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Optical properties of the Kara Sea

Donald R. Johnson,[1] Vernon Asper,[2] Thomas McClimans,[3] and Alan Weidemann[1]

Abstract. This study was motivated by the need to understand dispersion processes which affect the redistribution of nuclear wastes in the Arctic from dump sites in the Kara Sea and in the rivers which flow into the Kara Sea. We focus on vertical profiles of light beam transmission and fluorometry made over the delta region fronting the Ob and Yenisey Rivers and over the East Novaya Zemlya Trough (ENZT). The delta region fronting the Ob River Estuary contains a large repository of particles in a dense bottom nepheloid layer with a maximum centered ~100 km in front of the estuary entrance and covering an area of roughly 200 km diameter. This suspended particle mass repository appears to contain both sediments and detritus and lends credence to the *Lisitsyn* [1995] concept of the marginal filter zone. In the deep water of the ENZT we found a strong increase of beam attenuation with depth, indicating a relatively large increase of particle mass concentration from ~50 m to the bottom (depths in excess of 300 m). The strongest concentration was adjacent to the southeast coast of Novaya Zemlya. We suggest that a type of hyperpycnical flow occurs from accumulation of sediments in the bottom waters of Novaya Zemlya fjords which then cascades down the steep slopes adjacent to the island, producing the particle mass distribution as observed by the transmissometer. The accumulation of these repositories of high particle mass concentrations in suspension would suggest that the residence time is high but that storm-driven events could act to disperse the material.

1. Introduction

The Kara Sea is a Russian Arctic marginal sea with large inflow from two major rivers which together drain almost half of the Russian land mass. This sea has received increased attention in recent years due to reports of dumping of nuclear waste materials by the former Soviet Union both into the Kara Sea and into the rivers which flow into the Kara Sea [*Murkowski*, 1994; *Edson et al.*, 1997]. This is in addition to the large nuclear weapons explosions which were performed in both the air and sea around Novaya Zemlya, as well as dumping into the fjords of that island. Four Norwegian/U.S. Military expeditions to the Kara Sea during the summers (August–September) of 1993–1996 sought to explore the level of nuclear contamination [*King et al.*, 1997; *Krosshavn et al.*, 1998] in the Kara Sea and the eastern Barents Sea and to determine transport pathways for possible contamination of the Arctic in case of breechment of either the dumped containers or of the holding ponds along tributary rivers.

During both the 1994 and 1995 expeditions a fluorometer and a beam transmissometer were mounted on a conductivity-temperature-depth (CTD) profiler and lowered for each cast. All of the sensors were mounted at the same level, ~25 cm above the bottom of the CTD cage. Since the Kara Sea has a relatively soft bottom (principally a sedimented river delta), the CTD package was lowered to gently touch the bottom at each station. The time of touching could be easily seen on the records and discarded. Hence, although no attempt was made to calibrate the fluorometer in terms of in situ chlorophyll or the beam transmissometer in terms of particle concentrations, the casts are valuable in that they captured the interesting near-bottom layer and provide information on settling and resuspension. In this paper we relate fluorescence and beam attenuation to environmental forcing as a means of furthering our understanding of transport and resuspension processes which affect distribution of materials in the Kara Sea and fluxes into the Arctic basin.

2. Setting and Background

Figure 1 shows the geographical setting and some of the bathymetric features of the Kara Sea. The bathymetry is dominated by a delta formed from the outflow of two large rivers, the Ob and the Yenisey. Together these two rivers have a larger annual outflow than the Mississippi River and a much stronger seasonal signal. For most of the year they are ice-blocked. However, during June the river discharges quickly peak, with combined outflow of ~100,000 $m^3\ s^{-1}$, subsiding to ~25,000 $m^3\ s^{-1}$ during late summer (T. A. McClimans et al., Transport processes in the Kara Sea, submitted to the *Journal of Geophysical Research*, 1999) (hereinafter referred to as McClimans et al., submitted manuscript, 1999). The impulsive spring discharge dumps large quantities of nutrients and sediments into the Kara Sea and can be expected to have a major impact on optical properties. The extensive, flat delta area fronting the rivers is characteristically 25–30 m deep and dominates the eastern portion of the Kara Sea. A relatively sharp delta edge is located at the 50 m isobath (Figure 1).

