IN-SITU OPTICAL SENSING OF PARTICLES FOR DETERMINATION OF OCEANIC PROCESSES

WHAT SATELLITES CAN'T SEE, BUT TRANSMISSOMETERS CAN

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PARTICLES are introduced into the ocean by biological production, rivers, glaciers, wind and resuspension. Biological, chemical and gravitational influences then act to remove particles from the water column. These removal processes, however, occur on much shorter time scales than the formation, movement or mixing of oceanic water masses. Particles, therefore, do not act as conservative tracers of a particular water mass. However, their presence and concentration indicate the location and intensity of oceanic biogeochemical processes.

The production and destruction of particles is also a major control of biogeochemical cycles which influence the distribution of nonconservative elements and compounds that are used as tracers in the ocean. During biologic production, nutrients and CO_2 are taken up in surface waters and transformed into solid particles. Removal of particles results from grazing, sinking, dissolution and oxidation reactions. These degradation processes release nutrients in both surface waters and at depth and consume O_2. Therefore, to quantitatively use nutrients as tracers of water masses, it is important to measure all factors that influence sources and sinks of nutrients, including particle abundance and distribution. This is particularly true for surface and intermediate waters.

The use of satellites has established a global view of surface productivity through ocean color analysis. Upwelled radiance in the blue spectrum is proportional to pigment concentrations in sea water. Eppley *et al.* (1985) demonstrated that spectral ratios of reflected light can be related to the abundance of chlorophyll with an accuracy of about 35% in the open ocean and to a factor of about two in general. In turn, they showed that chlorophyll abundance in the upper part of the euphotic zone is fairly well correlated with primary production (generally within a factor of two). However, a satellite's sensing depth is a function of light attenuation, which varies with particle concentration. This depth is limited to about 20 m in open ocean gyres and only a few meters in productive shelf waters, thus seldom including depths at which chlorophyll maxima occur. Furthermore, satellite color sensors generally are correlated with chlorophyll-*a* concentration, which is <1% of the total concentration of particles, all of which play a role in biogeochemical cycles. Although algorithms to estimate total depth-integrated chlorophyll based on satellite surface color data are improving (Morel and Berthon, 1989), these relationships cannot be used to predict the vertical structure of particles (Kitchen and Zaneveld, 1990). Further improvements in estimates would be possible with more information about the vertical distribution of particles and chlorophyll in different biohydrographic regimes. Such regimes are likely to vary as a function of light levels, nutrient availability, wind mixing, convective cooling and other hydrographic influences, such as fronts, upwelling, etc., to create large regions where bio-optical properties are similar (referred to as bio-optical provinces by Mueller and Lange, 1989).

Through the use of an optical instrument such as a beam transmissometer it is possible to determine small-particle distributions, which can be used to define boundaries between regions of differing oceanographic controls. It must be realized that the time and space scales over which satellites and transmissometers provide data are very different. Satellite data are averages over large spatial areas (km^2/pixel) and generally are averaged temporally over periods of weeks, months, seasons, or years, with cloud cover causing patchy coverage in some regions. Ship stations are essentially instantaneous measurements at one location, but they can extend down through the entire water column to better define biohydrographic conditions. Shipboard measurements also provide "ground truth" data for satellites, while satellites provide synoptic information about horizontal homogeneity. As such, these two techniques provide complementary means of studying important phenomena.

During the last decade there has been a rapid increase in the application of the Sea Tech transmissometer to understand a diversity of oceanic processes. The transmissometer is easily interfaced with a con-

