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DISTRIBUTION OF PARTICULATE MATTER IN THE SOUTHEASTERN BEAUFORT SEA IN LATE SUMMER

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Abstract: As part of the Northern Oil and Gas Action Program (NOGAP) forty-one stations were occupied for measurements of CTD/transmissometer, suspended particulate matter (SPM), chlorophyll-*a* (Chl-*a*), and particulate organic carbon (POC) in the southeastern Beaufort Sea in September 1986. Preliminary results indicate that both the Mackenzie River and sediments in the nearshore (about 5 m or less) are two major particulate sources to the surface layer of the inner shelf (estuary). Further, a near-bottom light-attenuating layer was normally observed on the shelf. Compared to the interior Arctic Ocean, water over the Mackenzie Shelf has POC concentrations almost an order of magnitude higher throughout the water column (from surface to 350 m depth). This is probably a result of organic particles added to the surface layer by river input and phytoplankton production with subsequent settling into deeper water during the open-water season.

1. Introduction

The Canadian Beaufort Shelf offers a unique natural environment to study material cycling in the sea since it is the most estuarine of all arctic shelves and has an ice cover that varies both on seasonal and interannual time scales. As part of the Northern Oil and Gas Action Program (NOGAP), an interdisciplinary sub-project, Beaufort Sea Oceanography, has been undertaken to describe natural hydrocarbon distributions and primary productivity. Results of the project are to be applied to prediction of impact of industrial discharges of hydrocarbon in the shelf, and the setting of rational regulations for oil production.

The shelf receives large quantities of fresh, turbid water (15×10^6 t of suspended matter and 3.7×10^{11} m^3 of water annually) from the Mackenzie River, mostly between May and September (Thomas *et al.*, 1986). Understanding the behaviour of suspended particulate matter (SPM), therefore, is essential to the study of hydrocarbon and other substances in the Beaufort Shelf because SPM plays important roles in cycling as a transport agent for various natural and man-made substances, as a dynamic site for biological and chemical reactions and as a food source for marine organisms. In addition, hydrocarbon which is strongly hydrophobic tends to associate with solid particles (Karickoff *et al.*, 1979). Unfortunately, the particulate data base for the Beaufort Sea is meagre (Bornhold, 1975; Matsumoto and Wong, 1977), and no published information on particulate organic carbon (POC) is available. In September 1986, we collected more than 150 water samples for SPM, POC, and chlorophyll-*a*

(Chl-*a*) and ran profiles for conductivity, temperature, percent light transmission, and depth (CTTD) on three transects over the Mackenzie Shelf and slope. This paper presents preliminary results describing general features of particulate distributions and dynamics in the open water season.

2. Materials and Methods

Field work was carried out from 10 to 16 September 1986 aboard the "Arctic Ivik" on the continental shelf and slope offshore of the 3 main channels of the Mackenzie River (Fig. 1). Three transects were occupied, with water depths from 5 m to over 1000 m water depth on the slope. The eastern section (Transect C) was studied most intensively and, unless indicated otherwise, the results presented in this paper refer to it.