In the western Kara Sea the topography is dominated by the East Novaya Zemlya Trough (ENZT). With depths in excess of 380 m this trough is an unusual feature of a continental shelf

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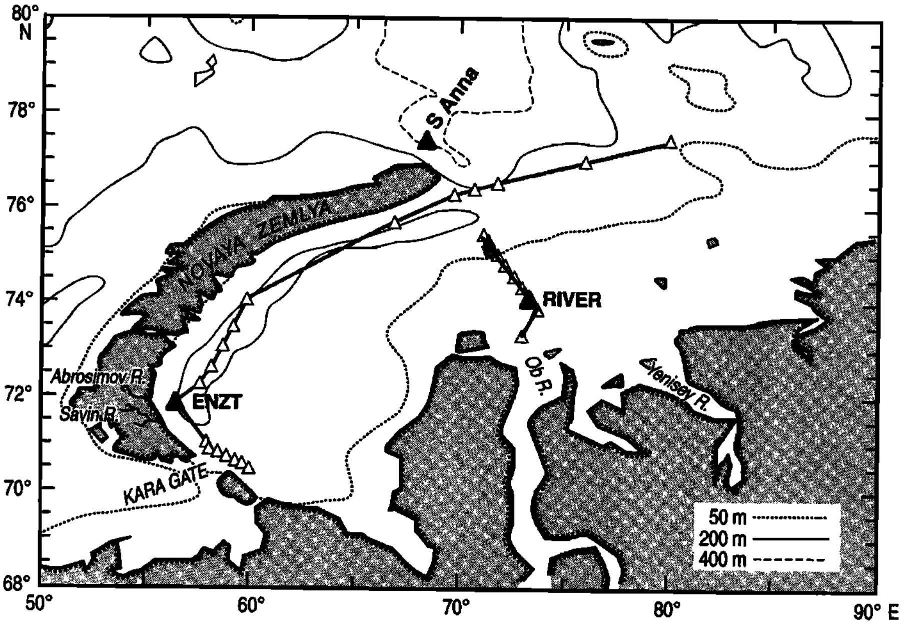

Figure 1. Key features of the Kara Sea and locations for sections presented in Figures 2 (delta section) and 5 (East Novaya Zemlya Trough (ENZT) section). Solid triangles represent locations of conductivity-temperature-depth (CTD) profiles presented in Figures 3 (delta section) and 6 (ENZT section). Location of a single CTD cast in the Santa Anna Canyon is also shown. The delta edge is given by the 50 m isobath (dotted line).

regime. The deep areas of this trough are blocked in the south by the Russian land mass and by a sill depth through the Kara Gate (Karskiye Vorota) of 70 m. In the north they are blocked from connection to the Santa Anna Trough, and hence access to the Arctic basin, by a sill at ~200 m depth.

Johnson et al. [1997] and McClimans et al. (submitted manuscript, 1999) reported on the hydrodynamics of the Kara Sea for the 1994 and 1993–1996 summer seasons, respectively. Surface currents flow westward from the rivers and then northward toward the Arctic (McClimans et al., submitted manuscript, 1999). However, owing to a strong halocline it was found that the surface currents are easily pushed by wind stress, and dispersion is strong above the halocline. In the deep basins of the ENZT the flow is also characteristically northward but weaker, and internal recirculation patterns are evident. Inflow of low-salinity, warm water from the modified Norwegian Coastal Current comes through the Kara Gate and influences the southern ENZT.

Both the surface and bottom ambient flows and the tidal flows during late summer are relatively weak (10–20 cm s^{-1}) with an exception near the river mouths where currents are about twice as large as that in the major body of the Kara Sea. Hence bottom stirring is not expected to be large during this season. It was also found that the relatively strong fronts along the delta edge inhibited exchanges with the deeper basin below the halocline, although eddies along the fronts may have contributed impulsively to the exchange.

There are very few studies of optical properties of the Russian Arctic Seas. The R/V *Dmitriy Mendeleev* Expedition of 1993 [*Lisitsyn and Vinogradov*, 1995] is an exception. This international expedition was carried out between mid-August and mid-October of 1993 and included studies of beam attenuation at 530 nm wavelength and fluorescence of dissolved organic matter [*Burenkov et al.*, 1995], and primary production with chlorophyll distribution [*Vedernikov et al.*, 1995]. It was determined that the most transparent waters occurred in the western Kara Sea and the most turbid occurred within the runoff areas of the Ob and Yenisey Rivers. This could be expected since river runoff carries large quantities of suspended and dissolved matter. An inverse relationship was found between salinity and surface chlorophyll concentration, and a strong frontal zone in beam attenuation as well as chlorophyll was observed separating river water from the more continental shelf waters of the western Kara Sea where exceptionally low productivity occurred. In this study we focus on two areas, the delta fronting the rivers and the ENZT. We also concentrate on the more extensive 1995 data, with some data from 1994 to demonstrate consistency between years.