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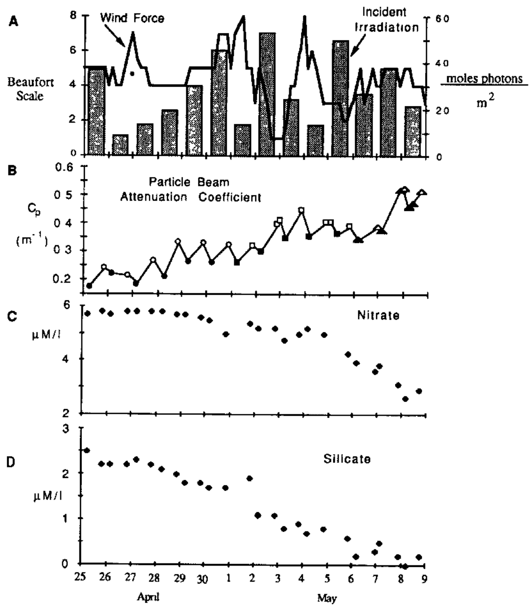
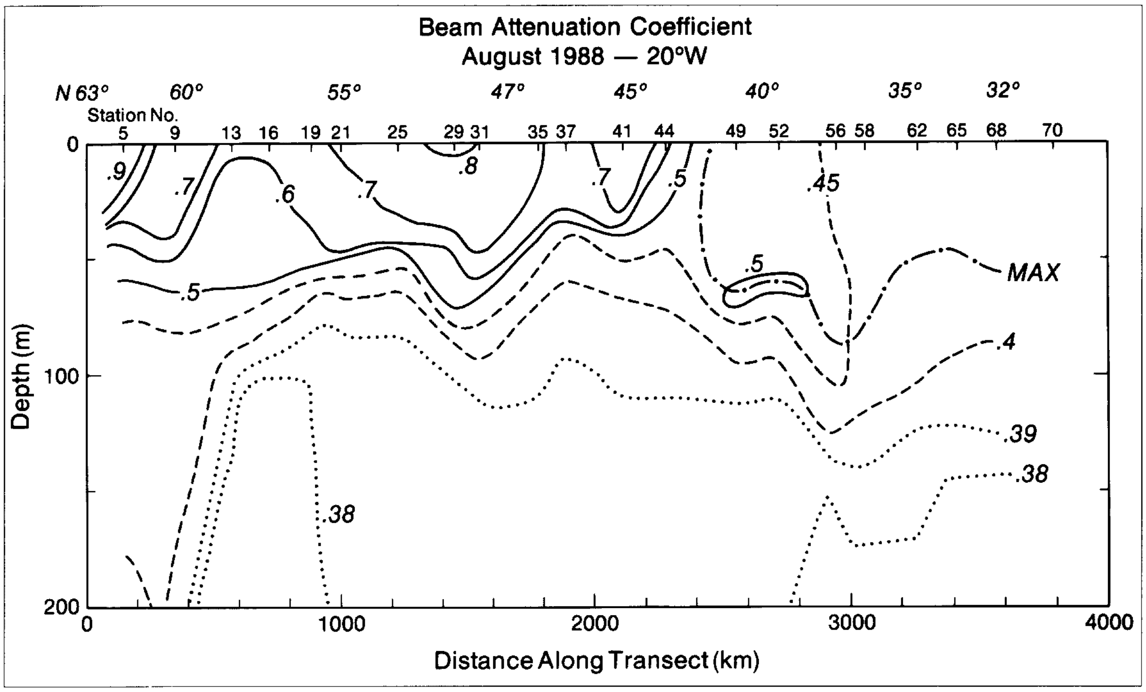


Fig. 1: (a) Wind force and incident irradiation, (b) beam attenuation coefficient at 20 m, (c) mixed layer nitrate concentration, and (d) mixed layer silicate concentration during the two-week occupation at 47°N, 20°W (see Fig. 3, ■) Filled symbols in (b) represent CTD casts made during the early morning. Open symbols represent CTD casts made after sunset. Different symbols in (b) are used for three groupings of ship locations between which the ship moved instead of drifted. Nitrate and silicate are depleted as particles are produced, though the nutrient levels decrease at different rates as the growth rates of the organisms utilizing them change. Primary production is highest when wind mixing is low and sunlight is high such as near May 2, 5 and 7.

Fig. 2 (below): Section of beam attenuation coefficient in the upper 200 m along 20°W from Iceland to 32°N (Fig. 3). Particle maxima are near the surface from Iceland to 42°N, but plunge to 60-90 m further south indicating a different biohydrographic regime.



ductivity, temperature and depth instrument (CTD) and provides a direct shipboard readout to reveal optical changes throughout the water column. In collecting attenuation data care must be exercised in cleaning the optical windows of the transmissometer and in correcting the data for decay of the LED light source and small effects of temperature, water density, and instrumental temperature hysteresis (Bartz *et al.*, 1978; Gardner *et al.*, 1985; Bishop, 1986) to obtain total attenuation due to water (c_w) plus particles (c_p). Subtraction of the attenuation due to water ($c_w = 0.364$ m^{-1} as calibrated for this instrument) yields the attenuation due to particles (c_p).

