Reports

Benthic Storms: Temporal Variability in a Deep-Ocean Nepheloid Layer

Abstract. *Time series measurements of light scattering were made for 2½ months at 20 meters above the bottom in the western North Atlantic. The highest values recorded with the nephelometer exceeded all previous measurements worldwide. Rapid changes indicated a high degree of activity near the sea floor, and some increases may have been related to atmospheric storms.*

A near-bottom nepheloid (cloudy) layer in the deep ocean has been noted (*1*) and mapped in the Atlantic Ocean from a considerable data base (*2, 3*). Little information is available, however, on the temporal variability of the concentration of suspended particulate matter (SPM) in deep-ocean nepheloid layers.

Published data showing temporal variability in the deep ocean have been derived from repeated lowerings of a Lamont-Doherty Geological Observatory (LDGO) Thorndike nephelometer (*4*) at four locations in the North Atlantic (*2, 5*), from 2-week deployments of a long-term nephelometer (LTN) at two locations in the North and South Atlantic (*2, 6*), from three repeated hydrocasts in the Gulf of Mexico (*7*), and from repeated nephelometer profiles on the slope off the coast of Washington state (*8*). On the basis of the calibration equation of Biscaye and Eittreim (*3, 9*), the concentration of suspended particulates measured by LTN varied by a factor of 1.8 (maximum, 35 μg/liter) on the Blake-Bahama outer ridge (15 m above bottom) and by a factor of 2.8 (maximum, 35 μg/liter) in the Vema Channel (12 m above bottom). Variations in the maximum concentrations determined from repeated lowerings at a single site were less than a factor of 2 where currents were thought to be minimal (Vema fracture zone and Hatteras abyssal plain), but by a factor of 4.3 (maximum, 85 μg/liter) on the Blake-Bahama outer ridge and of 10.7 (maximum, 290 μg/liter) on the lower continental rise, where western boundary currents are likely (*2, 3*). Differences in the concentrations of three filtered SPM samples obtained 1½ years apart near the bottom in the Gulf of Mexico exceeded a factor of 15 (maximum, 300 μg/liter) (*7*). Regionally, the bottom-water SPM concentrations in the North Atlantic vary by more than a factor of 70 (*2, 3*).

To further study the origin and temporal variability of nepheloid layers, an LTN was attached 20 m above the bottom to a sediment trap mooring in 4868 m of water on the northwest Bermuda Rise (35°41′N, 65°51′W). The LTN used was a modified LDGO Thorndike film recording nephelometer (*4*). The primary modification was the use of a strobe light source and single-frame advance to ob-