3. Methods

The principal instrument system used for this study was a Seabird 911+ CTD interfaced with a SeaTech 660 nm wavelength, 25 cm path length transmissometer and a SeaTech fluorometer designed to measure chlorophyll-a with an excitation filter of 425 nm peak response and an emission filter of 685 nm peak response which is centered on the chlorophyll-a spectral emission peak. During 1994 the transmissometer was mounted with the beam in a vertical position. Finding an extremely sharp peak of beam attenuation at the level of the strong halocline, it was suspected that turbulence on the halocline affected the bulk index of refraction, and the resulting light dispersion gave a spike at that level. In 1995 the transmissometer was mounted so that the beam was horizontal with the result that the spike was significantly reduced.

All of the sensors were mounted 25 cm above the bottom of the CTD cage, and the cage was allowed to touch bottom at each cast. The point at which the cage touched bottom could be easily recognized and data eliminated at that point. The CTD sensors were initially lowered to a depth of 1.5 m to eliminate bubbles and to bring the sensors to equilibrium with the water, hence our coverage of the water column is from 1.5 m from the surface to 0.25 m above the bottom.

The transmissometer measures a well-collimated beam of light, producing a voltage range of 5 volts with accuracy of ±0.5% and linearity of ±0.1%. Calibrations from subsequent cruises showed an in-air voltage change of 3% over a span of 3 years. Considering the large range of light transmission encountered in the Kara Sea, this level of uncertainty is negligible. The fractional voltage change (Tr is the voltage measured/voltage in air) from a collimated monochromatic beam of light in a scattering and absorbing fluid is related to the beam attenuation coefficient c by the function $\mathrm{Tr} = e^{-cz}$, where z is the path length of the beam in meters (0.25 m here). Although dissolved material does contribute to light loss, it has been observed that the response of the beam attenuation coefficient with this instrument is principally governed by and is linear with total suspended mass concentration [*Spinrad et al.*, 1983; *Gardner et al.*, 1993] and that variations in the correlation of c to suspended loads can be attributed to changes in particle size distributions or compositions [*Spinrad et al.*, 1989]. In our study we cannot differentiate between compositions or size distributions; hence our values represent the convolution of particle type and size. For a transmissometer at 660 nm wavelength it is expected that the majority of the variability found is due to nepheloid layers of suspended sediment.

The SeaTech fluorometer provides a measure of relative biological variability, with the retrieved values expressed in voltages from 0 to 5 volts. Although we did not calibrate it for composition or concentration, we did remove a constant minimum value (0.237 volts) which was found in the deep waters of the Santa Anna Canyon and considered to be an offset bias. The voltages presented represent a relative index of phytoplankton concentration (hereafter called F for fluorescence index).

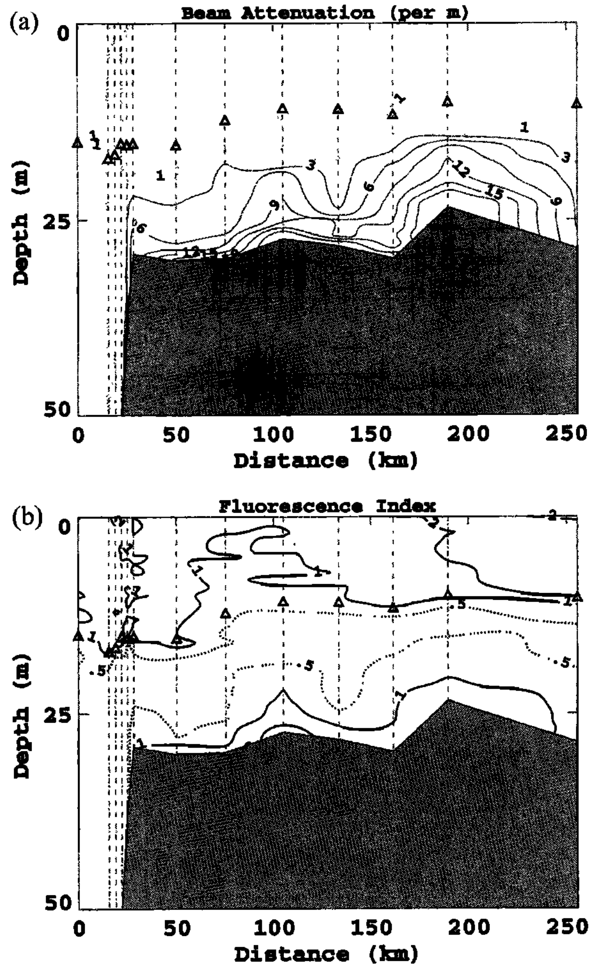

Figure 2. (a) River section beam attenuation c. Vertical dashed lines represent CTD profile locations (see Figure 1). Triangles represent depth of largest vertical density gradient. (b) River section fluorescence index F.

