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Temporal Variations of Beam Attenuation Coefficient on the Continental Rise off Nova Scotia

HASONG PAK AND J. RONALD V. ZANEVELD

School of Oceanography, Oregon State University, Corvallis, Oregon 97331

Two separate time series observations of light transmission in the bottom water on the Continental Rise off Nova Scotia show fluctuations of light transmission in a wide range, 0–50% transmission at $\lambda = 660$ nm. The range corresponds approximately to SPM concentrations of 12 mg/l to 150 μg/l. The former is the maximum value determined by filtration (Biscaye, 1980), and the latter is determined by an empirical relation between beam attenuation coefficient and particle volume determined by a particle counter. Nepheloid layers of significant turbidity, called benthic storms, were observed in 30 and 10% of the time, respectively, for the two observations, and each storm lasted 2–5 days. High frequency fluctuations represented by pulse lengths less than 10 min were observed superimposed on the low frequency fluctuations during 16 and 4% of the time. Both the major storms and the high frequency pulses are interpreted to be a result of resuspension of bottom sediments at varying distances from the instrument; the high frequency pulses are thought to be a result of erosion at a relatively short distance, while the low frequency fluctuations result from erosion at greater distance.

INTRODUCTION

In the region of the Western Boundary Undercurrent, Bottom Nepheloid Layers (BNL) have been observed to be more turbid and more extensive than in other areas, and such well developed BNL's are attributed to strong flow-boundary interaction [*Eittreim and Ewing*, 1972; *Biscaye and Eittreim*, 1974; *Biscaye et al.*, 1980; *Weatherly et al.*, 1980]. Since the well-developed BNL is generated by the high energy of the boundary current, we expect the process of interaction between the current and the bottom to be characterized by the temporal and spatial variations of the suspended sediment in the bottom water. Owing mostly to the lack of previous observations, the interrelation of the distribution of suspended sediments and the velocity fields are not well known.

To measure the temporal variation of suspended sediment concentration, a self-recording light beam transmissometer was moored on a tripod, the Bottom Ocean Monitor (BOM) of the Lamont-Doherty Geological Observatory. The light beam transmissometer mounted on the BOM was deployed 1 m above the bottom and was in operation from July 24 to September 27, 1979, at 40°05.2′N, 62°24.2′W, and from May 2 to September 22, 1980, at 40°23.3′N, 63°07.2′W. The sites were in water depths of 4890 and 4685 m, respectively. The sampling interval was approximately 4 min. In this paper we discuss the time series data and their spectra.

We infer suspended particulate matter (SPM) concentrations from beam attenuation coefficients based on an empirical relationship between beam attenuation coefficient and suspended particle concentration (volume) determined by a transmissometer and a resistive pulse particle counter, respectively. The beam attenuation coefficient is obtained by taking the negative natural logarithm of the beam transmission in a 1 m path. The relation obtained during the *Knorr*-74 cruise (September 1979) in the region of the mooring [*Spinrad*, 1982] is

$$V = 569.5\ c - 265.1 \pm 33$$

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where V is the particle volume concentration in parts per billion (ppb), and c is the beam attenuation coefficient in units of m^{-1} at $\lambda = 660$ nm. A density of 2.0 g/ml is used to compute the mass concentration.

THE 1979 MOORING

The time series data of beam attenuation coefficient obtained in 1979 (BOM-79) is shown in Figure 1. There are three large and two medium intensity maxima. The third maximum around the 58th day is an extraordinarily intense peak which was indicated by less than 0.01 ‰ transmission in a 1 m light path. The upper part of the peak is not plotted because the instrument measures light transmission, and the beam attenuation coefficient is not defined for zero percent transmission. The maxima, which last approximately 5 days (except for the second peak), are probably manifestations of major bottom erosion events either locally or upstream since no other source of high SPM is available, and we will refer to them as benthic storms. Benthic storms occur during approximately 37.5% of the deployment period.

The SPM concentrations during the storms were as large as 12 mg/l [*Biscaye et al.*, 1980], which is higher than any previous observation in the deep ocean. In between storms, SPM concentrations were in the range of 200–400 μg/l, which is higher than typical concentrations found in BNL's over the continental rise [*Jacobs and Ewing*, 1969; *Eittreim and Ewing*, 1972].

