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Particle (Plankton) Size Structure Across the Azores Front (Joint Global Ocean Flux Study North Atlantic Bloom Experiment)

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The horizontal distributions of particle size spectrum and chlorophyll *a* concentration across the northern edge of the North Atlantic subtropical gyre along 21°W were studied as part of the Joint Global Ocean Flux Study North Atlantic Bloom Experiment in March–April, 1989. An abrupt change in the particle size spectrum at 32°40′N was located within the broad thermohaline front between the central gyre water in the south and the Azores Current in the north. Whereas the small particulate fraction (1–10 μm) and chlorophyll *a* concentration were similar (within a factor of 2), the abundance of the "diatom" size fraction (28–72 μm) showed a drastic increase by more than an order of magnitude in the Azores Current. The diatom fraction seemed to contribute little to the chlorophyll pool, indicating a postbloom condition. Different trophic pathways, i.e., grazing of the picoplankton in the gyre versus the diatom bloom with the following detrital loop in the Azores Current and northward, can be conjectured. The increased scattering versus absorption due to the different particle size spectrum and composition could bias the algorithms of pigment retrieval from remote sensing data.

1. INTRODUCTION

The overall objective of the Joint Global Ocean Flux Study (JGOFS) Pilot Study, the North Atlantic Bloom Experiment, was to study aspects of the carbon cycling and related biochemical cycles with reference to the evolution of the spring phytoplankton bloom and its northward passage along 20°W in the eastern North Atlantic. R/V *Meteor* cruise 10-1 was organized by Institut für Meereskunde, Kiel, as part of the Pilot study. The two principal study areas were situated at about 18°N, 30°W and 34°N, 21°W. Underway transects at the areas as well as in between the two areas provided a highly resolved large-scale distribution pattern of planktonic particles in the eastern part of the North Atlantic subtropical gyre (NASG). NASG is bounded by the Azores Current and the related subtropical front from the north and by the North Equatorial Current from the south [*Stramma and Siedler*, 1988].

A drastic change in the size structure of the planktonic particle assemblage but not so much in the overall chlorophyll concentration marked the boundary between the central gyre water and the Azores Current water. It is conjectured that the different particle size structure indicates different trophic pathways in the gyre and the Azores Current.

It is pointed out that the modified scattering and absorption characteristics resulting from shifts in the quality and quantity of particles may effect the accuracy of the remote sensing algorithms of pigment retrieval [e.g., *Campbell*, 1989].

2. METHODS

Particle concentrations and chlorophyll *a* fluorescence were measured in two sampling modes: horizontal quasi-continuous transects were obtained when the ship was underway; vertical data were obtained from water samples from three discrete depths (5–10 m, the chlorophyll maximum depth at 40–70 m, 100 m).

On the underway transects the seawater intake was at a depth of about 3 m and the sampling interval was set at 1 min. Depending on the ship's speed, the spatial interval varied between 200 and 400 m. The water temperature and salinity were recorded on-track by the ship's thermosalinograph.

Hiac-Royco PC-320 particle size analyzer [*Pugh*, 1978; *Kahru and Nômmann*, 1990] with two sensors (CMH-60 and E-1000) registered particles with the equivalent spherical diameter from 1 to 1000 μm in 12 channels (Table 1). The sensors operate on the principle of light blockage. The counting time was 10 s during which, 1 cm^3 and 170 cm^3 of seawater, respectively, passed through the two sensors. Concentrations in the channels (size classes) are designated as Ch1 to Ch12. Counts in the top channels (Ch6, Ch12) of the both sensors were unreliable due to the relatively small volume sampled. Ch6 was totally discarded as it was mostly covered by Ch7 and Ch8 of the big sensor. As a measure of the relative importance of a size fraction, the percent contribution of a size fraction to the total particulate surface area (in the 1–1000 μm range) is used. The use of surface areas instead of the more commonly used particulate volumes is substantiated by the principle of the counter which explicitly measures projection areas and not volume (contrary to the Coulter counter) and by the known physiological principle [*Platt and Denman*, 1978] according to which the activity of organisms is generally linearly related to the surface area and not to the volume or mass. The total particulate surface (TPS) area in the range 1–1000 μm was calculated by multiplying the channel counts by the respective mean area and integrating over the size range.