4. Results

Figure 1 also gives locations of selected stations for sections of properties which demonstrate the two principal optical regimes of the Kara Sea: the river delta and the ENZT. All station locations for the 1995 expedition are shown in Figure 4 and McClimans et al. (submitted manuscript, 1999).

Figure 2 shows the river delta section, with c and F presented for this section. Figure 3 shows a CTD profile of salinity, temperature, c, and F at station 525 near middelta. Referring to both Figures 2 and 3, it is evident from the elevated levels of both c and F that a large mass of particles is in suspension near the bottom and at least part of the mass is of organic derivation. In this thin bottom nepheloid layer, values of c above 20 m^{-1} mean that light of 660 nm wavelength is diminished to 1% of its intensity over a distance of 0.23 m. This is a remarkably turbid layer. With a characteristic upper layer c of ~1 m^{-1}, the penetration depth (to 1% light intensity) at 660 nm is <5 m. *Vedernikov et al.* [1995] found that an euphotic layer thickness of 14.7 m occurs near this location. It can be expected then that the bottom nepeloid layer is composed of sediments in suspension plus decaying organic matter of upper layer origin but not matter in active photosynthesis since it is below the depth of effective light penetration. It should be noted that detritus can contain chlorophyll-a and can fluoresce even though it may not be living material. Since the bottom of the Kara Sea does not contain significant quantities of macrophytes, the fluorescing detritus must be related to a history of phytoplankton concentration or to the remnant of biological materials carried down by the rivers.

It should also be noted that although the S and T profiles show a bottom mixed layer of roughly 12 m in thickness, c and F both increase sharply only in the bottom 5 m. This means that the bottom stirring processes are insufficient to spread the suspended matter throughout the bottom mixed layer (mixed in S and T). McClimans et al. (submitted manuscript, 1999) found that stirring velocities on the delta, averaged over a 2 week period in September 1995, were 2.3 cm s^{-1} with characteristic peak values of 10 cm s^{-1}. Although these bottom stresses are small and the average bottom currents are weak (<5 cm s^{-1}), they are still sufficient to hold bottom materials in suspension.

This concentrated bottom nepheloid layer is not as dramatic in front of the Yenisey River. In Figure 4 the horizontal distribution of bottom c is presented, which shows that this layer is confined to a fairly substantial area (~200 km) fronting the Ob River. The highest concentration appears almost 100 km out onto the delta from the river entrances, where we can hypothesize that the biological, sediment, and nutrient loads of

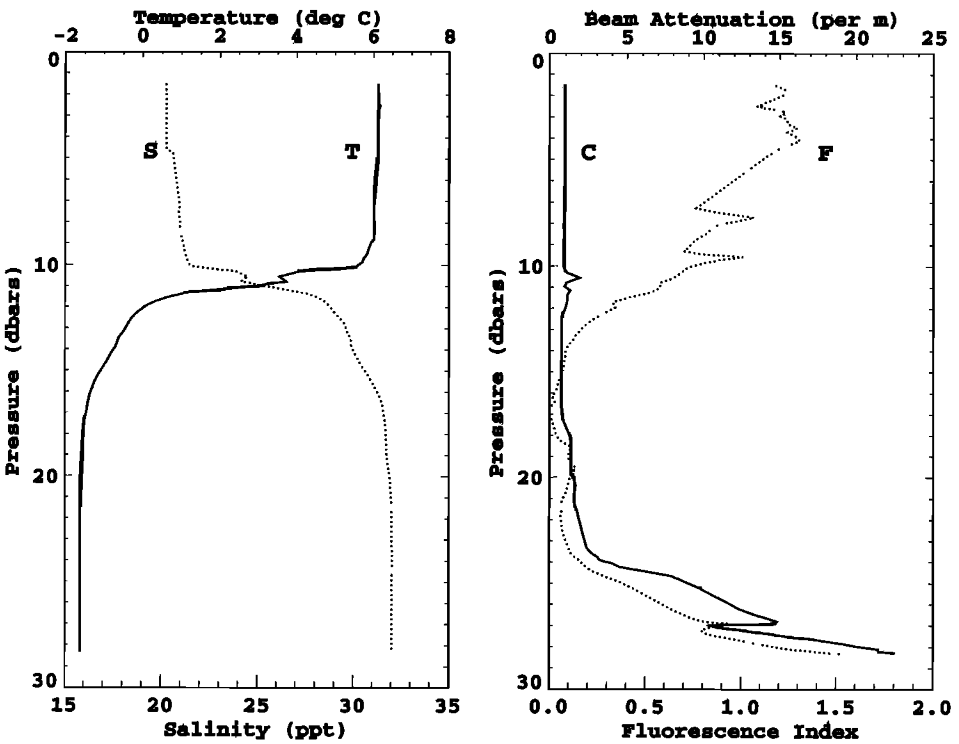

Figure 3. River section CTD cast (station 525) showing (left) salinity and temperature and (right) beam attenuation and fluorescence index. See Figure 1 for location.

