Chaetoceros sp.	52	74	70	71	76	55	93	91	96
Coscinodiscus marginatus	0	*T*	*T*	12	*T*	*T*	*T*	*T*	*T*
Distephanus speculum	27	24	30	17	38	35	59	63	10
Nitzschia delicatissima	*T*	*T*	*T*	*T*	2	*T*	14	*T*	*T*
Pennates	18	5	28	10	4	14	26	5	12
Thalassionema nitzschioides	6	20	13	4	5	7	12	29	50
Thalassiosira decipiens	0	16	96	160	*T*	42	140	*T*	*T*
Offshore stations:	14	24	35	42	43				
Chaetoceros concavicornis	0	6	*T*	*T*	*T*				
Coscinodiscus marginatus	0	*T*	*T*	*T*	*T*				
Distephanus speculum	24	16	18	52	14				
Nitzschia delicatissima	1	*T*	1	1	*T*				
Pennates	0	*T*	3	1	*T*				
Thalassionema nitzschioides	3	4	*T*	1	2				
Transition stations:	36	44	52	63					
Chaetoceros concavicornis	*T*	*T*	*T*	*T*					
Chaetoceros sp.	3	0	0	53					
Distephanus speculum	15	10	20	30					
Nitzschia delicatissima	1	3	*T*	3					
Pennates	*T*	22	5	15					
Thalassionema nitzschioides	2	*T*	10	32					

* $1 \times 10^{-8} > T > 0$ μ^3/m^3.

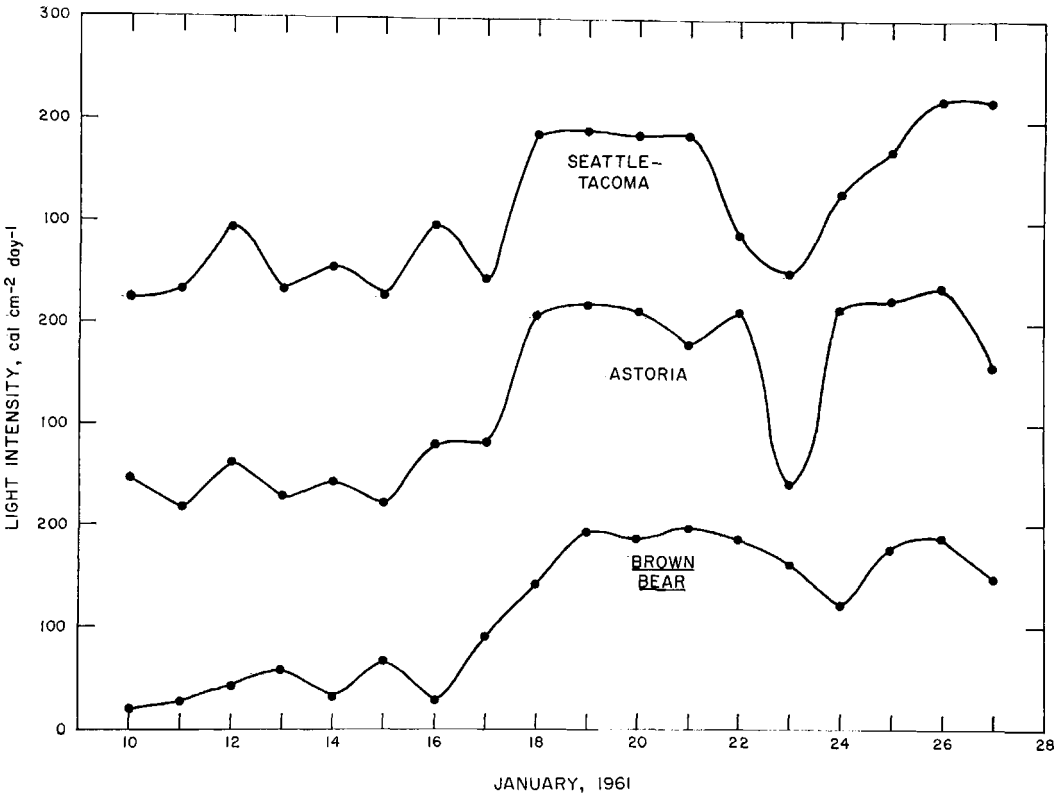

FIG. 5. Daily radiation as monitored by the *Brown Bear*, Astoria, Oregon, and Seattle-Tacoma, Washington, during January 1961.