In vivo fluorescence of the chlorophyll pigments was

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TABLE 1. Particle Size Classes Measured With the Hiac-Royco Particle Counter PC-320

Channel	Size Range, µm
CMH-60	
1	1–2
2	2–4
3	4–6
4	6–10
5	10–20
6	20–60
E-1000	
7	28–42
8	42–73
9	73–105
10	105–163
11	163–305
12	305–1000

measured with a Turner Designs 10-005R flow-through fluorometer and calibrated against extracted samples of chlorophyll *a* ($r = 0.87$, $n = 20$, $p < 0.001$). The extracted chlorophyll values spanned from 0.1 to 0.8 µg/L, including frontal areas, but the number of samples was too small for detecting shifts in the fluorescence/chlorophyll ratio.

Standard time series methods (e.g., spectral analysis, autocorrelation and cross-correlation) are not applicable to the nonstationary spatial series indented with individual fronts as acquired from our horizontal transects. A characteristic feature of these spatial series is the alternation of the sign of correlation between different series over space, i.e., subsections of positive correlation alternate with sections of negative correlation. To delineate subsections with consistent relations between the series, running correlation coefficients were calculated between two series over shorter, overlapping subsections of 30 sample pairs equivalent to a distance of ≈9 km. The calculated "moving" or "running" correlation coefficient is analogous to the moving average.

3. RESULTS

Figure 1 shows the results of a transect along 21°W across the subtropical gyre into the Azores Current in the north. While both temperature and salinity showed a more-or-less gradual decrease in a series of thermohaline fronts and the chlorophyll *a* showed a large-scale increase toward the north, the 28–73 µm size fraction (Ch7, Ch8) increased drastically north of 32°30′N forming a "particle front" (Figure 2). The 28–73 µm fraction, usually corresponding to diatoms, was on a very low level in the whole gyre area (a slight increase occurred between 30° and 31°N). The increase across the front was by a factor of 20 in a series of two bands of ≈30 km. The frontal area with the two bands of the maximal 28–73 µm fraction corresponded to minima of the chlorophyll *a* and the 1–10 µm fraction. The percent contributions of the different size fractions to the total particulate surface area changed drastically across the particle front (Figure 2). The highly indented form of the particle front was probably caused by frontal jets and meanders as shown by a high correlation with the surface temperature (Figure 3, left). The correlation was not homogeneous over the whole transect as sections with positive correlation were intermitted with sections with negative correlation. In the particle front at 32.6°N, the correlation with temperature had opposite sign for the 28–73 µm and 1–10 µm fractions, respectively (Figure 3, lower left). The relationships with the chlorophyll (Figure 3, right) showed that the 28–73 µm fraction was mostly negatively correlated with chlorophyll (especially in the particle front), while the 1–10 µm fraction was mostly positively correlated. Only one channel of the both size fractions is shown on Figure 3.

Principally the same pattern was observed when crossing the front twice 12 and 13 days later. The latitude of the particle front (32°40′ at 21°24′W) had remained stationary (Figure 4). The highest concentrations of the 28–73 µm fraction were located in a broad band adjacent to the sharp particle front and were bounded by smaller thermohaline