the rivers are being transformed, and suspended matter is settling. *Lisitsyn* [1995] calls this area a "marginal filter," where sea and river water mix and complex transformations occur which lead to the removal of almost all matter suspended in the outflowing water in addition to formation of precipitates from dissolved material. Considering breakup of river ice dams in June and exceptionally strong, impulsive outflow, it is not surprising that the mixing zone would be extended out onto the delta. With bottom temperatures less than −1.5°C, organic decay would be slow, and the ability to retain fluorescence would be lengthened. Although algae growing on the bottom of sea ice can be significant in developing a bottom nepheloid layer when the ice melts, the distribution would be more uniform than presented here owing to substantial ice motion over the delta. The extension of high bottom values of c past the delta edge indicates that leakage from the delta is occurring. This might be expected, as delta edge eddies [*Johnson et al.*, 1997] and rapidly moving small-scale storm systems with barotropic current responses can transport near bottom matter across sharp bathymetric changes, especially where there are canyons.

The second principal optical regime of the Kara Sea occurs over the ENZT. This area is subject to the inflow of Modified Norwegian Coastal Waters (MNCW) through the Kara Gate, to the impulsive inflow of the same water type around the north tip of Novaya Zemlya, and to wintertime convection, especially in the southwestern part of the trough where the halocline is weaker. In Figure 5 a section of T and c is presented which extends from the south side of the Kara Gate, up along the ENZT, over the northern sill and back up onto the delta (locations in Figure 1). From the T section in Figure 5a the warm inflowing MNCW is clearly observable, with a strong front separating it from the body of water in the ENZT. Warmer water at middepth just beyond the northern sill marks the boundary of this deep ENZT water. The body of ENZT water below the seasonal pycnocline (which occurs at ~20 m depth) has temperatures below 0°C. A minimum in temperature occurs below the seasonal pycnocline with a subsequent maximum at roughly 100–150 m depth. Below the seasonal pycnocline the body of ENZT water has little vertical or horizontal gradient in density, hence we can expect mixing to be relatively efficient in spite of the low current velocities.

From the section of c presented in Figure 5b the most striking feature is the relatively strong increase with depth in the body of the ENZT, especially in the southern basin where

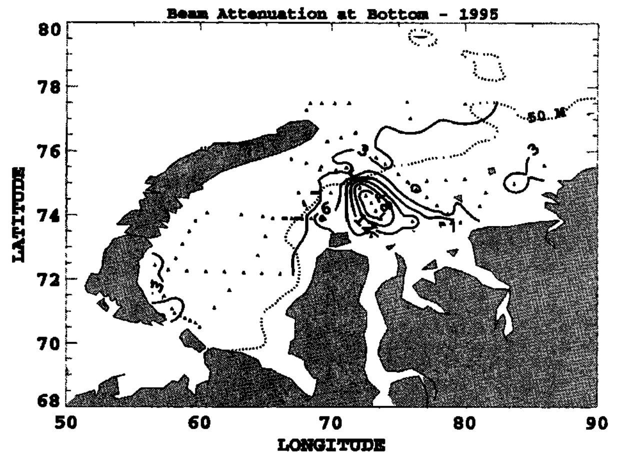

Figure 4. Horizontal distribution of beam attenuation c at the bottom. Dotted line represents the 50 m isobath, the delta edge.

a large "mound" of particulate mass appears. Checking with the horizontal distribution of bottom c from Figure 5b, we can identify this mound as an isolated area adjacent to Novaya Zemlya just north of the Kara Gate where c exceeds 3 m^{-1}. Using this distribution together with additional vertical sections (not shown), this area could not be connected with bottom levels of high particulate mass from either the Kara Gate inflow or from the delta region to the east.