The properties of particles that affect attenuation are their concentration, size distribution, index of refraction and shapes, with the first two being most important. If the size distribution, index of refraction, and shape of particles are constant, beam attenuation is linearly related to particle concentration (Spinrad *et al.*, 1983; Baker and Lavelle, 1984; Moody *et al.*, 1986). Although characteristics of particles in the ocean are very diverse, empirical studies in the open ocean have shown that beam attenuation is highly correlated (r = 0.85-0.97) with filtered mass concentrations or particle volume concentrations below the surface 100 m (Gardner *et al.*, 1985; Walsh, 1990; unpublished Joint Global Ocean Flux Study (JGOFS) data), so particle mass can be estimated. This suggests that below that depth the properties of the small particles that constitute most of the attenuation signal are fairly uniform.

In surface waters, however, there is significantly more scatter in correlations between the attenuation coefficient and particle volume or particle mass (r = 0.77-0.88), and the slope may change with depth, but the trend is still linear (Gardner *et al.,* 1985; Bishop, 1986; Spinrad *et al.,* 1989). This results from greater biological diversity and patchiness in the region where organisms are actively growing (which results in changes in size and shape), but may also be somewhat methodological as it is difficult to collect and sample seawater without disturbing the natural particle state or losing some of the particles (Gardner, 1977). Regardless of the cause, the gradients between surface and subsurface waters and across hydrographic fronts are much larger than the uncertainty in the correlation with particle concentrations. This makes the measurement of beam attenuation at 660 nm an important tool in studying the oceanic particle and optical fields and their relationship to oceanographic processes.

Temporal Variability of Optical Data

During the last two years we have used 25 cm pathlength Sea Tech transmissometers to measure: (1) temporal variability in particle production at a single location as part of the JGOFS North Atlantic Spring Bloom Experiment (NABE); (2) basin-wide spatial distributions in the North and South Atlantic during the HYDROS cruises along 20°W, the South Atlantic Ventilation Experiment (SAVE) (Berglund, 1989), and the first World Ocean Circulation Experiment (WOCE) cruise on the *Meteor;* and (3) processes in the Gulf of Mexico (Gardner and Walsh, 1990; Walsh, 1990).

To effectively use the transmissometer data one must know something about temporal variations. Siegel *et al.* (1989) reported very small diel variations in beam attenuation coefficients in the upper 150 m of an oligotrophic region of the Pacific. The variations (attenuation coefficient changes of $\pm 0.01\ m^{-1}$ in each cycle) were explained as a balance between primary production and consumption by grazing organisms. There was no net gain or loss over the period of a week. In the North Atlantic under bloom conditions, however, we have recently measured diel variations in the mixed layer up to five times as large as those measured by Siegel *et al.* (1989) and a tripling of the particle mass in the surface mixed layer during a two-week period.

During the April/May leg of the North Atlantic Spring Bloom Experiment, CTD/transmissometer profiles were taken at 47°N, 20°W every morning and evening. Results from the transmissometer show beam attenuation due to particles(c_p) in the surface mixed layer increasing substantially (from $0.17\ m^{-1}$ to $0.51\ m^{-1}$) over a two-week period, indicative of increasing particle concentrations during a phytoplankton bloom (Fig. 1). Superimposed on this increase were diel variations ($0.06\ m^{-1}$ to $0.12\ m^{-1}$) with evening highs and morning lows, which are related to the intensity of wind mixing, incident irradiation, and a decrease in nutrient levels (Fig. 1). Our assumption that increases in beam attenuation result primarily from increases in biomass and organic detritus through primary production is supported by the inverse correlation between beam attenuation and nutrient concentrations and both diel variations and cruise-long decreases in total CO_2 as measured by the Lamont-Doherty Geological Observatory CO_2 group. The inverse correlation between CO_2 and beam attenuation provides evidence that CO_2 is rapidly converted to the particulate phase. Photo-induced physiological changes in plankton may cause