THE 1980 MOORING

The time series record of beam attenuation coefficient during May–September 1980 (BOM-80) is approximately twice the length of the BOM-79 record, and it was obtained approximately 65 km to the northwest of the BOM-79 location where crag and tail features were found in bottom photographs [*Williams*, 1981]. The time series data are presented in Figure 2. We find one major storm and several peaks of medium intensity; compared with the BOM-79 record, fewer storms and events are found in the BOM-80 record (Table 1).

The word 'event' is a descriptive term indicating beam attenuation peaks of medium intensity. For this paper,

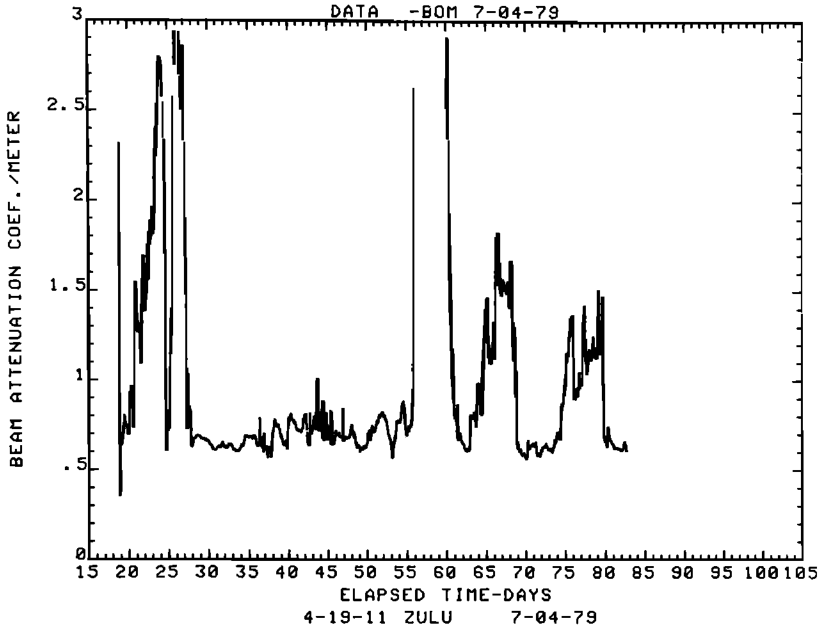

Fig. 1. The time series record of light beam attenuation coefficient obtained by a beam transmissometer, with 1 m pathlength of light at λ = 660 nm, mounted on the BOM-79 mooring (*L* 40°05.2′N, λ 62°24.2′W). The instrument was deployed 1 m above the bottom.

events are defined as those periods at which the beam attenuation coefficient is in excess of 0.8 m^{-1} but less than 1.0 m^{-1}. When the beam attenuation coefficient exceeds 1.0 m^{-1}, the term 'storm' is used. The frequency of events and occurrence of storms is approximately 32% of the time, slightly smaller than those of BOM-79.

The difference in frequency of storms between the two sets of observations may be due to effects of different observation times and locations. The strongest flow conditions are presumed to exist in a region with longitudinal ripples [*Williams*, 1981], and in 1979 the tripod was located closer to the ripple zone. Large spatial variations of the beam attenuation coefficient were observed over a relatively short distance in the experimental area during a R/V *Knorr* cruise in September 1979 [*Pak and Zaneveld*, 1982]; the observations, however, were made from a single ship, so the observed data contains a considerable amount of aliasing. The temporal variations shown in Figures 1 and 2 in this report demonstrate that a large change in beam attenuation can occur in a few hours, so that observations from a single ship may not be adequate to describe the spatial distribution of the beam attenuation coefficient in this region.