Figure 6 shows a CTD profile in this southern area of high beam attenuation which demonstrates the vertical relationships among F, c, temperature, salinity and σ_t. Below the strong seasonal thermocline/halocline (10–20 m depth) a relatively large peak in F occurs. This reflects weak stirring from the surface together with competition between decreasing downwelling irradiance at depth and enhanced nutrient levels below the seasonal pycnocline. The peak in F at this depth is actually as large as the F in the surface waters over the delta (Figure 3). Beam c is relatively large at the surface, decreasing to a minimum just below the fluorescence peak at a depth of ~45 m. *Vedernikov et al.* [1995] found a euphotic zone thickness of 35 m here in the summer of 1993. However, the remarkable feature of the CTD cast is the strong increase in c from this minimum down to the bottom. If the surface layer were the source of particles which contributed to the elevated values of c, then we would expect the profile to decrease downward. However, from this profile, it is clear that there is no connection of the elevated particle mass at depth with concentrations at the surface, hence we can expect that the surface is not the source for the elevated values of c toward the bottom. A profile of c from a cast at this location in the same season during the 1994 expedition is also shown in Figure 6. The similarity demonstrates that consistent processes create the vertical structure of c.

In Figure 7, profiles of c from depths >250 m in the ENZT are displayed together with a profile of c from the head of the Santa Anna Canyon (location in Figure 1). T/S characteristics from the ENZT did not connect to T/S characteristics from the head of the Santa Anna Canyon, indicating a different water type was found there with a different particle mass concentration. The relatively large increases in c toward the bottom of the ENZT appear to be real and consistent from year to year, although we do not know the seasonal variations.

One plausible hypothesis for elevated c at the bottom in the ENZT is that it is created by a low-density hyperpycnical flow originating in sediment accumulation from several Novaya Zemlya rivers which empty into fjords in this area. Hyperpycnical flow is a type of nonignitive turbidity current in which the suspended load produces a water mass of higher density than ambient [*Mulder and Syvitski*, 1995; *Wright et al.*, 1986]. It can occur during the transformation of failed delta foresets or during impulsively large river outflows which resuspend previously deposited mouth-bar material [*Prior et al.*, 1987]. On the positive side of this argument, *Pfirman et al.* [1995] discovered a region of high surface turbidity in red reflectance from an advanced very high resolution radiometer (AVHRR) image of August 5, 1988, at ~72°N along southeast Novaya Zemlya which appeared connected to discharges of the Savin and Abrosimov Rivers. This geographically coincided with our area of high bottom enhancement of c. The CTD cast, shown in Figure 6, is directly in front of Abrosimova Bay. In addition, it would seem reasonable that the relatively low flows and steeply sloping topography in this area would provide a proper setting for distribution of sediments from hyperpycnical flows within the water column without cleaning the area of suspensions. We surmise that hyperpycnical flow cascades down the steep slope from Novaya Zemlya into the trough, sloughing relatively dense masses of fine grain sediments (for which the transmissometer is especially responsive) into the ENZT water column. This would appear as a bottom source of particles, with the particle mass decreasing upward as recorded by the transmissometer.

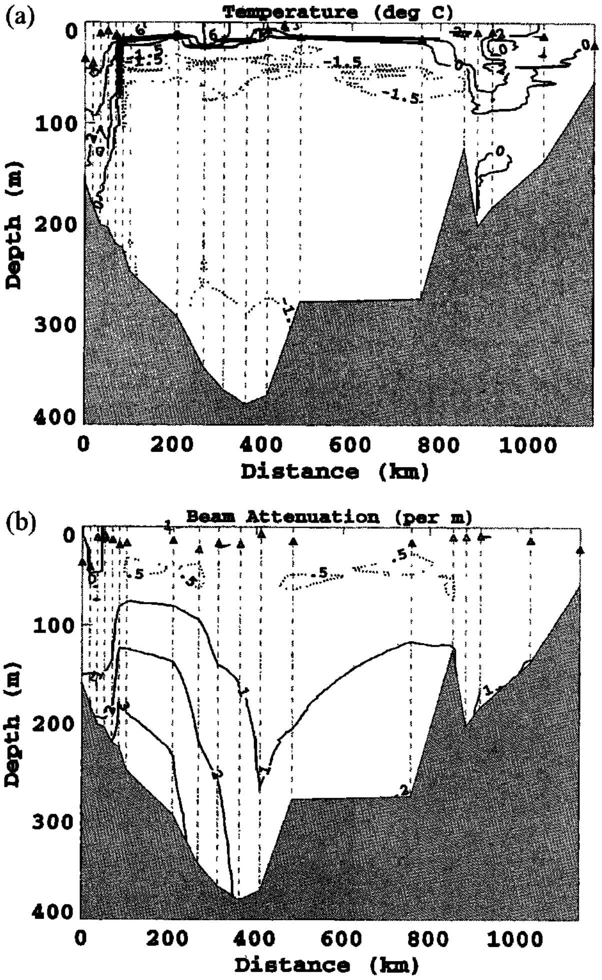

Figure 5. (a) ENZT section temperature. See Figure 1 for station locations. Section begins on south side of Kara Gate. (b) ENZT section beam attenuation c.