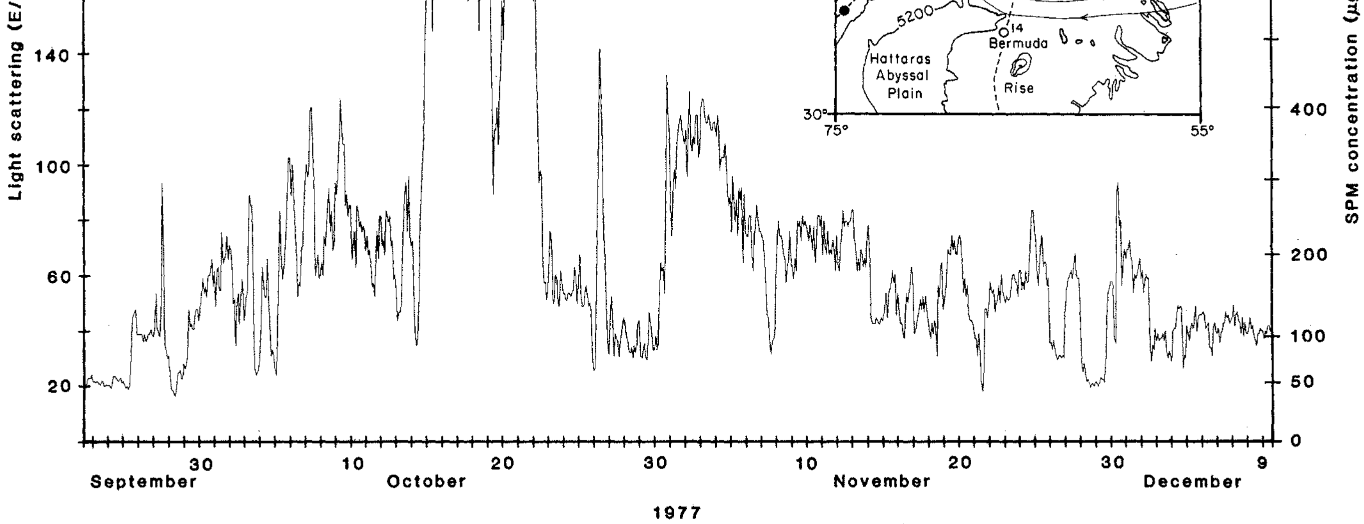

Fig. 1. The LTN data represent the quantity of scattered light divided by a direct reference light beam intensity (E/E_D). On the basis of the calibration of Biscaye and Eittreim (*9*), the scale of SPM concentration was added on the right. The tracks of hurricane Evelyn (14 to 15 October) and a tropical storm (29 to 30 October) are shown relative to the LTN site (*AII 96-3*). Open circles indicate position at 1200 GMT and closed circles position at 0000 GMT. The mean abyssal circulation below 4000 m inferred by Worthington (*13*) is shown north of Bermuda.

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tain an instantaneous measurement, rather than the time- and space-integrated sample obtained by using a continuous light source and film drive. A measurement of light scattering was made every 4 hours for 78 days from 23 September to 10 December 1977.

The resulting record (Fig. 1) showed unexpectedly rapid variations in light scattering. Some periods are so intense that they appear to be benthic "storms" in comparison to levels of light scattering typical of nepheloid layers. On the basis of the Biscaye and Eittreim calibration curve (*9*), the SPM concentration varied by more than a factor of 20, and daily changes of a factor of 2 to 10 were common. Both the maximum light-scattering values and rate of variation of this record were greater than those of any record previously obtained (*10*). The adjustable lens system on the instrument was in the open rather than "stopped" down because we did not anticipate such extreme values. As a result, the absolute values above log E/E_D = 1.9 have large uncertainties (± 0.2 to 0.5), although the relative shape of the curve is unaffected. Errors in log E/E_D are normally ± 0.05 (*4*).

Rapid changes in light scattering could result from any or all of at least four effects: (i) local (a few kilometers in scale) episodic erosion resuspending sediment up to 20 m above the bottom, (ii) upstream erosion and advection past the instrument, (iii) meandering of a current with high SPM concentrations, and (iv) changes in thickness of the well-mixed benthic boundary layer. The mooring had no current or temperature sensors, which would have helped to distinguish between these alternatives.

The well-mixed benthic layer can vary significantly in thickness. For instance, on the Hatteras abyssal plain the thickness of the well-mixed layer ranged from 5 to 60 m but remained between 15 and 25 m almost 50 percent of the time (*11*). The SPM concentration in the well-mixed layer at the bottom is usually higher than that just above this layer. If the LTN were near the boundary of the mixed layer and the SPM concentrations above and within the mixed layer were different, the LTN would record fluctuations as the mixed-layer thickness oscillated. Samples taken 9 hours before the mooring was launched showed a maximum concentration of 169 μg/liter 16 m above the bottom and 98 μg/liter 5 m above the level of the LTN (20 m). Changes in the LTN between these values could thus be attributed to fluctuations in the mixed-layer thickness, but we conclude that larger values, which

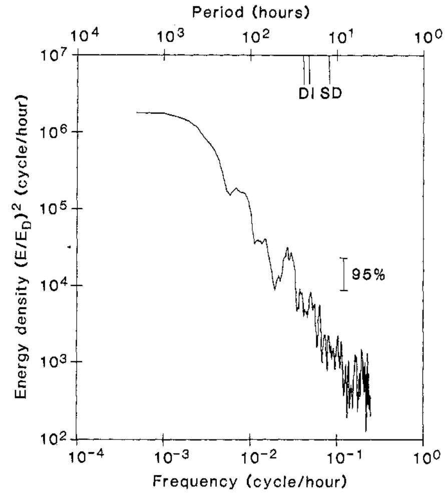

Fig. 2. Power spectrum of light scattering for site AII 96-3. Diurnal (*D*), semidiurnal (*SD*), and inertial (*I*) periods are indicated.

occur frequently and indicate much larger increases in SPM concentrations, result from other processes.