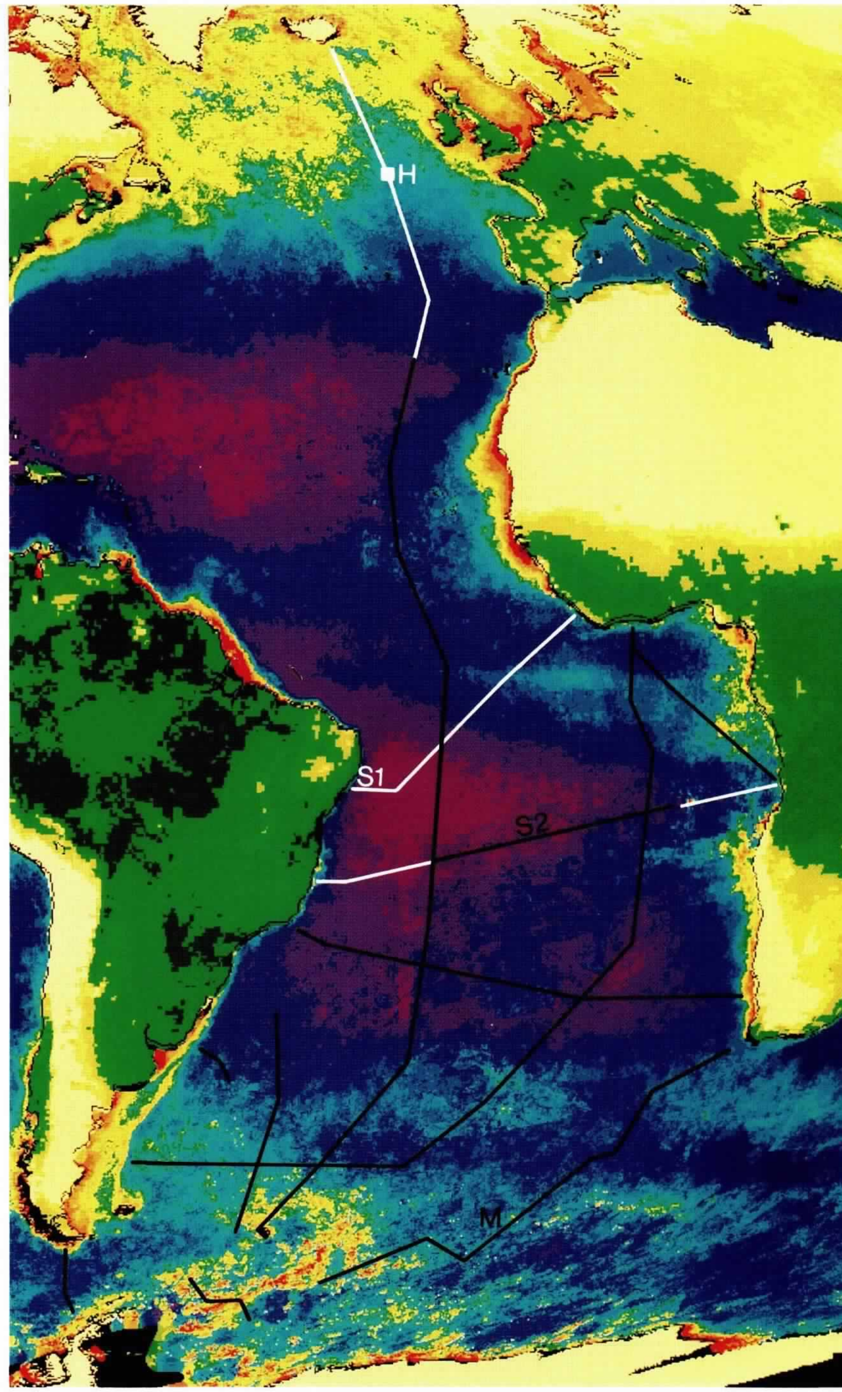


Fig. 3: Cruise tracks from HYDROS (H) along 20°W (Fig. 2), Legs 1-5 of the South Atlantic Ventilation Experiment (SAVE), and a Meteor *cruise (M) superimposed on the contours of pigment concentration (mg/m³) from the 32-month composite Coastal Zone Color Scanner map of Feldman* et al. *(1989). Pigment concentrations range from 0.05 mg/m³ in the central gyres to 0.3 mg/m³ in the light blue equatorial region to 0.8 mg/m³ in the yellow regions. Sections from tracks in white are shown in Figures 2, 4 and 5. The southern tracks are still being analyzed.*