HIGH FREQUENCY FLUCTUATIONS

High frequency fluctuations were often found to be superimposed on a relatively constant background. Examples of

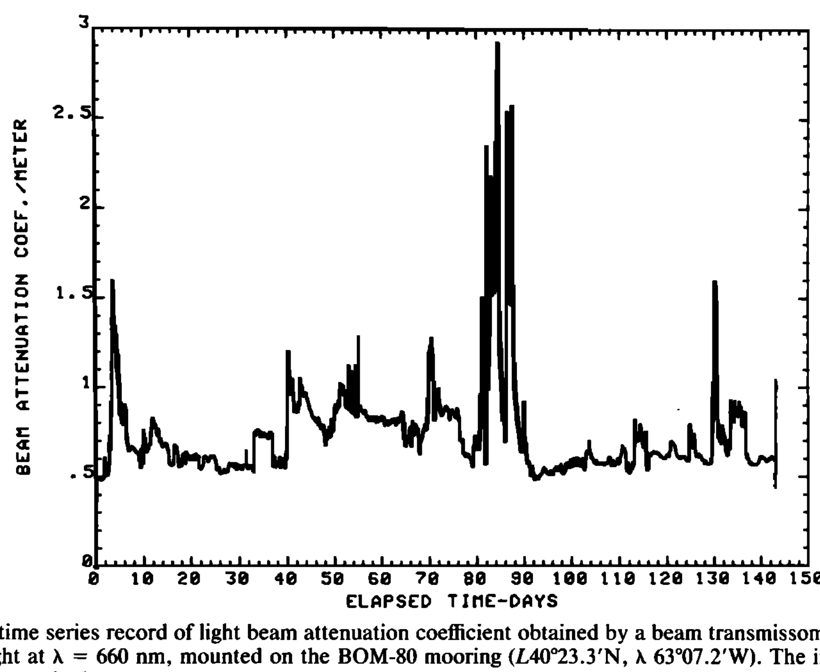

Fig. 2. The time series record of light beam attenuation coefficient obtained by a beam transmissometer, with 1 m pathlength of light at λ = 660 nm, mounted on the BOM-80 mooring (*L*40°23.3′N, λ 63°07.2′W). The instrument was deployed 1 m above the bottom.

TABLE 1. Number of Days With Events as Indicated by Beam Attenuation Coefficients

	BOM-79		BOM-80	
	Days	%	Days	%
$c > 0.7\ m^{-1}$	39	61	66	46
$c > 0.8\ m^{-1}$	24	37.5	46	32
$c > 1.0\ m^{-1}$	19	30	14	10

such high frequency fluctuations are presented in Figures 3 and 4 in an expanded time scale. Notice in Figures 1 and 2 that the high frequency fluctuations occurred during periods when the beam attenuation coefficient was high as well as low. Amplitudes of the high frequency pulses were approximately 0.15 m^{-1} in the BOM-79 record (Figure 3), but they were considerably larger, up to 3 m^{-1}, in the BOM-80 record (Figure 4).

The high frequency pulses usually occurred in groups. Since such high frequency pulses entail large horizontal gradients in particle concentration, they cannot be long lived and must be due to resuspension events. Let us then define a resuspension event as a group of high frequency pulses with beam attenuation coefficient amplitudes larger than 0.10 m^{-1}. The duration of resuspension events ranged from 0.2 to 3.6 days, which is slightly shorter than the duration of the benthic storms. The resuspension events occurred approximately 16% of the time during the BOM-79 mooring and only 4% of the time during the BOM-80 mooring.

The high frequency pulses shown in Figures 3 and 4 closely resemble those observed by using a much higher sampling rate on another tripod (BASS) moored in the same region [*Pak*, 1982]. By using a sampling interval of 16 s, the pulse lengths were observed to be approximately 2 min. Thus, the pulses observed during the BOM moorings are possibly aliased as a sampling interval of 4 min was used. The high frequency events observed on the BASS tripod were interpreted to be due to resuspension of bottom sediments within a short distance of the instrument [*Pak*, 1982]. Supportive evidence for this viewpoint came from (1) similarity between the high frequency pulses observed from the moored instrument and the high frequency pulses of SPM generated when the instrument tripod landed, (2) very large vertical gradients of SPM concentrations in association with the high frequency pulses, and (3) pulses are observed later at points higher above the bottom, which indicates that the sediment is the source of the SPM defining the high frequency pulses. Figures 3 and 4 show high frequency pulses superimposed on a slowly varying background. The clearer background water in between the pulses did not increase in beam attenuation appreciably. Because the background beam attenuation remains relatively stable during the high frequency events, it appears that only limited horizontal mixing has taken place between the clear background water and the water containing resuspended SPM represented by the high frequency pulses. Accordingly, the distance between the resuspension site and the instrument must be relatively small.