A power spectrum of the LTN record showed no peaks in the tidal range (Fig. 2). A peak at 35 to 37 hours was statistically significant at the 95 percent confidence level, but we know of no driving force, including interval waves, at that period. The peak may be related to changes in mixed-layer thickness, if such oscillations are recorded as peaks in the LTN record.

The mooring was located on top of the Gulf Stream outer ridge (*12*), a smooth, broad, gently sloping ridge which was the highest known topographic feature for 150 km. The site was selected to minimize the chance that material advected past the LTN was being scoured from a nearby topographic high. The location was also in the region where the proposed deep Gulf Stream gyre (*13*) changes from northwesterly to northeasterly flow, and it appeared to be in an erosional region, based on the presence of truncated reflectors seen on 3.5-kHz profiling records (*12*). Although the structure of the flow in the proposed Gulf Stream gyre is uncertain, it is probably a broad-band flow or series of large-scale eddies rather than a narrow current, and is therefore unlikely to cause rapid changes in SPM concentration by the meandering of a high-velocity core containing high SPM concentrations.

The most probable cause of large SPM fluctuations appears to be episodic erosion. Whether the erosion is local or distant is only hinted at by the slopes of the light-scattering curves. Local erosional events resuspending clouds of sediment would allow little time for entrainment of cleaner water by turbulent and diffusional mixing and therefore would register a more rapid increase in SPM values than distant events. The SPM concentration at any point, however, is a complex function of the initial concentration at the site of resuspension, the height of entrainment, the turbulence field, the velocity field, the time and distance of transport, and the fall velocity of the particles in the cloud. Although such detailed information cannot be derived from a point measurement of light scattering, we interpret the LTN record from 29 September to 30 October, which exhibits a broad peak of increased light scattering, as showing the passage of a distally resuspended cloud of sediment punctuated by frequent local events of resuspension. The large peaks, such as those of 14 to 23 October and 30 October to 7 November, are interpreted as "local" benthic storms.

The lateral extent of benthic storms can be estimated by their duration and an estimated current velocity. Based on an estimated current of 5 cm/sec, the 1-day events are at least 4 km across, since the portion of the cloud passing through the mooring may be only an edge. One-day events due to local erosion could be 16 km across, since critical erosion velocities are closer to 20 cm/sec (*14*). With that velocity, the large event from 14 to 23 October would indicate a cloud at least 145 km across.

The circulation pattern of the deep Gulf Stream gyre (*13*) (Fig. 1) indicates that the source of particles would be to the east, which is also the area (southern Sohm abyssal plain) where the maps of Biscaye and Eittreim (*3*) show the highest concentrations of SPM (although none as high as those recorded by the LTN and reported here). Recent hydrocast samples have shown concentrations of SPM up to 400 μg/liter in a region 750 km southeast of our mooring (*15*), but concentrations dropped below 100 μg/liter within 100 km of our mooring. An area with near-bottom SPM concentrations in the range of milligrams per liter was recently reported 800 to 1000 km northeast of our mooring (*16*), and in 1979 SPM concentrations up to 12 mg/liter were measured only 400 km to the northeast in 4900 m of water (*10*). These measurements indicate that bottom waters to the southeast and northeast of our site are at least occasionally very turbid.

A single photograph at the site of the mooring showed a featureless bottom which may have been smoothed by current. It is possible, therefore, that at least some of the events on the LTN record are due to episodic erosion locally, and we need not appeal to transport from distant places where high SPM concentrations have been reported.

The onset of two of the largest peaks in the LTN record are of particular interest because they coincided with the closest approach of two atmospheric storms. At 1600 hours on 14 October, hurricane Evelyn made its closest approach only 40 km from our mooring. The most intense peak in light scattering also began at this time and lasted several days. A weaker, unnamed storm made its closest approach of 250 km on 30 October. These are the only developed storms that passed within 400 km during sampling.