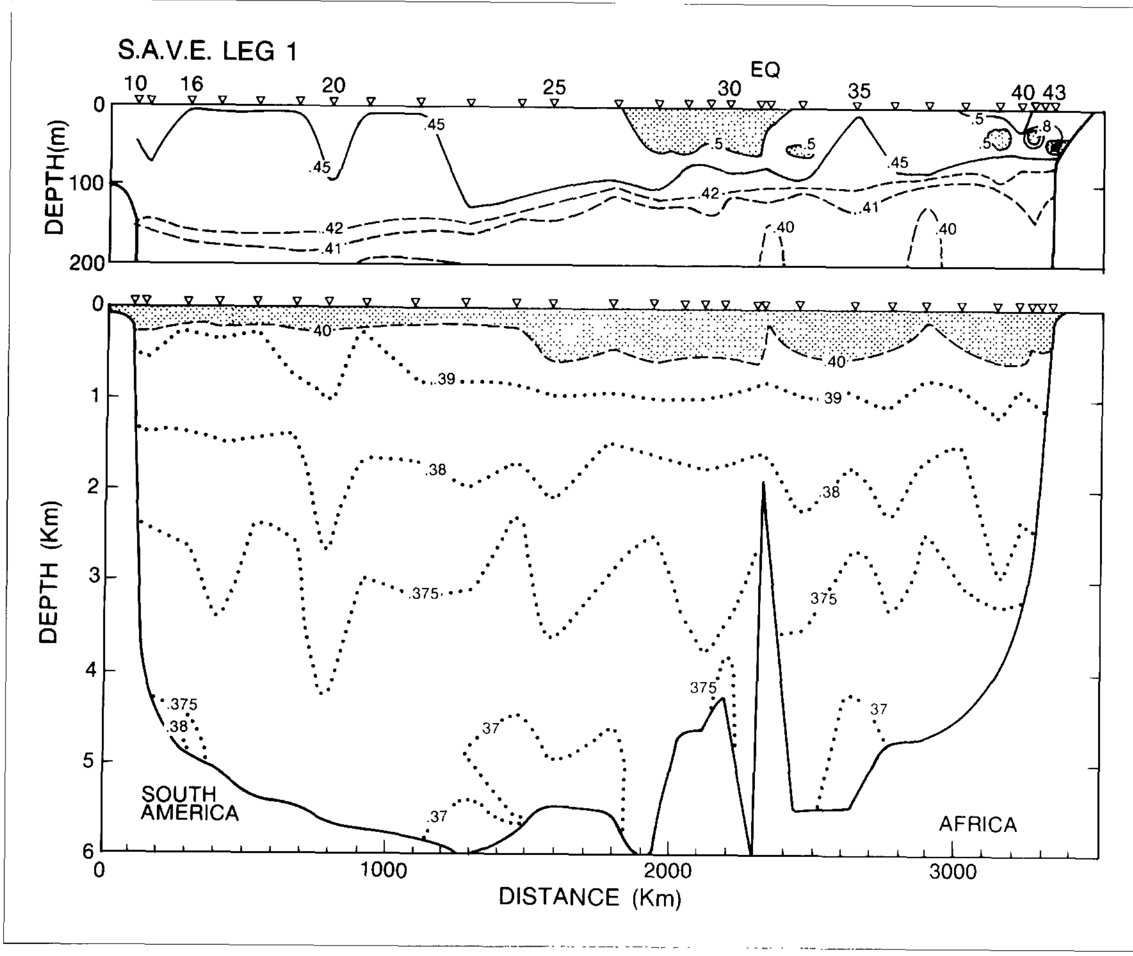


Fig. 4: Section of beam attenuation, leg 1 of SAVE (Fig. 3). Note increased concentrations in surface waters near the equator (EQ) and the African margin.

some of the diel variation (Olson *et al.*, 1990), but cannot account for the three-fold increase in two weeks. Decreases in beam attenuation are presumably associated with biological consumption, large-particle production, and subsequent particle settling (fecal pellets, aggregates) or consumption and bioactive transport by organisms migrating to deeper depths. Integration of beam attenuation over various depths will allow the quantification of particle mass which, in a mid-ocean bloom, is equivalent to biomass and organic detritus.

Basin-Wide Sections

North Atlantic

Although rapid changes can occur during bloom conditions, there are also basin-wide distributions that can be mapped to characterize the biohydrographic conditions. A transmissometer transect along 20°W from Iceland to 10°S made in August 1988 reveals high particle mass in surface waters from Iceland (~60°N) to about 45-40°N where there is a rapid decrease in particle concentration (Fig. 2, p. 12). Although not plotted in Fig. 2, particle concentrations again increase as western Africa is approached. The lateral gradients in near-surface concentrations are also well correlated with chlorophyll concentrations determined from composite satellite ocean color maps from previous years for the North Atlantic (Fig. 3, p. 13). A feature not detectable in the satellite photos, however, is that from 60°N to 45°N the particle maximum is at or near the sea surface, whereas south of that region the particle maximum drops to deeper than 60 m, well below the sensing depth of satellite color sensors. Since the total particle concentration and vertical distribution are related to primary production and mixing, it is likely that vertical chlorophyll distributions, including the depth of the chlorophyll maximum, also change across that same boundary, although we do not have concurrent chlorophyll data. A similar change in the depth of the particle maximum was seen along a north-south transect of the Pacific, and was found to be correlated with changes in the depth of the chlorophyll maximum (Pak *et al.*, 1988). We propose that changes in the depth of the particle maxima from surface to subsurface mark changes in biohydrographic regimes resulting from differences in mixing due to wind and convective night cooling, nutrient availability, and resultant primary production. Thus, if one is attempting to predict integrated chlorophyll concentrations along this track from satellite color data (and further extrapolate to primary production and particle fluxes), it is likely that different algorithms should be used on either side of that boundary.

