Distribution of macroaggregates and fine-grained particles across a continental margin and their potential role in fluxes

WILFORD D. GARDNER* and IAN D. WALSH*

(Received 24 March 1989; in revised form 1 September 1989; accepted 11 September 1989)

Abstract—The distribution and size of large marine aggregates (>0.5 mm) photographed in situ were compared with the small-particle distribution determined from beam attenuation (660 nm) in a section across the shelf and slope of the northern Gulf of Mexico. On the shelf changes in beam attenuation matched the trends in large particle concentration. Over the slope, beam attenuation profiles resembled the aggregates profiles in the upper 400 m with a small surface mixed layer maximum, a decrease through the upper thermocline to a minimum, and a small intermediate nepheloid layer (INL) in both large and small particles between 300 and 400 m. At the two deepest stations beam attenuation remained low from the bottom of the INL to the seafloor, while concentrations of large particles increased through the lower water column to concentrations greater than in the surface water. The distributions suggest that both large and small particles are resuspended from the upper slope and advected seaward, but on the mid slope this mode of transport occurs mostly as large aggregates. From calculations of settling speeds based on estimates of particle density, it appears that these aggregates are important in both the horizontal and vertical flux of particles along continental margins.

INTRODUCTION AND BACKGROUND

From their production and introduction in surface waters to their incorporation into the sediments, particles in the ocean are cycled and redistributed by biological, chemical and physical processes. The redistribution of these nutrient-rich materials has important implications for understanding and quantitatively modeling biogeochemical processes in the oceans. In the open ocean, surface production is generally the most significant source of particles, but near the continental margins the seafloor can also be an important source of particles as a result of resuspension and lateral advection.

The distribution of particles in the oceanic water column traditionally has been studied by making optical measurements of light scattering or beam attenuation (BISCAYE and EITTREIM, 1977; PAK et al., 1988), by collecting water samples for filtration or electronic particle volume analysis (BREWER et al., 1976; SHELDON et al., 1972), or by in situ filtration

* Department of Oceanography, Texas A&M University, College Station, TX 77843, U.S.A.
These methods generally indicate particle distribution in the open ocean to be in the range of 10s-100s of \( \mu g \, l^{-1} \) in the surface layer, decreasing rapidly to 10–20 \( \mu g \, l^{-1} \) below the surface layer and increasing to 10s–100s \( \mu g \, l^{-1} \) if a nepheloid layer is present. Near ocean boundaries intermediate nepheloid layers are often detected.

Although the above methods adequately measure the concentration of small particles, some of them, because they sense only small volumes of water, do not adequately quantify rare, large particles that dominate the vertical flux of solids (McCave, 1975). For example, while large particles may be collected in water bottles, they can settle quickly (in minutes) below the bottle spigots (Gardner, 1977) or break up during extraction from the bottle (Gibbs and Konwar, 1983). Quantifying the influence of the continental margin on the supply of particles to the deep ocean requires an ability to determine the spatial and temporal distribution of both large and small particles as well as settling velocity as a function of particle size and the horizontal and vertical flux of particles. No practical means presently exists to provide all this information simultaneously with sufficient spatial or temporal coverage to explain fully processes along the continental margin.

Sediment traps have been used in several studies to demonstrate a substantial flux of rapidly settling material to the deep water column that is horizontally derived from resuspended material (Baker and Hickey, 1986; Monaco et al., 1987; Biscaye et al., 1988; Gardner, 1989). However, while sediment traps allow quantification and compositional analysis of the particle flux, they do so at an economically limited number of points and necessarily integrate the flux over time periods that may be longer than natural events (blooms, episodic upwelling, benthic storms) and also too long for adequate modeling with short-term physical and biological data. Furthermore, transmissometers or other standard particle-sampling techniques cannot be used to determine the deployment depths of traps if those techniques do not sample adequately the large particles responsible for the vertical flux. Bishop et al. (1980) measured the size distribution of large particles filtered in situ, estimated particle densities, and calculated fall velocities to estimate vertical flux of particles. This is a reasonable first-order approximation when sediment trap data are not available, but as much as 50% of the flux reported for pump filters was estimated by extrapolating the size distribution beyond that which was actually measured.

The confirmation that large particles dominate the vertical flux of detritus in the ocean has redirected biogeochemical research in the last decade. Fecal pellets were first declared to be the major transport mechanism in the vertical flux, but the majority of material by weight collected in traps was not in pellets. Renewed attention has been directed to the role of aggregates (Trent, 1985; Fowler and Knauer, 1986). Recently, camera systems have been developed to characterize aggregate distributions in the water column (Honjo et al., 1984; Asper, 1987; Gardner et al., 1988). The main source of aggregates has been assumed to be surface waters (All dredge and Silver, 1988), but Asper (1986) has found deep-water and benthic aggregate maxima which he ascribes to resuspension and advection from boundaries.