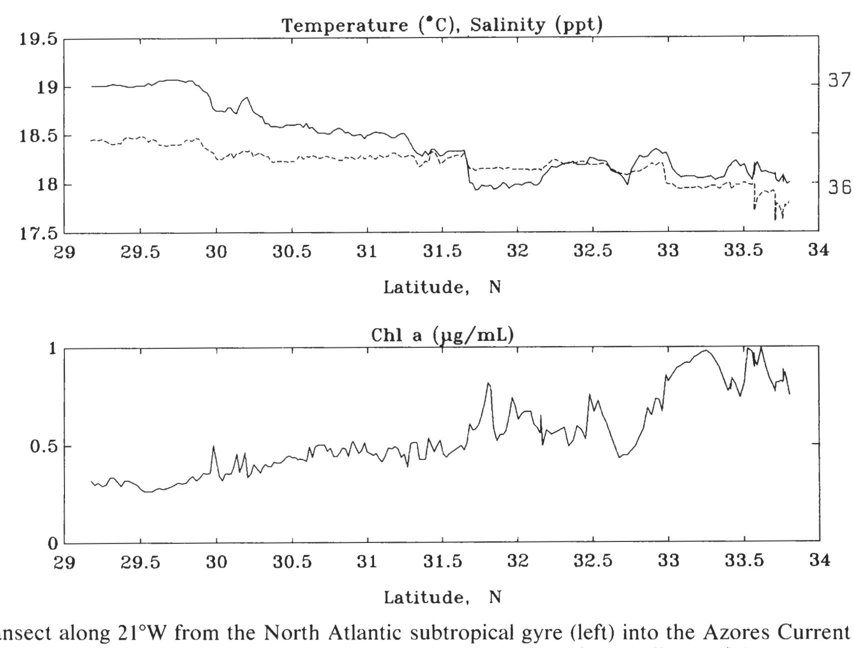

Fig. 1. Transect along 21°W from the North Atlantic subtropical gyre (left) into the Azores Current (right) on April 11–12, 1989. Temperature, salinity (dashed), chlorophyll *a* (µg/L).

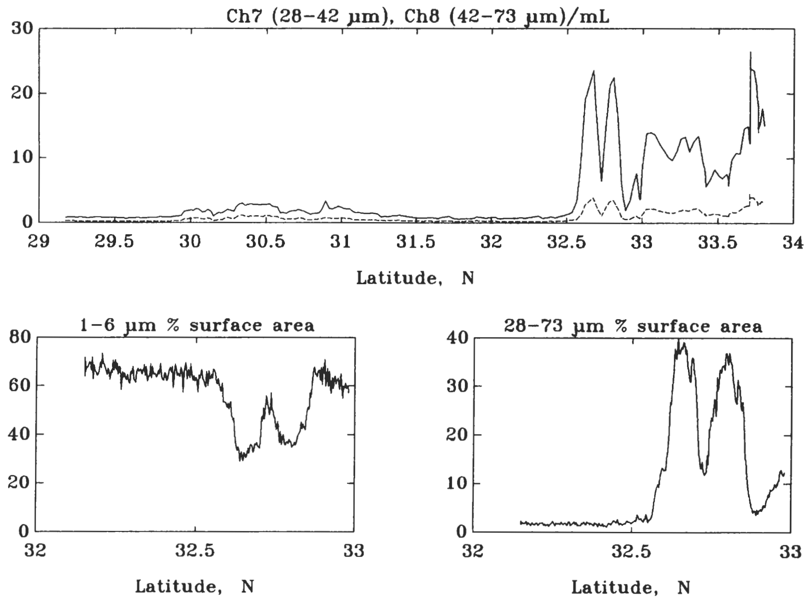

Fig. 2. As Figure 1. Concentrations of particles in the 28–42 μm and 42–73 μm (dashed) fractions (mL^{-1}); percent contributions of the 1–6 μm and 28–73 μm fractions to the total particulate surface area in the area of the particle front.

fronts. The order-of-magnitude higher concentrations continued at a slightly lower level northward in the Azores Current. In contrast, the small particulate fraction (1–10 μm) and the chlorophyll *a* concentration changed only by a factor of 2 across the front (Figure 5). The shift in the planktonic size structure is shown by the changing percent contributions of the different size fractions (Figure 5, bottom). In the gyre, 50–70% of the total particulate surface area in the 1–1000 μm range was made up solely by the 1–6 μm size fraction. The contribution of the 28–73 μm fraction increased from 2–10% in the gyre up to 40% in the Azores front area.