South Atlantic

Basin-wide hydrographic and transmissometer sections in the South Atlantic obtained as part of the SAVE project further demonstrate the utility of optically mapping the particle distribution as a means of revealing the location and intensity of oceanic processes (Berglund, 1989). Sections of the beam attenuation coefficient reveal basin-wide variations that are related to the mixed-layer thickness and nutrient concentration in surface waters. Particle concentrations are high in surface waters in upwelling regions such as at the equator and along the African coast (Figs. 4 and 5). Particle concentrations rise only slightly, if at all, near the South American margin because hydrographic conditions are not favorable for primary production—there is neither upwelling nor riverine input of nutrients (Fig. 6, p. 16). Near the Congo River on the African margin particle concentrations are extremely high as nutrients move across the shelf and fuel biological production (Fig. 5).

Satellite color maps averaged over thirty-two months reveal highs and lows in the same regions for chlorophyll as for those observed in beam attenuation sections (Figs. 3-5). It follows that most particles in the open ocean result from primary production. The significance of this relationship is that rates of lateral mixing in surface waters must be slow compared to rates of particle removal; otherwise, total particle concentration would not reflect primary production. What is not revealed in the satellite data, however, is that the same relative concentration patterns observed in surface waters extend deeper in the water column, resulting from a vertical rain of particles from surface waters. Where concentrations are elevated in surface waters the concentration isopleths are depressed in the deep water. This is seen in comparing the eastern and western basins. Surface water concentrations are higher in the eastern basin where the 0.38 m^{-1} contour is significantly deeper than in the western basin (Fig. 5). It is also evident in the upper water column along the African coast and at the equatorial crossing (Figs 4 and 5). The depression in isopleths probably results from exchange between pools of large, rapidly settling particles that are not sensed quantitatively by transmissometers and the pool of small particles that constitute most of the attenuation signal (Gardner and Walsh, 1990).

Oxygen Minimum and Particles

The Angola Basin is characterized by an oxygen minimum at about 400 m (Fig. 6). It is assumed that the oxygen minimum is related to high productivity, off-shelf advection of water and particles (Pak *et al.*, 1980), and regional circulation, but the linking mechanism has not been fully explained. Four possible causes for the O_2 minimum include (1) oxidation of organic matter at the seafloor and advection of low O_2 water and organic carbon in the regional circulation, (2) respiration by animals in the oxygen minimum, (3) oxidation of organic matter as it settles through the oxygen minimum, and (4) regional circulation causing stagnation of water in this zone.