Since a camera system yields particle diameters, particle volume is calculable. Given particle volumes and size distributions, fluxes are calculable from camera data if reasonable estimates of particle density can be made, and a settling mode (e.g. Stokesian) is assumed. The accuracy of the calculated flux will depend on the accuracy of the assumed relationship, and considerable scatter and uncertainty can be expected in such flux estimates. If transmissometers, water filtration and electronic particle analysers fail to
sample adequately the aggregate concentration and size distribution, in situ camera data may elucidate the distribution and, therefore, the source of aggregates near the continental margins. In this study we present particle concentration profiles using a large-particle camera and transmissometer along a shelf/slope section of the northern Gulf of Mexico to compare the spatial distribution of large and small particles. Size distributions of the aggregates are used to estimate particle mass and flux and to produce a synoptic section of vertical mass flux.

METHODS

In April 1987, profiles were made at four sites on the shelf and upper slope of the northern Gulf of Mexico from the R.V. Gyre (Fig. 1) using a large-particle camera (fashioned after the camera of Honjo et al., 1984) and CTD/transmissometer. Our camera is a Lobsiger Deep-Slope camera with a wide-angle (90°) lens. Illumination was from a 150 W s⁻¹ strobe. The strobe head was masked with aluminum tape to emit light from a 2 × 1 cm hole directed toward a Fresnel lens. The Fresnel lens collimates the light normal to the camera field of view where an area approximately 35 × 25 cm was photographed. The light slab thickness was controlled by baffles to yield an illuminated volume 9.5 cm deep (8.3 liters). The field of view included a wire with cm marks for scale. Because the camera has a wide-angle lens there is a difference in the apparent size of a particle in the negative dependent on its position in the light slab normal to the camera. This difference is less than a factor of two, and is minimized by placing the calibration wire in the center of the light slab and relying on randomness to average out the error. The camera has a button panel for inserting multiple photographic sequences, including delays, with data (date, time, photo number) recorded on each frame. Our firing rate and lowering rate yielded photographs at

![Fig. 1. Location of stations on the Louisiana shelf and slope.](image)
about 6 m intervals beginning at 10 m. A pinger on the CTD and camera allowed bottom approaches to within 5-10 m.

Images from the camera were analysed directly from the film negatives using a video camera input to a Luzex model 450 image digitizer and Hewlett Packard 87XM microcomputer for control and data storage. The area analysed in each frame corresponded to approximately 4 liters. Each image was analysed for the number of particles in each of six diameter size classes ranging from \( d = 0.526 - 3.156 \) mm. Total volume of particles in each negative was calculated from the size distribution assuming sphericity and diameters equal to the mean for the five smallest size ranges, and, as a conservative estimate, the minimum size (3.156 mm) of the unbounded largest size bin.

Mass concentration of large particles was calculated by using the particle diameter/density relationship of AllDredge and Gotschalk (1988). The settling velocity and mass flux of aggregates was calculated using Stokes' law (Table 1). Stokes' law was used in preference to the settling velocity/diameter relationship of AllDredge and Gotschalc (1988) \( W_s = 50D^{0.26} \) where \( D \) is in millimeters and \( W_s \) is in meters per day) because of the general familiarity with the Stokes relationship and the greater scatter in the Allredge and Gotschalt settling velocity data as compared to their excess density to diameter relationship. This results in slightly higher settling rates for the largest of our size classes and a slightly lower settling rate for the smallest. For the largest aggregate sizes the Reynolds number is <2; at this Reynolds number the empirical settling velocity of particles is only 5% slower than that predicted by Stokes' law, an acceptable error given the other assumptions.