Asterionella kariana Grunow; and 3) a transitional group between the offshore and inshore groups, closely related to the offshore assemblage.

Determinations of flagellate numbers and volumes were difficult and variabilities were large. Spatial and vertical distributions were considered homogeneous at 40 ± 30 mg/m^3 except north of Grays Harbor, where the biomass was greater than 70 mg/m^3—much larger than the biomass of diatoms.

Small numbers of ciliates (ca. 1×10^6 cells/m^3) were present at each station.

The relationship between phytoplankton standing stock and chlorophyll *a* was examined to determine the validity of using chlorophyll *a* as a measure of standing stock. Cell volume and area were plotted against chlorophyll *a* (Figs. 8 and 9) and regression analyses carried out showing correlation coefficients of 0.85 and 0.57 (valid at the 95% level), respectively. The relationship

$$Y = b + mx,$$

where Y is the chlorophyll *a* concentration (mg/m^3), x is the cell volume (μ^3/m^3), and b and m are constants of 0.14 mg/m^3 and 0.065×10^{-10} mg/μ^3, respectively, was used to convert chlorophyll *a* to cell volume, even though the relationship probably is not constant for different seasons or over large areas. The positive constant b is not a result of dead chlorophyll (Anderson 1964) but probably is a reflection of inadequate preservation of the phytoplankton samples.

Eight measurements of simulated *in situ* productivity were made during the

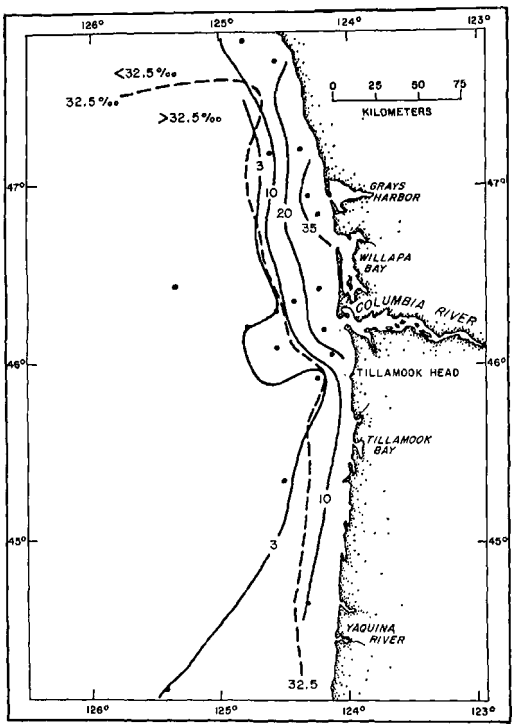

FIG. 6. Marine diatoms (mg/m³), average over four light depths, and 32.5‰ salinity isopleth.

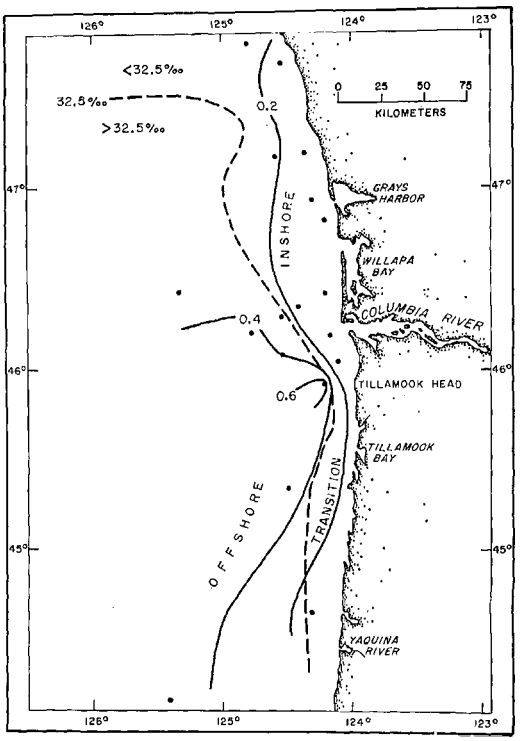

FIG. 7. Diversity indices and boundaries of the three species assemblages, and 32.5‰ salinity isopleth.

study. Only two stations (20 and 50) were from the inshore community (Table 3). Productivity, as mg C(mg chlorophyll *a*)$^{-1}$(light day)$^{-1}$, varied little from 2.6 to 6.7. Productivity indices were calculated to assess any potential differences of the phytoplankton in the area. High indices occurred just off Grays Harbor and low indices were found just south of the Columbia River mouth but were otherwise uniform over most of the area (Fig. 10).