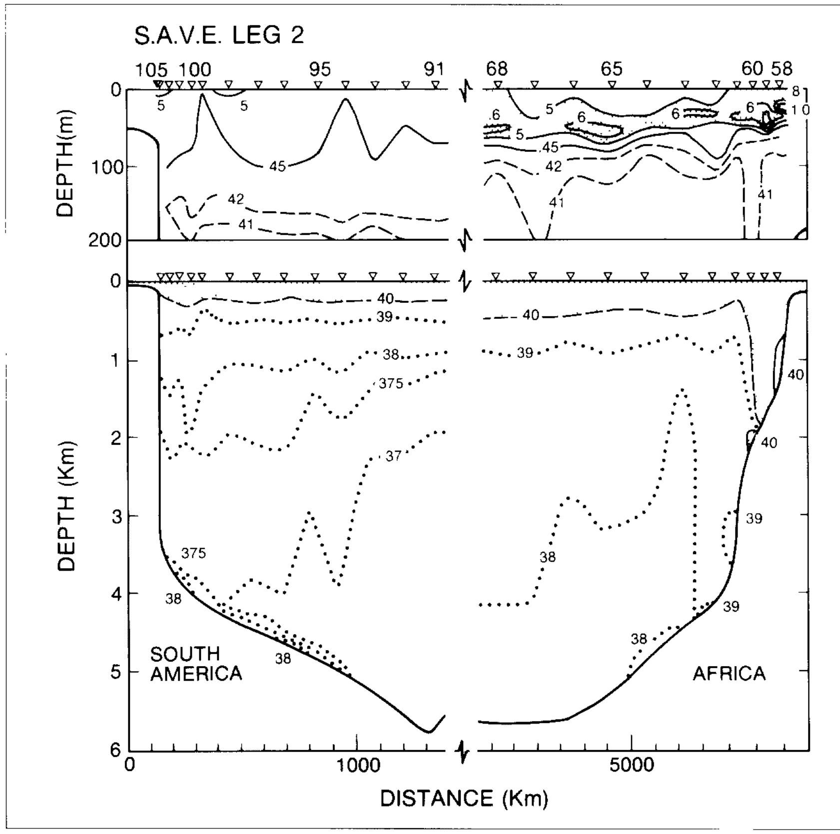


Fig. 5: Section of beam attenuation, leg 2 of SAVE (Fig. 3). Particle concentrations are much higher in the eastern basin in both surface and deep waters than they are in the western basin. Nutrient input from upwelling greatly enhances particle production near Africa. The deep Western Boundary Current causes slightly higher concentrations along the rise in the western basin.

The core depth of the O_2 minimum in the SAVE data in the Angola Basin approximately follows the trend of a sub-pycnocline near the 27.0 sigma theta contour (300-400 db), suggesting the O_2 minimum is a density related phenomenon. Many profiles in this region show very high surface water particle concentrations and a slight particle maximum along that sub-pycnocline. The core of the O_2 minimum is at the base of the sub-pycnocline. Is it possible that the settling velocity of particles decreases sufficiently within the sub-pycnocline to increase the residence time for oxidation of organic matter? It is unlikely for small (<20 µm) individual particles, but Alldredge and Gotschalk (1988) have shown that large organic-rich aggregates in the size range of 1-10 mm can have excess densities (over sea water) as small as 10^{-3} to 10^{-5} g cm^{-3}. In the Angola Basin at station 58 (Fig. 5) the water density changes by 4.0 x 10^{-4} g cm^{-3} across the sub-pycnocline. Encountering a sub-pycnocline with this density change could cause such particles to slow down and even stop their vertical settling until further transformations increased their settling velocity. Such transformations would include an exchange of pore water within the aggregates, further aggregation, disaggregation, or consumption by zooplankton and a potential decrease in O_2. If large organic-rich aggre-