A 660 nm wavelength SeaTech beam transmissometer with 25 cm path length was interfaced with a CTD for profiling at the same stations. CTD data were digitized with 12-bit resolution, but only an 8-bit digitizer was available for the transmissometer data instead of the 12-bit resolution we normally use to match the transmissometer sensitivity \((\pm0.001\%)\). Percent transmission \( T = \text{voltage recorded/voltage output} \) is related to beam attenuation coefficient \( (c) \) by \( T = e^{-cz} \), where \( z \) is pathlength in meters. Our attenuation data have a resolution of only \( \pm0.01 \text{ m}^{-1} \), but based on later cruises with 12-bit resolution, this is still sufficient to observe and map distributions across the shelf and upper slope. The transmissometer had not been calibrated for several years, so we compared

| Table 1. The settling velocity and mass flux of aggregates (calculated using Stokes' law) |
|---------------------------------|--------|--------|--------|--------|--------|--------|--------|
| Particle size \((\text{mm})\) | \( D \) \((\text{cm})\) | Volume \((\text{cm}^3)\) | \( \Delta \rho \) \((\text{g cm}^{-3})\) | Mass \((\mu g)\) | \( W_s \) \((\text{cm s}^{-1})\) | Flux \((\mu g \text{ cm}^{-2} \text{ day}^{-1})\) |
| 0.526-1.052 | 0.0789 | \(2.57 \times 10^{-4}\) | \(2.6 \times 10^{-3}\) | 0.67 | 0.052 | 3.00 |
| 1.052-1.578 | 0.1315 | \(1.19 \times 10^{-3}\) | \(1.2 \times 10^{-3}\) | 1.43 | 0.064 | 7.90 |
| 1.578-2.104 | 0.1841 | \(3.27 \times 10^{-3}\) | \(6.8 \times 10^{-4}\) | 2.22 | 0.074 | 14.2 |
| 2.104-2.630 | 0.2367 | \(6.94 \times 10^{-3}\) | \(4.5 \times 10^{-4}\) | 3.12 | 0.081 | 21.9 |
| 2.630-3.156 | 0.2893 | \(1.27 \times 10^{-2}\) | \(3.3 \times 10^{-4}\) | 4.18 | 0.088 | 31.8 |
| >3.156 | 0.3156 | \(1.65 \times 10^{-2}\) | \(2.9 \times 10^{-4}\) | 4.77 | 0.091 | 37.5 |

\( D \) is the assumed diameter for all particles in a given range. Volume per particle calculated assuming spherical particles. \( \Delta \rho \) from AllDredge and Gotschalk (1988). Mass per particle calculated by multiplying density and volume for a given particle. Settling rate assumes Stokes' law. Flux calculated from the mass and settling rate, assuming one particle per liter.
readings with attenuation values from calibrated transmissometers and filtered samples from subsequent cruises in the Gulf of Mexico.

The beam attenuation coefficient is linearly correlated with particle concentration, though the correlation is empirically derived and is a function of particle size and index of refraction (Baker and Lavelle, 1984; Moody et al., 1986). Only 44 cm$^3$ of water are in the light beam during each measurement. Conversions from beam attenuation coefficient to particle concentration in this study use an equation derived from transmissometer and filtration data from subsequent cruises in the Gulf of Mexico.

**RESULTS**

Abundances of marine aggregates in terms of number of particles per liter have been reported to range from 0.0005 to 35 for environments from neritic depths to nearshore surface waters (Silver, 1986). At our four sites aggregate abundance declined from 10–60 per liter on the shelf (Sta. 22) to a range of about 0.2 to >3 per liter on the slope (Fig. 2). The slope stations show similar profiles of abundance. Abundance in the mixed layer at all three sites was about 1 per liter, declining through the top of the mixed layer to minimums of 0.2–0.3 per liter, and then increasing with depth to near bottom maximums of 1.6–3.3 per liter.

Comparisons of the transmissometer and LPC profiles from Stas 22 and 25 are made in Figs 3 and 4. On the shelf (Sta. 22) both the beam attenuation and total volume of large

![Fig. 2. Profiles of particle abundance for the three slope stations. Data were smoothed with a nine point moving average filter. Note the common values for the mixed layer and upper thermocline and increasing abundance with depth to the bottom.](image-url)
particles increase monotonically to the bottom. The rapid increase in the beam attenuation very close (within 10 m) to the bottom corresponds to a layer of cold, more saline water indicated in the CTD record. The intense bottom nepheloid layer was also seen in the LPC photographs but those data are not shown in Fig. 3 as the density of particles on the negative was too large for the image analyser to distinguish individual particles. Comparison of the particle concentration profiles shows that the mass of large particles is only a few percent of the suspended particle load in the upper water column, increasing to 10–15% of the suspended load near the bottom, above the intense bottom nepheloid layer. The large-particle flux also increases to the bottom, with a larger degree of increase than the total volume due to the weighting of the flux on the basis of particle size.
The transmissometer and LPC data indicate a large decrease in particle concentration of both large and small particles from the shelf to slope waters. Total volume of large particles decreased by 1–2 orders of magnitude. Beam attenuation decreased from 0.6–0.9 m\(^{-1}\) on the shelf to a maximum of 0.5 m\(^{-1}\) on the slope, a decrease of 1–2 orders of magnitude in mass concentration.