On all of the transects (mostly not shown) the horizontal variability in the gyre water (south of 32.5°N) was lower than in the Azores Current. The smaller particle size fractions were especially homogeneous in space (coefficient of variation, CV = 100 * SD/mean, 8–16% for Ch1, 10–20% for Ch2, 13–23% for Ch3), while the 28–73 μm fraction fluctuated at a very low mean level (CV 18–30% for Ch7 and Ch8). North of the particle front, the variability of the 1–10 μm fraction remained low (being only insignificantly higher), whereas the variability of the 28–73 μm fraction increased sharply together with their mean values (CV 47–74% for Ch7 and Ch8).

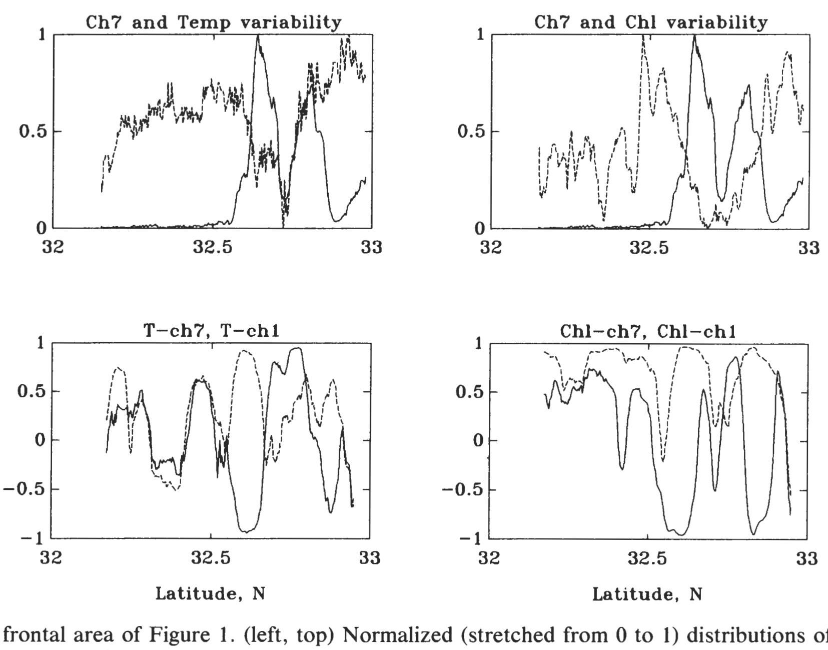

Fig. 3. The frontal area of Figure 1. (left, top) Normalized (stretched from 0 to 1) distributions of the 28–42 μm fraction and temperature (dashed); (left, bottom) "moving" correlation coefficient, *r*, over 30 adjacent points ($\approx$9 km) between temperature and 28–42 μm and 1–2 μm (dashed) fraction, respectively; (right, top) Normalized distributions of the 28–42 μm fraction and chlorophyll *a* (dashed); (right, bottom) moving correlation coefficient between chlorophyll and the 28–42 μm and 1–2 μm (dashed) fraction, respectively. The levels of significance for *r* are ± 0.36 ($p < 0.05$) and ± 0.48 ($p < 0.01$).