Critical-to-mixed-depth ratios were larger than unity at all stations and larger shoreward of the 32.5‰ salinity isopleth than offshore (Fig. 11).

DISCUSSION AND CONCLUSIONS

The size of the standing crop of phytoplankton per unit volume in any area at any time is a function of grazing by zooplankton; cells sinking out of the euphotic zone; respiratory, excretory, and photosynthetic rates; and stability of the water column. Grazing rates of zooplankton and sinking rates of phytoplankton cells are difficult to measure and were not studied. The respiratory, excretory, and photosyn-

TABLE 3. *Daily simulated* in situ *production* [*mg C m*$^{-3}$*(light day)*$^{-1}$***] *(CP) and carbon assimilation per unit standing crop* [*mg C(mg Chl* a)$^{-1}$ *(light day)*$^{-1}$] *(CA)*

Station	CP	CA
14	62	5.2
20	36	3.0
24	47	2.6
30	80	6.7
35	60	3.3
44	83	4.6
50	26	3.2
55	105	4.2

* Light day is defined as the time interval between sunrise and sunset.

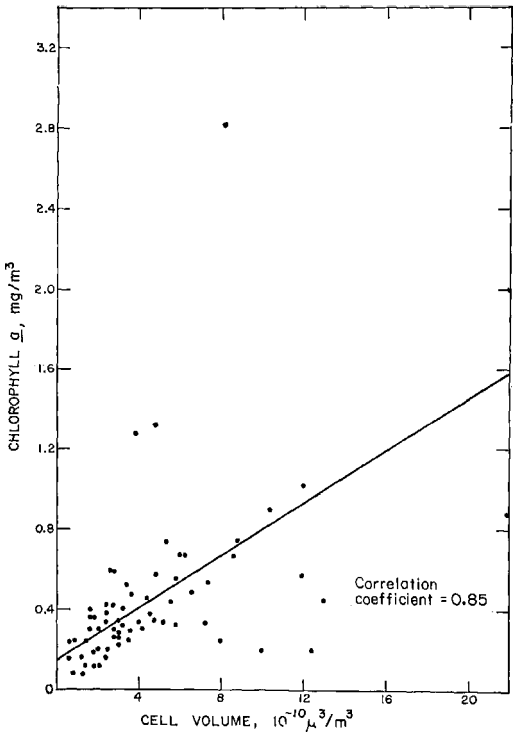

FIG. 8. Cell volume (μ^3/m^3) vs. chlorophyll *a* (mg/m^3).

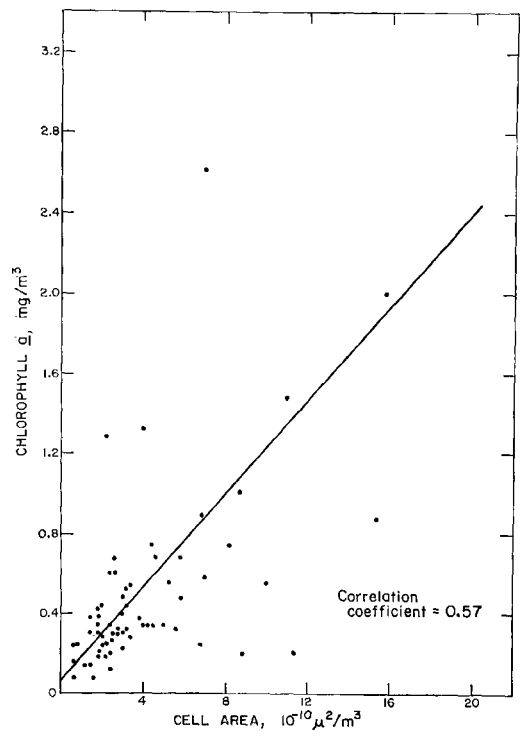

FIG. 9. Cell area (μ^2/m^3) vs. chlorophyll *a* (mg/m^3).

thetic rates of a phytoplankton crop are mainly functions of nutrient concentration, species composition, and subsurface light intensity.