At the deepest slope station (Fig. 4), the data on the total volume of large particles show a large amount of scatter, but indicate a trend of decreasing particle volume from the surface to 200 m and increasing particle volume from about 600 m to the bottom. Beam attenuation was constant through the surface mixed layer and decreased rapidly at the top of the thermocline. An intermediate nepheloid layer (INL) was indicated at 350–450 m. The clear water minimum is reached just above the INL, and again just below, where it extended to the bottom, with no indication of a bottom nepheloid layer. Transmissometer profiles made with 12-bit resolution on later cruises showed no indication of bottom nepheloid layers.

In the surface mixed layer the mass of large particles was a small percentage of the suspended particle concentration (Fig. 4). The large particle concentration had a small peak within the beam attenuation INL, and increased slightly to the bottom. From 600 m to the bottom the large particle concentration was of the same order as the suspended particle concentration. The smoothed particle number profiles (Fig. 2) and the unaveraged large particle flux data (Fig. 4) show a small peak corresponding to the beam attenuation INL, and a general increase to the bottom from about the base of the beam attenuation INL.

**Transmissometer section**

The cross-slope section derived from the beam attenuation profiles (Fig. 5) is typical of slope/shelf environments. The difference in beam attenuation from the shelf to the slope clearly shows that the existence of a shelf front must be inferred. The surface mixed layer is a zone of high attenuation on the slope. Beam attenuation decreases rapidly through the top of the thermocline. On the upper slope (Sta. 23) a bottom nepheloid layer is evident, but no bottom nepheloid layer is apparent at the deeper stations. An intermediate nepheloid layer appears from 300 to 380 m at Sta. 24 and deepens and thickens to 350–450 m at Sta. 25. At both of these stations the clear water minimum extends from below the INL to the seafloor.

**Flux section**

Over the slope the smoothed flux data are similar to the transmissometer section in the upper 400 m (Figs 5 and 6). The flux decreases by 1–2 orders of magnitude from the shelf to the slope, implying a shelf–slope front. On the slope, near-surface maximums of flux occur in the mixed layer. The large-particle flux decreases at the top of the thermocline, increasing again on the upper slope (Sta. 23, Fig. 6) in a large-particle bottom nepheloid layer. An intermediate large-particle nepheloid layer is seen at Stas 24 and 25 (Fig. 6), contiguous with the INL seen in the beam attenuation section. In contrast with the beam attenuation data, large-particle bottom nepheloid layers exist at Stas 24 and 25 (Fig. 6). At the deepest station two large-particle intermediate nepheloid layers occur where beam attenuation values are constantly low. The large-particle intermediate nepheloid layer at 750 m contains the highest flux (>24 \(\mu g\) cm\(^{-2}\) day\(^{-1}\)) calculated for the slope.
Fig. 5. Contoured section of beam attenuation across the shelf and upper slope. The large decrease in attenuation between Stas 22 and 23 implies a front at the shelf-slope break. An intermediate nepheloid layer exists at 300 m, but no small particle layers are present below that depth.

Fig. 6. Contoured section of particle flux from estimates discussed in the text. The large decrease between Stas 22 and 23 again imply a front across which particles are not easily moved. The minimum between 100 and 300 m coincides with the minimum in beam attenuation, but there are multiple maxima in particle flux below that depth, unlike the section of beam attenuation.
Although fluxes calculated from these data undoubtedly have considerable scatter, our range of aggregate settling velocities (45–79 m day\(^{-1}\) from Stokes) overlaps substantially with the Aldredge and Gotschalk relationship (47–67 m day\(^{-1}\)) and Shank and Trent (1980; 43–95 m day\(^{-1}\)), and is lower than the mean water column settling velocity (100 m day\(^{-1}\)) predicted from open ocean sediment trap data (Deuser, 1986). Asper (1986, 1987) obtained much lower settling velocities (1 m day\(^{-1}\) for 4–5 mm aggregates and 36 m day\(^{-1}\) for 1–2.5 mm aggregates) by measuring the number concentration in the water column and photographing their arrival rate at the bottom of a sediment trap. The low values could result from differences in methodology, geographic regions, or, as Asper suggests, that aggregates resuspended in the Panama Basin have much lower settling rates than aggregates settling from the surface.