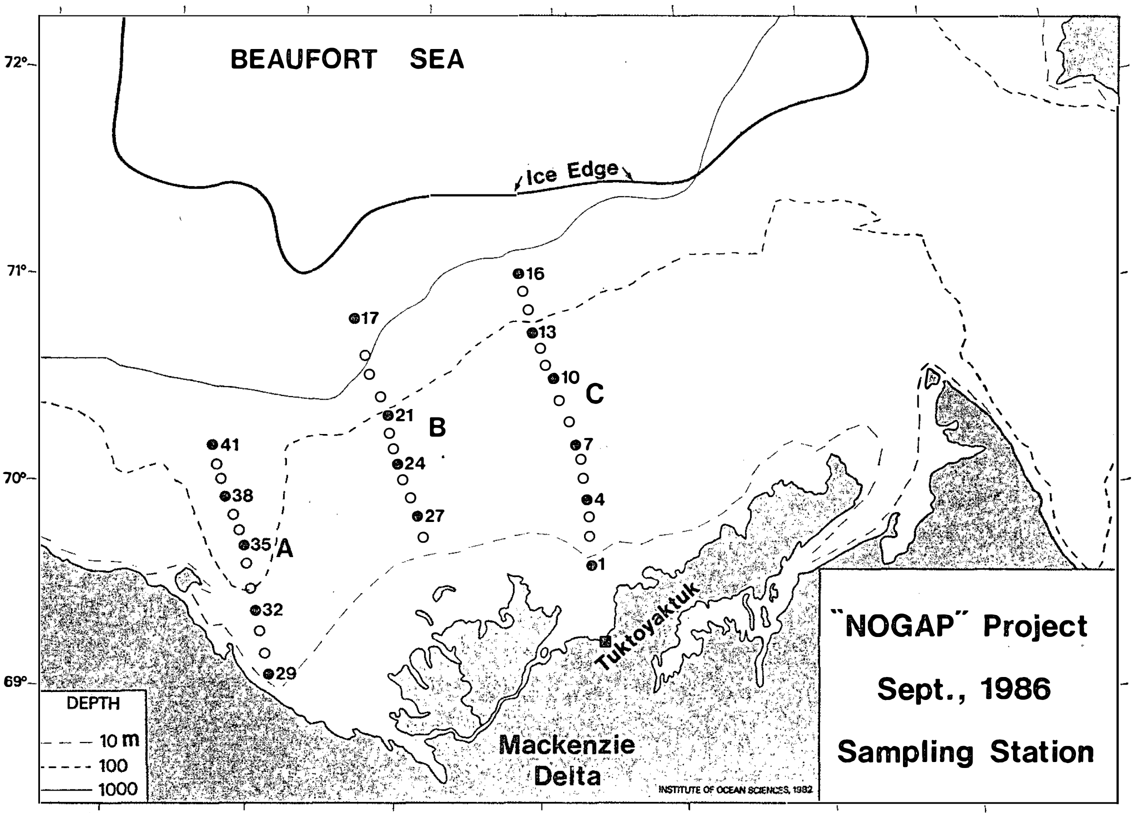

Fig. 1. Location of oceanographic stations and the ice-edge in the Beaufort Sea Shelf study in September 1986. The three north-south transects are noted as A, B and C.

Vertical profiles of temperature, conductivity and percent light transmission were made at each station using a Guildline or an Applied Microsystem CTD probe equipped with a Sea Tech 0.25 m path length (660 nm) beam transmissometer. Water samples were collected with 5-*l* Niskin and 10-*l* Go-Flo bottles. Immediately after bottles were retrieved, samples for salinity, dissolved oxygen, nutrients, and $^{16}O/^{18}O$ were drawn ($\sim$1 *l*) and the remaining water was drained into polyethylene carboys. After thorough mixing, subsamples (1 to 4-*l*) were vacuum filtered ($<$150 mmHg) through single, precombusted (500°C for 1 h) 47 mm Whatman GF/C glass fiber filters. After filtering, the filters were rinsed with 3% NaCl solution and stored in precombusted, aluminum foil. Bank filters were prepared by treating them like sample filters without filtering a water sample. Organic carbon and nitrogen on the filters were analyzed using a Perkin-Elmer Model 240 elemental analyzer after filter treated with conc. HCl vapour in a closed container for 8 h to remove inorganic carbon. Blanks were equivalent to 6.1 μg C l^{-1} (s=1.5 μg l^{-1}, n=5) for a 1 *l* sample. Another 1–4 *l* water sample was filtered through a preweighed 47 mm diameter, 0.4 μm pore size Nuclepore polycarbonate filter to determine dry weight in suspended particulate matter. Blanks, determined by double filtration on a random basis, were found to be less than 0.01 mg l^{-1} (s=0.012, n=22), and the pooled standard deviation of replicate determinations 0.04 mg l^{-1} (n=9). For Chl-*a* determination, 0.25–0.50 *l* water samples were filtered through 24 mm diameter Whatman GF/C filters. Chl-*a* was determined fluorometrically with a Turner Designs fluorometer. Blanks were estimated from deep samples to be less than 0.02 mg m^{-3} (s=0.01, n=10), and pooled standard deviation of replicates less than 0.04 mg m^{-3} (n=12).

3. Results and Discussion

3.1. Distribution of water properties

Sections of temperature, salinity, SPM, POC and Chl-*a* along transect C are shown in Fig. 2. Water over the shelf could be described as approximately a two-layer system except for the nearshore (station 1). Warm (>5°C), brackish water (<25‰)