On the other side of the argument, it is not clear that the amount of sediment distributed through the water column is capable of producing hyperpycnical flow. If we assume that 10–1000 micrograms of suspended mass per liter results in an increase of c by 0.015 m^{-1}, then the added density given by a bottom c in excess of 3 m^{-1} would be between 0.001 and 0.1 σ_t units. The uncertainty in our argument depends on the nature of the particles and how they are physically distributed within the water column.

5. Summary and Discussion

This study has focused on several important aspects of optical properties of the Kara Sea in an effort to gain some understanding of particle dispersion processes which may impact the distribution of radioisotopes. It is known, for example,

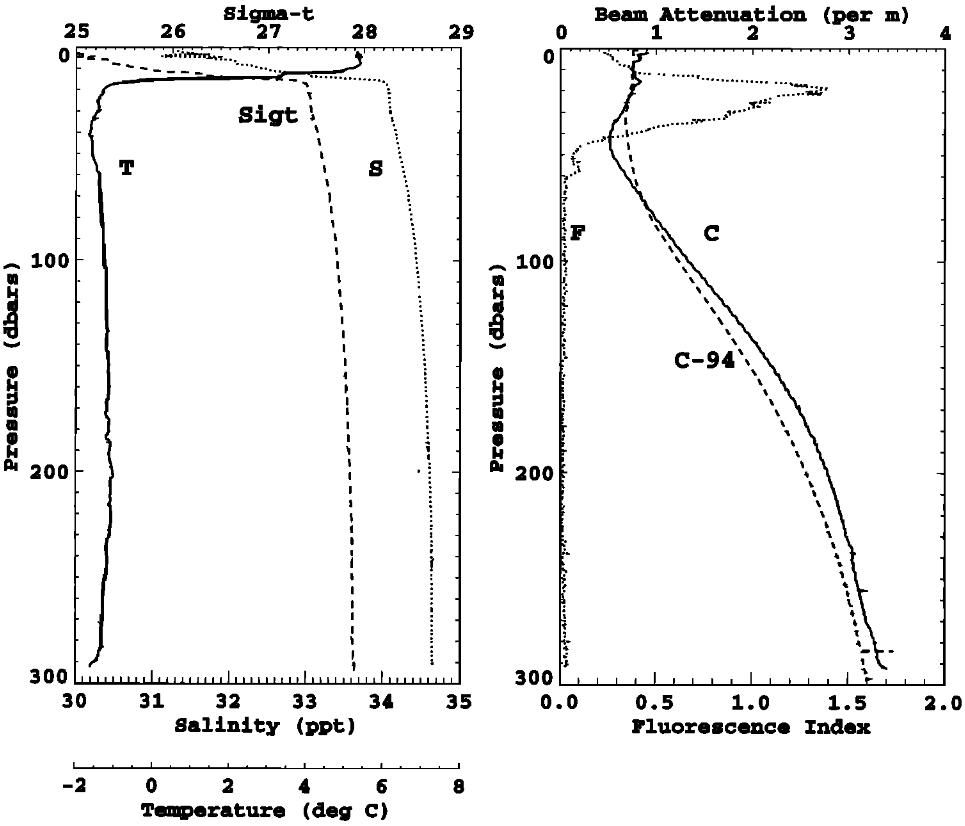

Figure 6. ENZT section CTD cast (station 5600) showing (left) salinity, temperature, and density and (right) beam attenuation and fluorescence index. See Figure 1 for location. The dashed line in Figure 6 (right) is beam attenuation taken during 1994 at the same location.

that ^{137}Cs easily sorbs to both organic and inorganic particles and hence can accumulate with particle accumulations and be transported in their suspensions.

We have shown that the delta region, fronting the Ob River Estuary, contains a large repository of particles in a dense bottom nepheloid layer with a maximum centered ~100 km in front of the estuary entrance and covering an area of roughly 200 km diameter. This suspended particle mass repository appears to contain both sediments and detritus and lends credence to the *Lisitsyn* [1995] concept of the marginal filter zone. The area fronting the Ob River Estuary has also been shown to contain large quantities of ^{137}Cs in the sediments (McClimans et al., submitted manuscript, 1999). Measured currents over the delta indicate that stirring is relatively small but sufficient to maintain particles in suspension. It should be expected that impulsive motions of the particles in this layer can take place from rapidly moving Arctic storms whose oceanic current responses are principally barotropic and hence result in enhanced bottom stresses. We would also expect that the energy content and stirring of the delta is enhanced during June with the strong impulsive outflow of the two rivers. *Johnson et al.* [1997] identified relatively strong eddy motions at the delta edge. This cross-isobath eddy motion can trigger bottom particle leakage from the delta into the deeper basins of the ENZT, where it may spread further with middepth advection.