The distinct difference between the distribution of large and small particles below 400 m on the slope in our study can be explained by the resuspension of large organic aggregates from the slope and subsequent horizontal advection and diffusion into the basin. The resuspension of large organic aggregates in a process distinct from the resuspension of sediment was indicated in bottom photography in the northeast Atlantic (Lampitt, 1985) and Pacific (Gardner et al., 1984) and in sediment traps in the Pacific (Walsh et al., 1988). These large particles result from a rapid flux from surface waters during plankton blooms and are resuspended before they have time to become mixed into the surface sediments through bioturbation. This type of resuspension has been termed particle rebound (Walsh et al., 1988). It appears that lower threshold velocities (or critical bed-shear stresses) are required for resuspension of the large aggregates than for the older, reworked, fine-grained deep-sea sediments. Lampitt (1985) correlated the resuspension of bloom-derived aggregates with current speeds as low as 7 cm s\(^{-1}\) (measured 1 m above bottom), while photographs of the seafloor showed no discernible difference in pre-bloom sediment cover. Since rebound can occur at critical shear stresses below those required for resuspension of the bioturbated sediment surface, rebound may explain the existence of large-particle nepheloid layers below 400 m on the slope in the absence of changes in the small-particle concentrations. Near the top of the slope, stronger currents may produce the shear stresses needed to resuspend sediment, concurrently forming both small- and large-particle nepheloid layers as indicated in transmissometer and LPC data.

Since the rebounded large aggregates, which form large-particle nepheloid layers, are directly derived from the vertical flux of surface material, they will have compositions distinct from older resuspended sediment (e.g. higher percent organic carbon). Their contribution to settling flux will be chemically distinguishable in sediment trap data from particles resuspended from the reworked sediment [e.g. lower percent organic carbon (Walsh et al., 1988)]. This type of cross-slope deep transport of biogenic-rich material has been seen in the SEEP sediment trap deployments (Biscaiy et al., 1988), and the magnitude of fluxes calculated from our LPC data are in the same range of fluxes measured with sediment traps on the shelf and slope (Biscaiy et al., 1988; Gardner, 1989; Walsh, unpublished data). Thus, the continental margin may be a significant source of biogenic material in the deep basins, with the degree of influence dependent on the productivity gradient, the settling speed of the rebound particles, and the advective flow regime.

This mode of resuspension and lateral advection also would explain the paradox of why fluxes measured with sediment traps often increase with depth where the measured particle concentration is constant with depth. If the settling velocity distribution of
particles in the water column remained constant, the vertical flux of particles should be proportional to particle concentration, yet this has not always been the case, especially close to margins, e.g. the Panama Basin (Honjo et al., 1982). Particle fluxes at the mouth of Baltimore submarine canyon increased by 100 times between 200 and 1000 m, even though profiles and time series measurements showed increases in particle concentration of less than 5–10 times over the same depth and deployment period (Gardner, 1989). It seems unlikely that the settling velocity distribution would increase significantly with depth, and such an increase would deplete the standing stock with only a steady state supply of particles from the surface. So there must be another source of particles to account for the increasing flux of particles with depth. Based on chemical and particle size analysis of the material in the traps, ancillary field measurements, and modeling of the aluminosilicate fluxes (Spencer, 1985) the continental margin is the likely source for the particles. Our data and that of Asper (1986) indicate that transport could occur as large particles, a mode that is inadequately sampled by standard filtration of water bottle samples or sensed by transmissometers.

CONCLUSIONS

While a camera system such as that used here does not provide particle samples from which compositional analyses can be made, it does yield a rapid survey of the distribution of large particles. A comparison with small-particle distributions (beam attenuation) shows that oceanic processes can affect large and small particle pools differently. If assumptions are made for particle density and settling behavior, the large-particle size distribution and abundance data from the LPC can be used to make first-order estimates of vertical flux. Further work must be done to establish the density and settling characteristics of the LPC aggregates in various oceanic environments, as well as correlations between fluxes measured with sediment traps and estimated from LPC data. The distribution of large aggregates should be considered when planning depths at which sediment traps are deployed.

Acknowledgements—This work was funded partially by the Office of Naval Research Contract N000-14-87-K-0102, the Texas Sea Grant College Program (Walsh), and the Texas A&M University Office of University Research. Ship time was provided by the State of Texas through Texas A&M University. We thank Ulrich Lobsiger and David Rilling of Lobsiger Associates, Inc. and Bret Berglund for help in acquiring the data. Dr Vernon Asper of USM/CMS kindly made available and assisted us with his image analysis system and provided stimulating discussion.

REFERENCES


GARDNER W. D. (1977) Incomplete extraction of rapidly settling particles from water samples. Limnology and Oceanography, 22, 764–768.