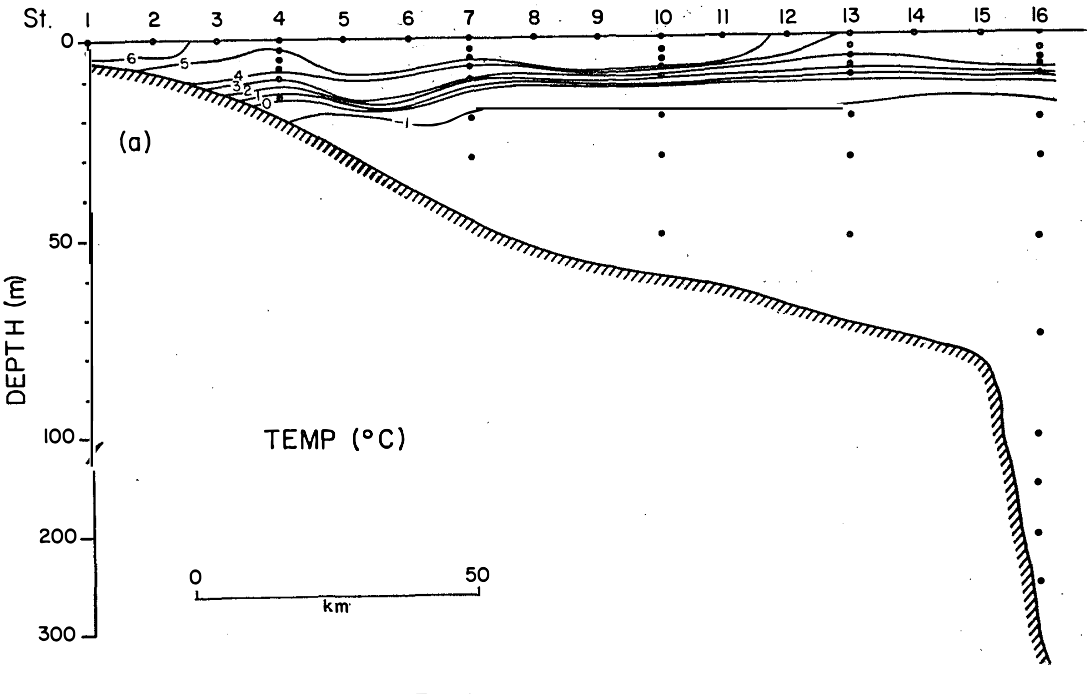

Fig. 2a. Temperature.

Fig. 2. Temperature (a), salinity (b), SPM (c), POC (d) and Chl-a (e) distributions across the transect C.

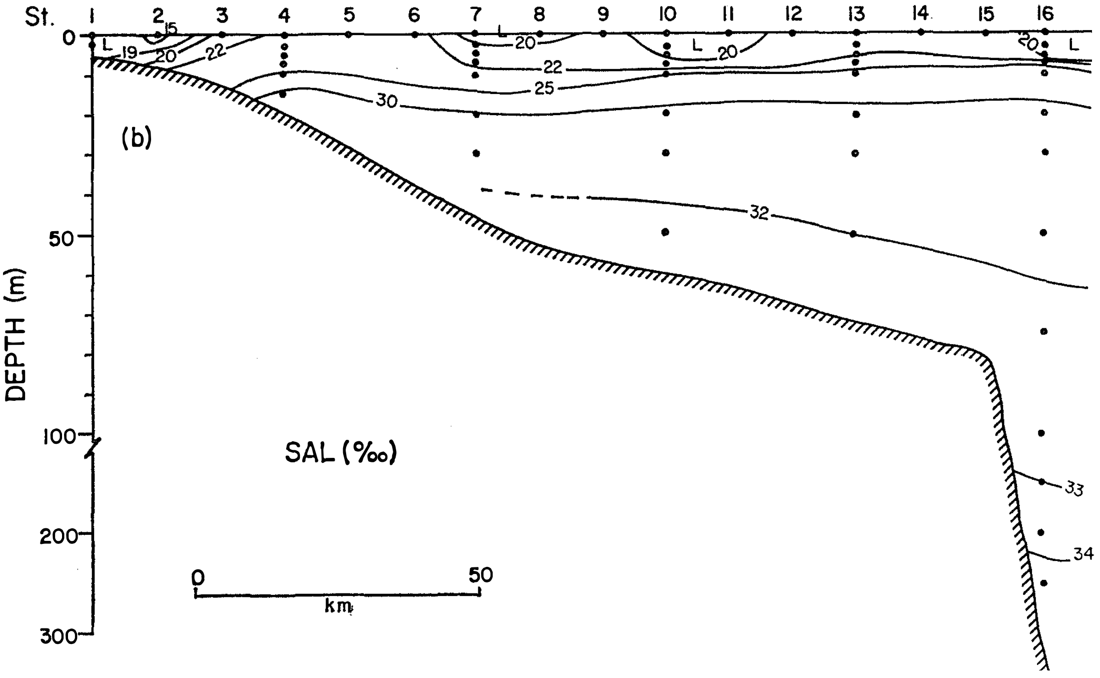

Fig. 2b. Salinity.