We also focused our attention in the deep water of the ENZT where we found a strong increase of beam attenuation with depth, indicating a relatively large increase of particle mass concentration from ~50 m to the bottom (depths in excess of 300 m). The highest concentration was adjacent to the southeast coast of Novaya Zemlya. This concentration could not be connected to the delta or to inflow through the Kara Gate and could not be connected to the surface, which had lower particulate mass concentration than at depth. In

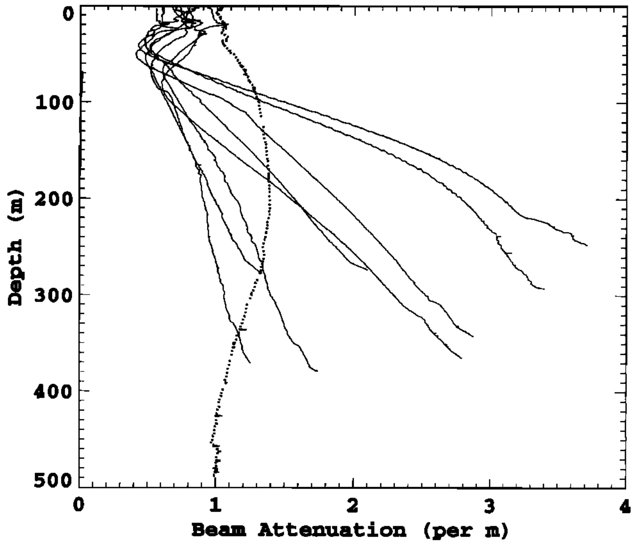

Figure 7. Profiles of beam attenuation *c* for water depths >250 m in the ENZT. Dashed line is beam attenuation profile at the head of the Santa Anna Canyon.

addition, currents were quite low in that area, reducing the probability of local stirring. However, on the basis of the observation through satellite imagery of a highly turbid river outflow from the Savin and Abrosimov Rivers [*Pfirman et al.*, 1995] we surmise that hyperpycnical flow from accumulation of sediments in the mouth-bars of Novaya Zemlya fjords can cascade down the steep slopes adjacent to the island, producing the particle mass distribution as observed by the transmissometer.

This hyperpycnical flow hypothesis fits into observations from previous explorations of several of the fjords along Novaya Zemlya [*Foyn and Nikitin*, 1994] in which poor visibility was reported during searches for dump sites within the fjords due to exceptionally high turbidity. The northern half of Novaya Zemlya is capped with glaciers, which produce very fine sediments and high beam attenuation. This hypothesis further suggests that radioisotopes from dump sites within the fjords can indeed be transported, through particle sorption, into the body of the Kara Sea from where advective flow throughs can transport it elsewhere.

Several important issues remain to be explored including interannual variations and sea ice contributions. Interannual circulation patterns of the Kara Sea are covered in a companion paper (McClimans et al., submitted manuscript, 1999) where it was suggested (following *Pavlov et al.* [1996]) that variations are governed by the position of an atmospheric low-pressure center which develops during summer at ~80°N. Circulation patterns can change depending on the position of this low relative to the Kara Sea. During 1995 the position of the low was opposite to that of 1994 with resulting moderate adjustments in the circulation pattern. We did not have sufficient optical coverage during other years to satisfactorily address the issue of how much these changing circulation patterns could change the optics. However, we did show a comparison (Figure 6) of beam *c* profiles from 1994 and 1995 at the same ENZT location, demonstrating that the same feature was present. In addition, a section across the high bottom beam *c* area fronting the Ob River during 1994 (not shown) indicated that that feature was also present. Hence we expect that the basic features described here are consistently found during summer.

Winter sea ice can be expected to provide a rafting mechanism for airborne particles and for ice algae, both of which can contribute to the optical character of the Kara Sea. Although we do not have winter measurements of sea ice, we expect that these loads are not high compared to river loads during the impulsive spring outflow. In addition, sea ice over most of the delta is not fast ice but rather moves under wind and current forcing which would tend to spread its contributions over a larger area. It would be expected that the high beam *c* found fronting the rivers is most likely attributable to the impulsive river outflow mixing with sea water. The major uncertainty with sea ice, however, concerns the potential for transportation of contamination by airborne particles.

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