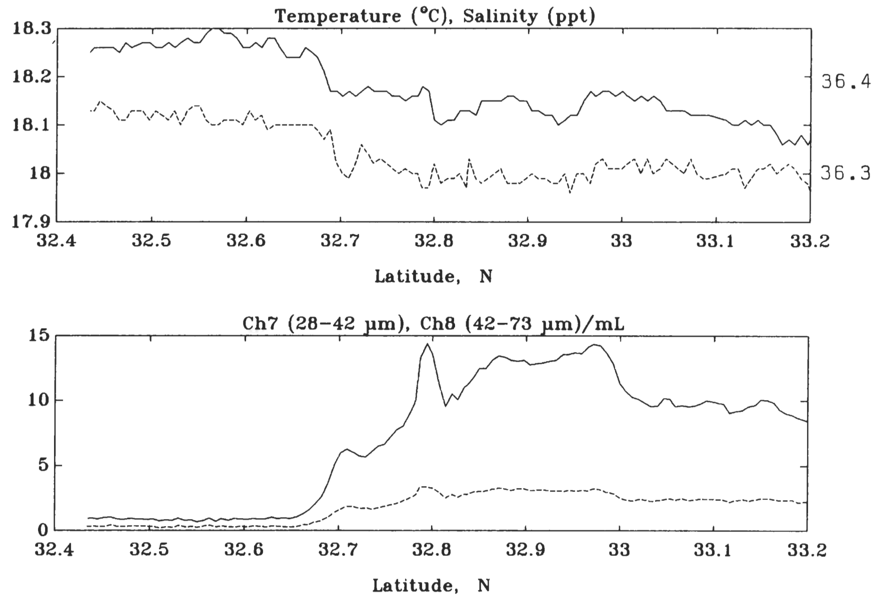

Fig. 4. Transect along 21°W across the boundary between the central gyre water (left) and the Azores Current (right) on April 24, 1989. Temperature, salinity (dashed), concentrations of particles in the 28–42 μm and 42–73 μm (dashed) fractions (mL^{-1}).

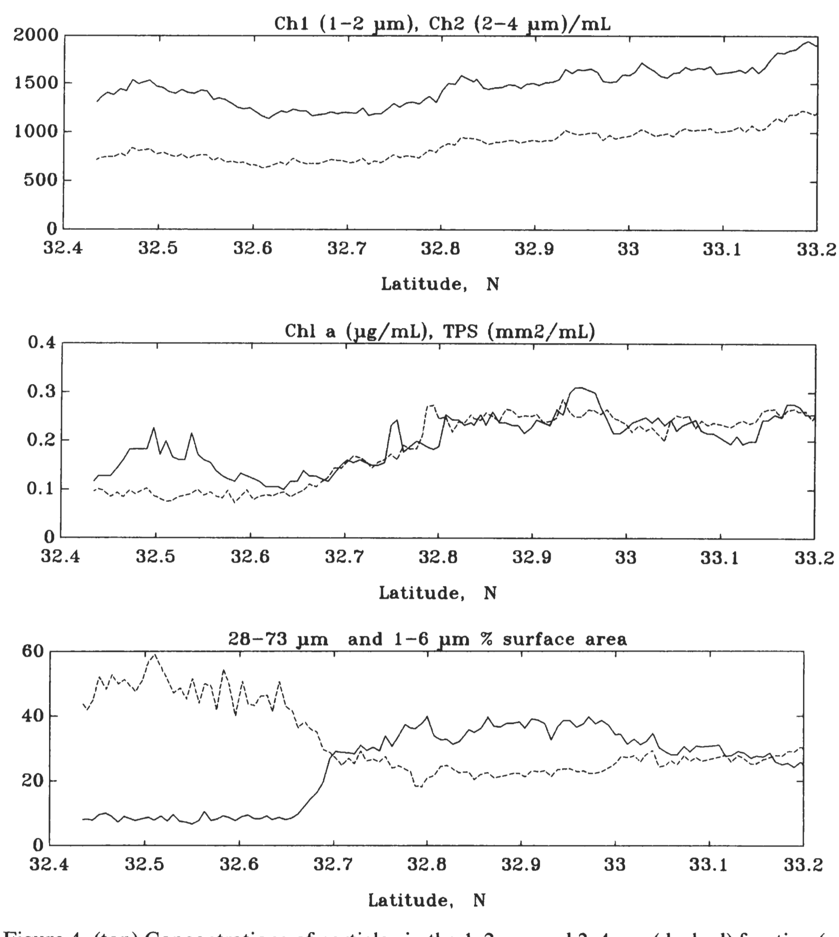

Fig. 5. As Figure 4. (top) Concentrations of particles in the 1–2 μm and 2–4 μm (dashed) fraction (mL^{-1}); (middle) chlorophyll *a* (μg/L) and the total particulate surface area (TPS, dashed) (mm^2/mL); (bottom) percent contributions of the 28–42 μm and 1–6 μm (dashed) fractions to the total particulate surface area.