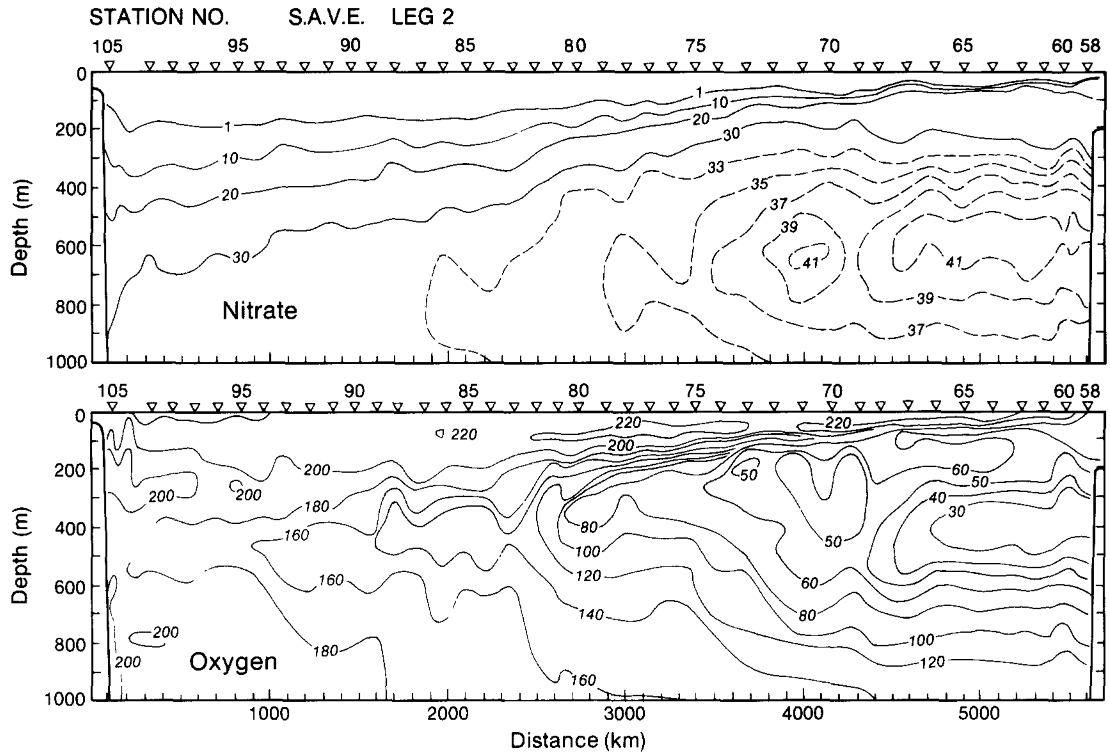


Fig. 6: Nitrate (μM/kg) and oxygen (μM/kg) in the upper 1000 m, SAVE leg 2 (Fig. 3). Particle concentrations in the western basin (Fig. 5) are low because nutrients are not available for primary production. As the nutricline shallows, the particle concentration increases. Low oxygen water may be created due to oxidation of organic matter on the seafloor along the African margin, but it may also be enhanced by in-situ utilization within the oxygen minimum beneath productive waters (see Fig. 5).

gates exist in this region, it is very possible that this subpycnocline could increase their residence time and concentration, contributing to oxygen consumption both by in-situ oxidation and through respiration of organisms feeding in a mid-water oasis. Such remineralization would also contribute to the nitrate maximum at the same or slightly deeper depth (Fig. 6).

Particles and Ocean Heating

The heat flux into and out of the ocean is an important parameter in ocean circulation. Ackleson *et al.* (1988) found that over a nine-day period sea surface temperature (measured via satellite Advanced Very High Resolution Radiometer thermal imagery) increased five times faster in a region of the Gulf of Maine which was experiencing a coccolithophorid bloom than a hydrographically similar region nearby that was not experiencing a bloom (0.32°C d^{-1} vs 0.06°C d^{-1}). The more rapid heating would increase stratification, which decreases mixing. Production may be rapid for a while, but once nutrients are depleted, production is limited to recycling within the surface layer. If it is confirmed that more rapid heating results from the presence of particles, it further demonstrates the importance of knowing the global distribution and total concentration of particles in surface waters.

Particles as Indicators of Bottom Currents

The presence of resuspended sediment has been used successfully as an indicator of the location and intensity of bottom currents (Biscaye and Eittreim, 1977; Spinrad and Zaneveld, 1982). Our data have been consistent with those of previous workers in identifying the location and relative intensity of bottom currents in the South Atlantic. For example, the western bottom boundary currents are weak in the Brazil Basin (Fig. 5), but they do resuspend some sediment. Data from the Argentine Basin (not shown) indicate intense bottom nepheloid layers with concentrations as high as those in surface waters. Although satellites are now used to determine surface ocean currents, we know of no attempts to extract bottom currents from sea surface topography, nor is there any means to detect deep resuspended sediments via satellite. WOCE sections will be taken in many places where no particle data exist, and transmissometer data would be useful in indicating the location and relative strength of bottom currents world wide.

Conclusions

We are just beginning to discover the relationships that can be observed in basin-wide studies of particle distributions and time-series monitoring of particle production events. Some of the emerging relationships are as follows:

- There is a strong correlation between zones of high surface chlorophyll concentrations observed by satellites and surface particle concentrations measured with transmissometers.
- Where particle concentrations are high in surface waters, isopleths are depressed in the water column indicating that vertical settling of particles is important in determining particle distribution.

- Biohydrographic regimes need to be defined globally so that algorithms can be developed to convert satellite color data to depth-integrated chlorophyll concentrations based on a specific regime rather than using a single algorithm for the entire ocean.
- Beam attenuation increases as an immediate response to the production of particles during primary production. The correlation between particle increases and CO_2 decreases on diurnal and longer time scales suggests the rapid conversion of CO_2 to POC in surface waters through biological processes.
- Particles are an essential component of the nutrient cycles and should be measured to fully understand nutrient distribution. We especially need measurements at high latitudes where water masses are formed and where satellite data don't exist or are poor because of low sensing angles and ice cover.
- A reduction of the settling rate of some large aggregates through the pycnocline will contribute to utilization of O_2. This process may contribute to the oxygen minimum and nitrate maximum.
- The presence of particles in surface waters may increase adsorption of solar insolation. If so, global particle distributions need to be known to better model heat budgets.
- Processes in deeper water associated with intermediate and benthic nepheloid layers generated through resuspension of bottom sediments by boundary currents are seen in the transmissometer data, but are absent from the satellite signal.

Our data demonstrate the vital need to include transmissometers in global programs to measure the particulate phase of biogeochemical cycles to fully explain nutrient distributions and interpret oceanic systems.

Acknowledgements

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