Experiments on the continental shelf measuring currents, pressure, light scattering, and bottom topography have shown a correlation between the passage of atmospheric storms and periods of resuspended sediments (*17*). Bottom-current velocities, which regularly exceeded the critical erosion velocity during each tidal cycle, did not increase during the storms, but there was a strong correlation between large pressure gradients measured at the sea floor and sharp increases in the turbidity of the water (*17*). Atmospheric pressure variations on time scales longer than several days and space scales of thousands of miles should not alter the isostatic equilibrium of the deep ocean, because the change in atmospheric pressure is balanced by a change in the height of sea level and the pressure on the sea floor should remain constant (*18, 19*). Pressure measurements in the Mid-Ocean Dynamics Experiment (MODE) showed low coherence between atmospheric and sea-floor pressure in both deep and shallow water (*20*). However, if nonisostatic conditions are created by a rapidly moving tropical depression and a pressure gradient is propagated to the sea floor, a corresponding mass transport of water would be required (*19*).

In the deep ocean there has not been an experiment like that of Butman and Folger (*17*) which could definitely show a correlation between atmospheric and benthic storms, but there has been a report of large increases in near-bottom current velocities coincident with the passage of atmospheric storms (*21*). In an attempt to detect any relation between atmospheric and abyssal conditions in this study, atmospheric pressure and pressure gradients above the mooring were measured from daily weather charts and plotted next to the LTN record. No correlation was apparent other than the nearby passage of the two storms mentioned.

To verify a causal relation between atmospheric conditions and conditions on the deep-sea floor, it will be necessary to simultaneously measure pressure, SPM concentrations, and current velocity near the sea floor as well as atmospheric pressure during the passage of surface storms. Whatever the cause of the benthic storms shown by our data, their frequency and intensity are much greater than previously measured in the deep ocean.

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9. The Biscaye and Eittreim calibration equation used here was from data on the Blake-Bahama outer ridge and lower continental rise and is: $\log Y = 1.19 \log X + 0.13$, where Y is the SPM concentration (micrograms per liter) and X is the scattered light intensity divided by the direct reference beam intensity (E/E_D).
10. After this study, higher values were recorded in the HEBBLE (High Energy Benthic Boundary Experiments) study area south of Nova Scotia in 4700 to 5000 m of water [P. E. Biscaye, J. R. V. Zaneveld, H. J. Pak, B. Tucholke, W. D. Gardner, *Eos* **61**, 1014 (1980); R. A. Kerr, *Science* **208**, 484 (1980)].
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Holocene Sea-Level Curves for Santa Monica Shelf, California Continental Borderland

Abstract. *A curve is constructed showing changes in sea level at the Santa Monica shelf over the past 18,000 years. The curve is based on radiocarbon dates, sedimentologic data, and high-resolution seismic stratigraphic analysis of late Quaternary terrace deposits. Sea level was 117 meters below its present position about 18,000 years ago. During the first 8000 years of the Flandrian transgression, sea level rose to at least 24 meters, fell to about 46 meters, and then rose to 20 meters, all below present sea level. Subsequently, sea level rose more slowly and without discernible interruption to its present position.*

Secular change in sea level is an important process variable in models of shelf sedimentation. Consequently, marine geologists have put forth a great deal of effort to determine the detailed history of Quaternary sea-level fluctuations. As a result of the interest in constructing a eustatic sea-level curve applicable to any shelf in the world, most of the studies have been restricted to areas thought to be tectonically stable. For this reason, a program aimed at deciphering sea-level

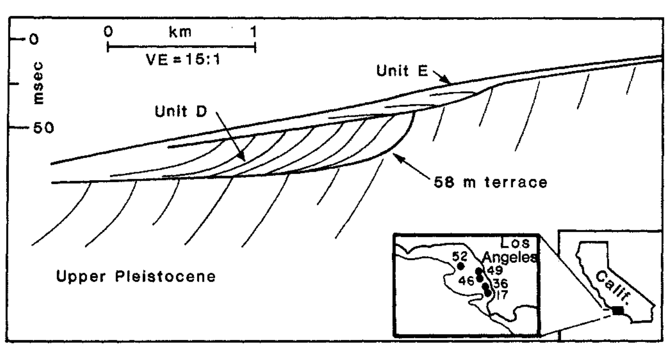

Fig. 1. Composite of inner shelf high-resolution profiles showing seismic facies and stratigraphic relations among late Quaternary units. Parallel onlapping beds of Holocene unit E and truncated clinoforms of Holocene unit D unconformably overlie upper Pleistocene foreset strata. Vertical scale is two-way travel time. Inset shows location of the study area.