In the process of calculating the spectra, the data were averaged over four points resulting in one data point every 1024 s. Events longer than 5 days were detrended by hand. Most of these events were of a sawtooth or trapezoid shape. The storm in BOM-79 was replaced by a constant value. A low pass filter of sin x/x form with a half power point at 0.34 cph was applied. The data was decimated every five points resulting in a sampling interval of 5120 s. A Fourier transform was applied to 1024 points (60.68 days) for the BOM-79 record and 2048 points (121.36 days) for the BOM-80 record. Energy density spectra for the two time series records are shown in Figures 5 and 6. Near 0.1 cph (10 hour period) a peak is found in the BOM-79 record, but two peaks are found at 0.09 and 0.11 cph, respectively, in the BOM-80 record. The slopes of the spectra are nearly the same except at the high frequency end above 0.15 cph, where the spectral energy density drops sharply in the BOM-79 record. Because of the lengths of the records are different, a compari-

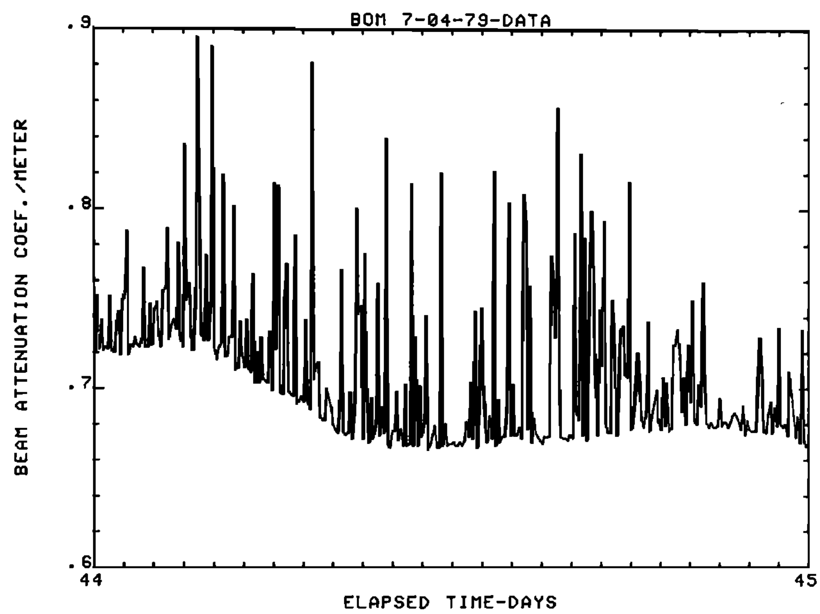

Fig. 3. Beam attenuation coefficients recorded during a high frequency 'event' in the 44th day of the BOM-79 mooring.