Respiratory and excretory rates were not measured. But potential productivity measurements may determine approximately the organic material produced and retained by phytoplankton because the ^{14}C technique was used (Antia et al. 1963; McAllister et al. 1961). That is, the amount of carbon retained by the phytoplankton was about equal over the entire area.

Phosphate, nitrate, and silicate were present and probably not limiting to phytoplankton growth. The species composition of the diatoms varied in the area. *C. concavicornis* was the only diatom found exclusively in the offshore area and is known to be an oceanic, Arctic form (Cupp 1943). Small volumes of the neritic forms, *N. delicatissima* and *C. marginatus* (Cupp 1943), and large volumes of the ubiquitous silicoflagellate *D. speculum* were found in the three areas. *T. nitzschioides*, a pelagic coastal form (Cupp 1943; Hustedt 1930) was observed in the three areas, but large volumes occurred only in the inshore area. Large volumes of *Chaetoceros* sp. were found in the inshore area and occasionally in the transitional area. *B. hyalinum*, *T. decipiens*, and *B. aurita*, a neritic form sometimes found in estuaries (Hustedt 1930), a coastal north temperate form, and a littoral, coastal form (Cupp 1943; Hustedt 1930), respectively, occurred exclusively in the inshore area. The species composition of the microflagellates could not be determined. Measurements of potential productivity indicate that there was little difference in the photosynthetic rates of the phytoplankton of the three species

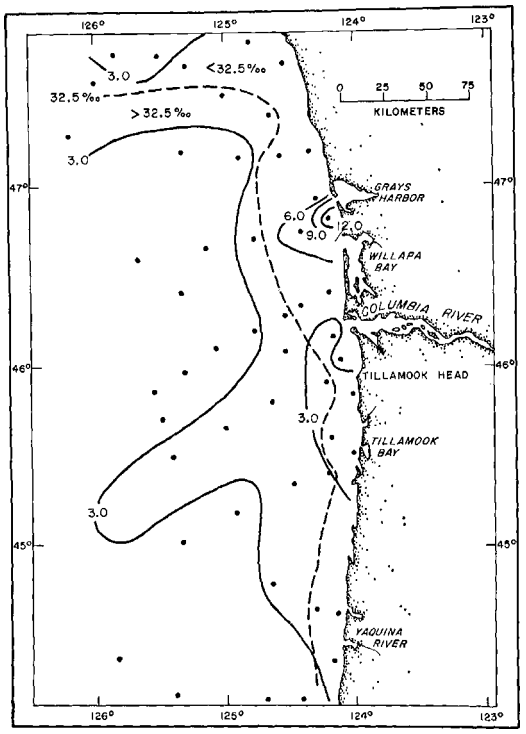

FIG. 10. Productivity index [mg C(mg Chl a)$^{-1}$ at 3.0 cal cm^{-2} hr^{-1}], average over four light depths, and 32.5‰ salinity isopleth.

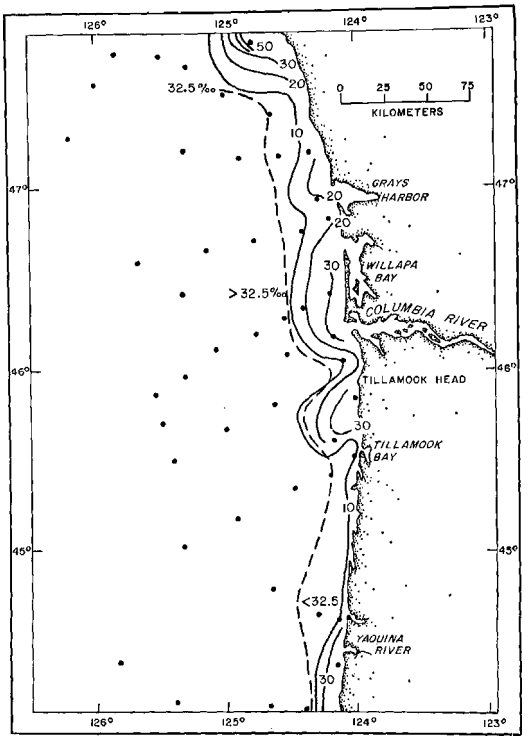

FIG. 11. Critical-to-mixed-depth ratios and 32.5‰ salinity isopleth.