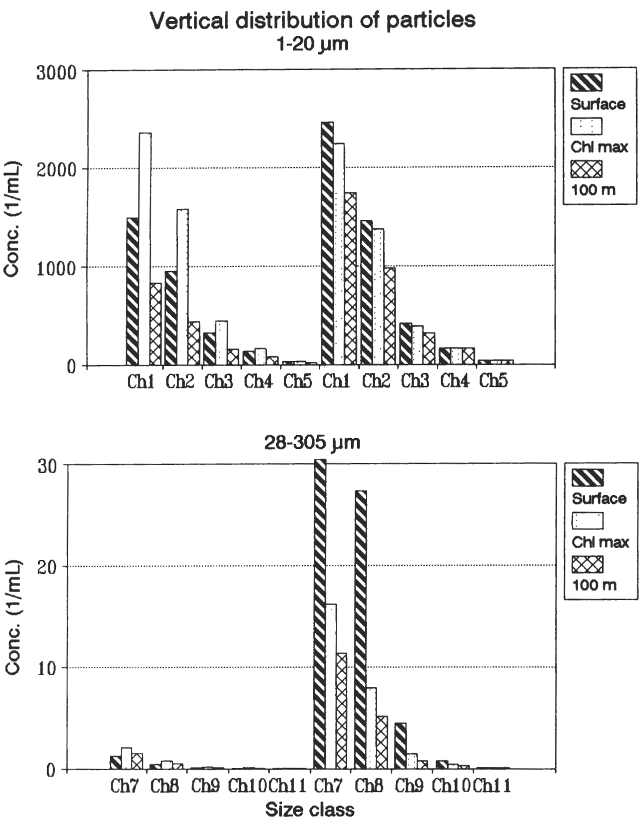

Fig. 6. Distribution of particles at three depths in the gyre water (left, station 268, 18°30′N; 30°0′W, April 1) as compared to the Azores Current (right, station 362, 33°54′N; 21°01′W, April 16) for (top) the small particulate fraction and (bottom) the large particulate fraction.

Microscopical examination of freshwater samples showed that diatoms were dominant in the 28–73 μm size fraction, but no direct calibrations were performed. Samples analyzed by epifluorescence microscopy by T. Weisse (personal communication, 1989) showed that the 1–2 μm fraction was dominated by heterotrophic nanoflagellates and also contained cyanobacteria, autotrophic eukaryotic cells, and very large bacteria. The size range 2–10 μm mostly contained autotrophic algae. As shown by flow cytometry (P. Burkill, personal communication, 1989), a significant fraction of the chlorophyll pool was contained in cells smaller than 1 μm and therefore not covered by our particle counter.

On most of the transects, chlorophyll *a* had significant positive correlation with the 1–10 μm fraction and negative or no significant correlation with the "diatom" size fraction. In no case, was the sharp increase in the diatom fraction matched with a reciprocal increase in the chlorophyll *a*. We can therefore conclude that the contribution of the diatom fraction to the chlorophyll pool was insignificant.

The vertical data collected in the study areas in the gyre (near the North Equatorial Current) and the Azores Current support the idea of a particle front in between them. A comparison of two characteristic stations in Figure 6 shows that whereas the concentrations in the 1–20 μm fractions were not very different, the increase in the 28–305 μm fractions in the Azores Current area was more than an order of magnitude. The increase was especially conspicuous in the surface layer (>20-fold).

At least at some of the gyre stations, the deep chlorophyll maximum clearly corresponded to the maxima in all the particle size ranges (Figure 6, left), whereas in the Azores Current the chlorophyll maximum could not be associated with a particle maximum. Instead, maxima in all the size fractions were in the surface water. The very high numbers of the bigger particles in the surface layer did not produce a respective increase in the chlorophyll concentration that had its maximum at about 50 m.