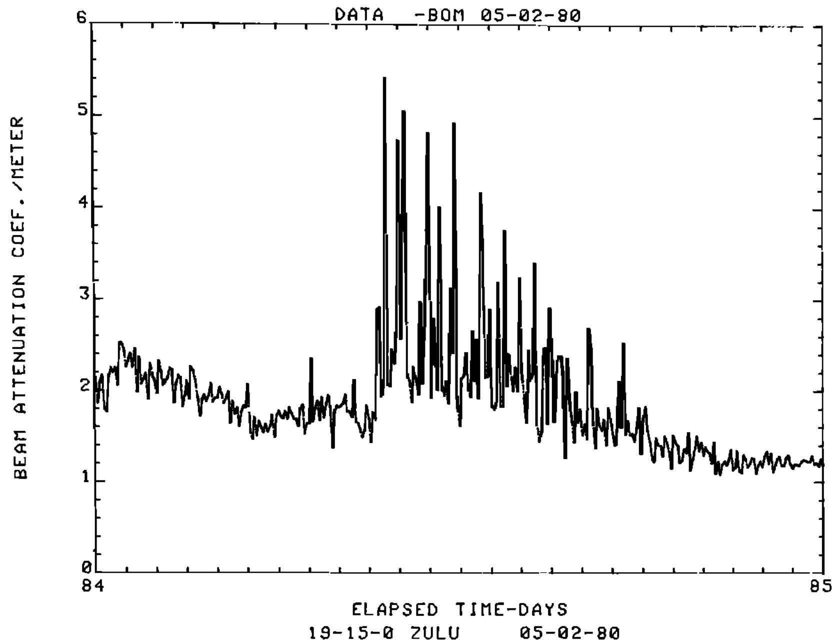

Fig. 4. Beam attenuation coefficients recorded during a high frequency 'event' in the 84th day of the BOM-80 mooring.

son of the spectra should be made carefully. The BOM-79 spectrum is smoother than the BOM-80 spectrum in the high frequency range.

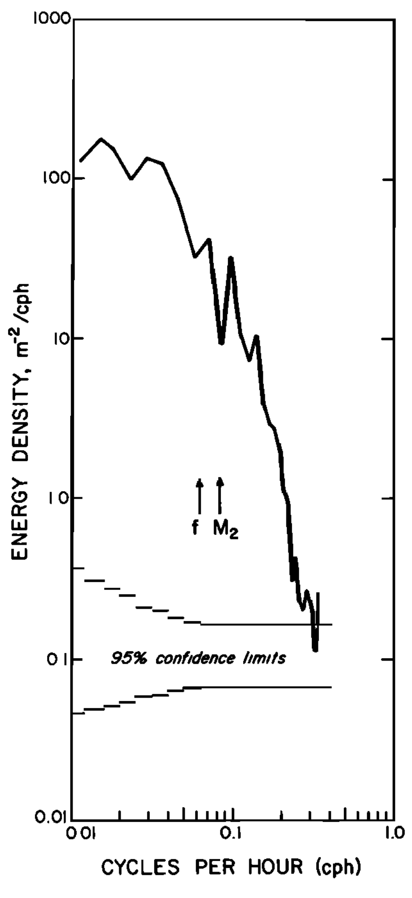

Fig. 5. Beam attenuation coefficient energy density spectrum for the BOM-79 record. Semidiurnal and inertial frequencies are indicated by M_2 and f.

DISCUSSION

During both BOM-79 and BOM-80 under quiet conditions, the beam attenuation coefficients were approximately 0.6–0.7 m^{-1} (Figures 1 and 2), which corresponds to 150–270 μg/l of SPM concentration, assuming a particle density of 2.0 g/ml. The high frequency pulses in Figures 3 and 4 correspond to contrasts of SPM concentrations over their background water by factors of approximately 2 and 34, respectively. From the 56th to the 60th day of the BOM-79 mooring (Figure 1), the transmission was lower than the instrument could detect (<0.01%), and SPM concentrations up to 12 mg/l were observed by direct filtration [*Biscaye et al.*, 1980] during the same period. The only conceivable source for such a high concentration of SPM in the deep ocean is the bottom sediment as the site is too far away from both the surface layer and coastal water, which are the two other prominant SPM sources.

During the 44th day of the BOM-79 mooring (Figure 3), the high frequency pulses corresponded to sediment concentrations of ~400 μg/l. The background concentration was ~230 μg/l. The pulses thus represent a concentration contrast of 170 μg/l relative to the background. During the 84th day of the BOM-80 mooring (Figure 4), the pulses contained 5.165 mg/l of sediment, while the background water contained 1.78 mg/l of sediment, which represents a concentration contrast of more than 3.467 mg/l. Pulse lengths previously determined by a higher sampling rate during a high frequency event was approximately 2 min [*Pak*, 1982]. Assuming a 10 cm/s horizontal current, this pulse length corresponds to a turbid cloud of ~12 m in horizontal extent. In time, these turbid clouds will dissipate by mixing with the surrounding water, which will result in increases in sediment concentration in the surrounding water and decreases of sediment concentration in the clouds. Since we made observations at one point only, these changes could not be observed directly. We notice in Figure 3, however, that the background during the BOM-79 moorings was not affected by the high frequency