assemblages. Samples taken in the Grays Harbor area had larger standing crops of phytoplankton and higher potential productivities than did other inshore areas where the same species were present. Phytoplankton productivity in other areas may have been limited by the absence of some unknown factor produced in the Grays Harbor region. Thus, the size of the phytoplankton crop would be expected to be related to the subsurface light intensity, which was greater offshore than inshore because of the turbidity of inshore water (apparently arising from large numbers of detrital particles in the river water). However, the largest standing crops were in the inshore area, possibly due to the greater stability of the surface water.

Salinity and temperature measurements indicated that in the oceanic area surface water was mixed to 60–80 m, and in coastal areas influenced by freshwater the density of the surface water was low, increasing the stability of the water column. Ratios of critical-to-mixed-depth take into account effects of photosynthesis and stability on the phytoplankton standing crop. Sverdrup (1953) assumed, in deriving the equation for critical depth, that the extinction coefficient of the water column is constant with depth and production is proportional to light intensity. Extinction coefficients of offshore water tend to be relatively constant with depth (Sverdrup et al. 1942); however, the inshore transparencies may have been a function of depth. The turbid water of the river effluent overlay more saline water and the transparency of the water column probably increased with depth. Thus, the critical depth would be underestimated at inshore stations. Simulated *in situ* production was proportional to light intensity at most stations, but inhibition of photo-

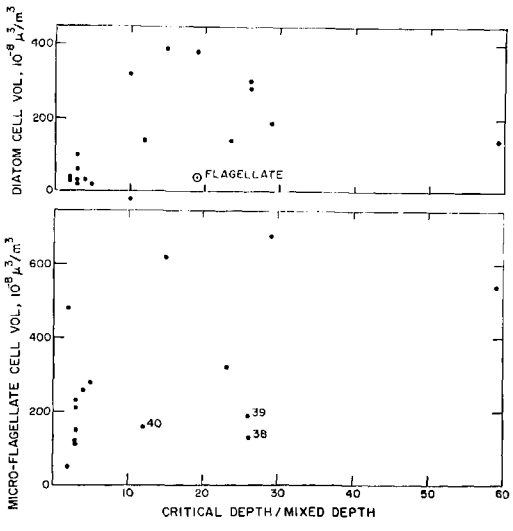

FIG. 12. Critical-to-mixed-depth ratios vs. microflagellate and diatom cell volume.

synthesis occasionally occurred, giving an overestimation of the critical depth. Also, critical depth varies with incident light intensity, and data taken on different days may vary over a wide range. The critical depth concept can be used to give an approximation of changes of phytoplankton standing crop, even though some of the assumptions may not be completely justified.

The ratios of critical-to-mixed-depth were compared with diatom and microflagellate standing crops (Fig. 12). In general, the larger standing crops occurred at stations where ratios were large (i.e., at stations in the plume water). Two low microflagellate concentrations were observed at stations 38 and 39, just off the Columbia River mouth. The observation may have been the result of technical errors or of inhibition of microflagellate photosynthesis by the freshwater.

The depth of the mixed layer was negligible and the critical-to-mixed-depth ratio was large at stations in plume water. Thus, the phytoplankton standing crop would have increased at depths less than the 24-hr compensation depth at a rate dependent on the subsurface light intensity. The daily variation of light intensity and sinking of the phytoplankton may explain non-uniform vertical distributions of the crop at the inshore stations. The mixed layer was deep and the critical-to-mixed-depth ratio was slightly greater than unity at stations in the ambient water. Thus, phytoplankton populations would have been increasing in the mixed zone, although at much slower rates than in the plume water.

Therefore, a consideration of critical- and mixed-layer depths seems adequate to explain the observed standing crop distributions. The larger area of the inshore species assemblages north of the river mouth demonstrates the increase in the area of the neritic environment by freshwater runoff. Turbidity of the freshwater may have decreased light penetration sufficiently to keep the total standing crop of phytoplankton smaller than would have been the case in a similar situation with more transparent water.

In conclusion, it appears that, in winter, river runoff increases the stability of seawater in its area of influence and provides an environment in which marine phytoplankton can accumulate and in which diatoms that would not be present otherwise can exist.

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