4. Discussion

The spatially highly resolved measurements in the North Atlantic subtropical gyre and in its northern boundary, the Azores Current, along 21°W revealed a distinct difference in the size structure of the planktonic community. South of 32°30′N all the distributions were extremely homogeneous and the planktonic community was dominated by the smallest size fraction (50–70% of the particulate surface area in the 1–1000μm range due to the 1–6 μm fraction). Horizontal homogeneity in subtropical gyres has been noted by several authors [*Hayward et al.*, 1983; *Odate and Maita*, 1988/1989]. North of a very sharp particle front in the Azores Front, the size fraction corresponding to diatom cells and chains increased sharply in dominance. Intense horizontal heterogeneity was observed, particularly in the larger size fraction.

The decrease in the chlorophyll *a* concentration in narrow areas of the maximum concentration of the diatom size fraction (Figure 3) suggests that they probably contained a water mass in the declining stage of the diatom bloom, advected by frontal jet currents. The whole Azores Current area was probably in a postbloom stage with the concentrations of the diatom fraction an order of magnitude higher than in the gyre water. The decline of a diatom bloom usually results in a large number of cells in poor physiological condition, decreasing chlorophyll content, and increasing detritus levels [e.g., *Kahru and Nõmmann*, 1990]. Therefore the drastic increase in the concentration of the diatom fraction did not produce a respective increase in the chlorophyll concentration, indicating a small percent contribution of the larger diatoms to the chlorophyll pool. The chlorophyll content and other parameters can be measured individually for each particle by flow cytometry, but the measured volume (0.377 cm^3) was too small to get reliable results on the diatom size fraction.

The vertical data confirmed the existence of the surface layer with a high particle concentration in the 28–73 μm range in the Azores Current. There the particle concentrations decreased with depth, and the discrepancy between the particle maximum near the surface and the chlorophyll maximum at 40–70 m indicated that the near-surface particles were low in the chlorophyll content. We can therefore conclude that the quality of the particulate matter was drastically different both horizontally and vertically. Our measurements at the depth of the deep chlorophyll maximum were not sufficient to resolve its horizontal variability [see *Fasham et al.*, 1985]. However, the drastic changes in the planktonic community and its size structure, as observed in this study, could not have been detected by chlorophyll measurements only.

The 28–73 μm particle size fraction seems to be an excellent indicator of the boundary between the gyre water and the Azores Current. The boundary remained sharp for weeks, most probably due to the frontal jet currents. Unfortunately, no data on the seasonal variation are available to the authors. Compared to earlier hydrographical studies [*Stramma and Siedler*, 1988; *Stramma and Müller*, 1989], the area of the sharpest near-surface thermohaline gradients and, conceivably, the Azores Current had shifted southward from about 35°N to 32–33°N.

Using size-fractionated chlorophyll measurements, *Odate and Maita* [1988/1989] have obtained results that in essence show a similar south-to-north shift in the size composition of phytoplankton communities in the eastern North Pacific.

It is tempting to conjecture that the sharp difference in the size structure of planktonic particles gives an indication of different trophic pathways, i.e., grazing and fast recycling of the picoplankton in the subtropical gyre versus the diatom bloom with the following detrital loop in the Azores Current. However, more direct data are needed to prove that.

Another aspect of the present study concerns the satellite-derived maps of plant pigments and the estimation of primary productivity from these maps [*Esaias et al.*, 1986; *Platt and Sathyendranath*, 1988; *Campbell*, 1989]. The presence of large quantities of particles containing little or no chlorophyll in the oceanic surface water may increase the reflectance of these waters by increasing scattering versus absorption. The effect could be similar to the coccolithophore blooms [*Holligan et al.*, 1983] and difficult to correct on the coastal zone color scanner imagery. The accuracy of the algorithms could be increased on future ocean color sensors with more spectral channels available for pigment retrieval.

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