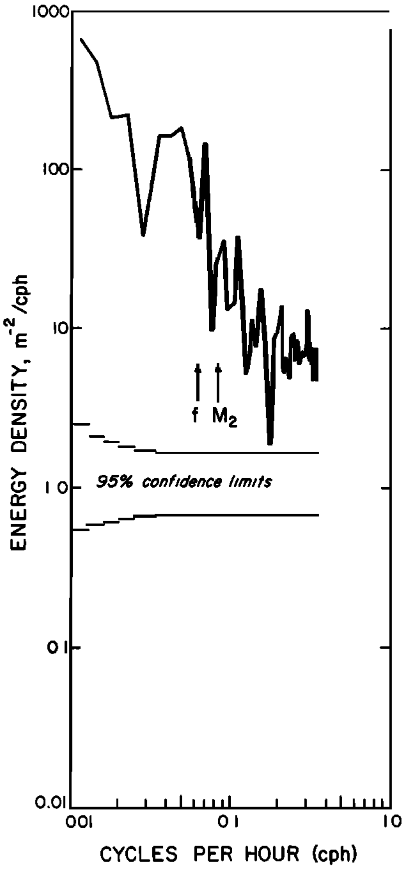

Fig. 6. Beam attenuation coefficient energy density spectrum for the BOM-80 record. Semidiurnal and inertial frequencies are indicated by M_2 and f.

pulses, so that the pulses appear to ride on the background. In Figure 4, on the other hand, the background appears to have been changed somewhat by the high frequency event; beam attenuation coefficients of the background are less before and after than during the period with the high frequency pulses. The background beam attenuation was approximately 0.4 m^{-1} higher during the period with the large pulses. In comparing the two high frequency events as shown in Figures 3 and 4, particularly the changes in the backgrounds, more mixing is apparent in Figure 4, so that if the mixing rate were the same during both time series observations, the sequence in Figure 4 would have been observed a longer time after the resuspension event. It is highly unlikely however that conditions were the same during both observations, so that no inference as to elapsed time since erosion can be made.

If a resuspension event is represented by a series of high frequency pulses, both BOM records show that local resuspension was not so frequent, and most of the high SPM concentrations during bottom storms are due to advection of SPM from distant sources. The distance from the erosion site must be large enough to attenuate the high frequency pulses during their advection.

Once a storm or smaller event generates a pool of turbid water by means of sediment resuspension, the turbid pool can be dissipated only by diffusion and particle settling. Characteristics of the time series record indicate that the low frequency variations are due to advection rather than local changes. For example, a pool of turbid water ($c = 0.75$ m^{-1} or 324 μg/l of SPM) was observed around the 35th day of BOM-80 for approximately 4 days (Figure 7) with a nearly constant SPM concentration. Both the leading and trailing edges of the pool are sharp. Before and after the pool was advected past the mooring, the prevailing SPM concentrations were about 153 μg/l. The pool contained a SPM concentration that was about 2.1 times higher than its surrounding water. Since local resuspension was characterized by high frequency pulses of ~2 min long, the stable values of the SPM concentration in the pool without short pulses indicate that the pool was generated in a distant upstream area and was modified during its advection.

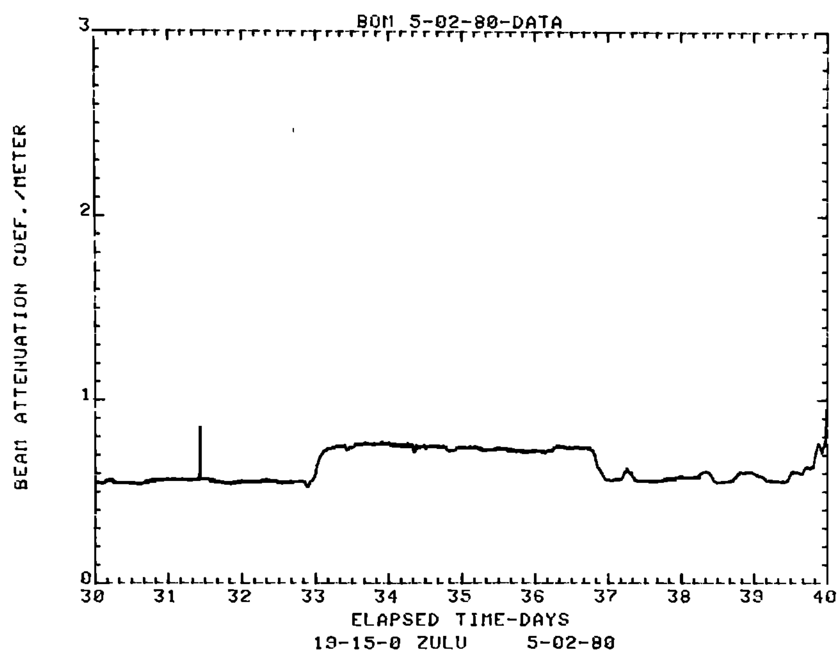

Fig. 7. Beam attenuation coefficients recorded during 10 day periods from the 30th to the 39th day of the BOM-80 mooring.

The observations presented in this paper were made at a distance of 1 m above the bottom. Observations made in the same general area but at a different time on the BASS tripod (at approximately 0.5, 1.0, and 2.0 m above the bottom) showed that the high frequency pulses were largely confined to within 1.0 m above the bottom [*Pak*, 1982]. There is no evidence, pro or con, that the high frequency SPM pulses described in this paper were also largely confined to the lower few meters. Further experimental observations relating the concentration of the resuspended SPM to the vertical gradient of SPM in various conditions need to be carried out. Light beam attenuation profiles observed simultaneously with CTD profiles at 44 stations in the same area during September 1979 showed that the lower part of the BNLs were nearly homogeneous over an average thickness of approximately 60 m and the homogeneous part of the BNLs corresponded to nearly isothermal bottom mixed layers [*Pak and Zaneveld*, 1982]. The low frequency variations shown on Figures 1 and 2 thus represent changes that occur in layers with an average thickness of 60 m in contrast to the high frequency fluctuations. The similar thicknesses of the bottom mixed layers and the homogeneous bottom nepheloid layers imply that vertical mixing had a similar effect on the vertical structure of temperature and beam attenuation coefficient. The concentration of SPM in the bottom nepheloid layer can be nonconservative primarily due to two causes: particle settling and sediment resuspension. The matching thicknesses then suggest that vertical mixing over a 60 m thick layer occurs in shorter times than the time required for restructure of bottom nepheloid layers by settling and resuspension of particles.

The BOM moorings were deployed in the approximate area where a 'cold filament' was observed [*Weatherly et al.*, 1980]. The BOM-79 mooring was located near the center of the 'cold filament.' It has not been established, however, that the 'cold filament' is characterized by higher SPM concentrations, but turbid bottom nepheloid layers were often observed in the area occupied by the 'cold filament' [*Pak and Zaneveld*, 1982]. BOM records (Figures 1 and 2) also clearly show that SPM concentration in the area of the 'cold filament' fluctuates in a wide range. If we accept the observation that the high frequency fluctuations indicate nearby sediment erosion, then such erosion occurred during 16% of the BOM-79 observation period and during 4% of the BOM-80 observation period. These high frequency fluctuations, however, do not always coincide with events or storms, the major characteristic of which is higher beam attenuation coefficients than during quiescent periods. By using the observed mean current of 7 cm/s in the 'cold filament' [*Weatherly et al.*, 1980], the 5 day long benthic storms correspond to turbid pools of water about 30 km long along the direction of the mean flow.

The most significant conclusions from the BOM observations are (1) benthic storms (beam attenuation coefficient > 1.0 m^{-1}) were present in the area 10–30% of the observation periods, (2) these storms last 2–5 days, and (3) during 4–16% of the observation period, local resuspension events, characterized by high frequency fluctuations, were present.

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