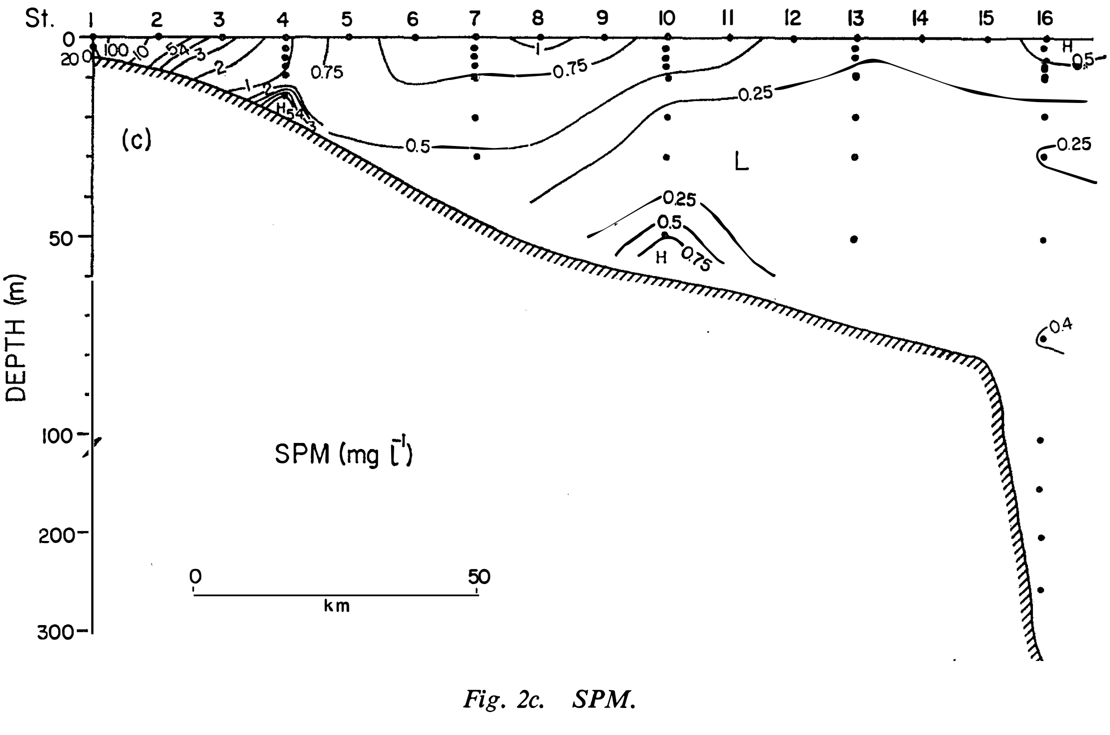

Fig. 2c. SPM.

in the top 10–15 m was separated from the underlying cold, saline waters by a strong pycnocline. It has previously been estimated (Macdonald *et al.*, 1987) that the Mackenzie River contributes sufficient water to the shelf annually to account for a 5 m layer of fresh water. Ice-melting in summer adds a further 1.8 m of fresh water with a salinity of about 3‰ (Melling and Lewis, 1982).

Figures 2c and 2d show high SPM and POC concentrations in both surface waters

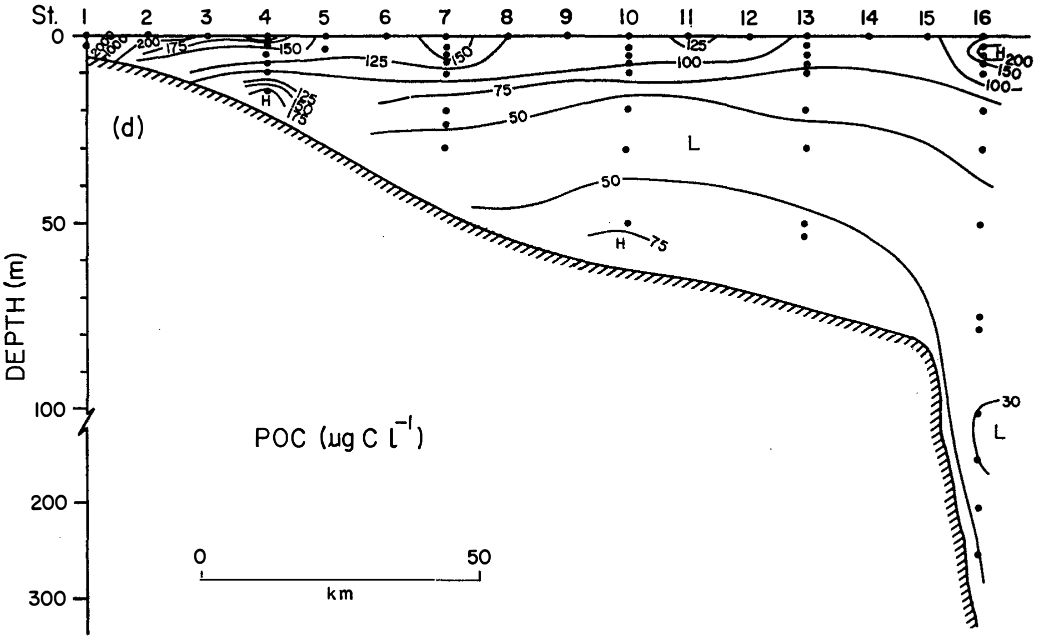

Fig. 2d. POC.

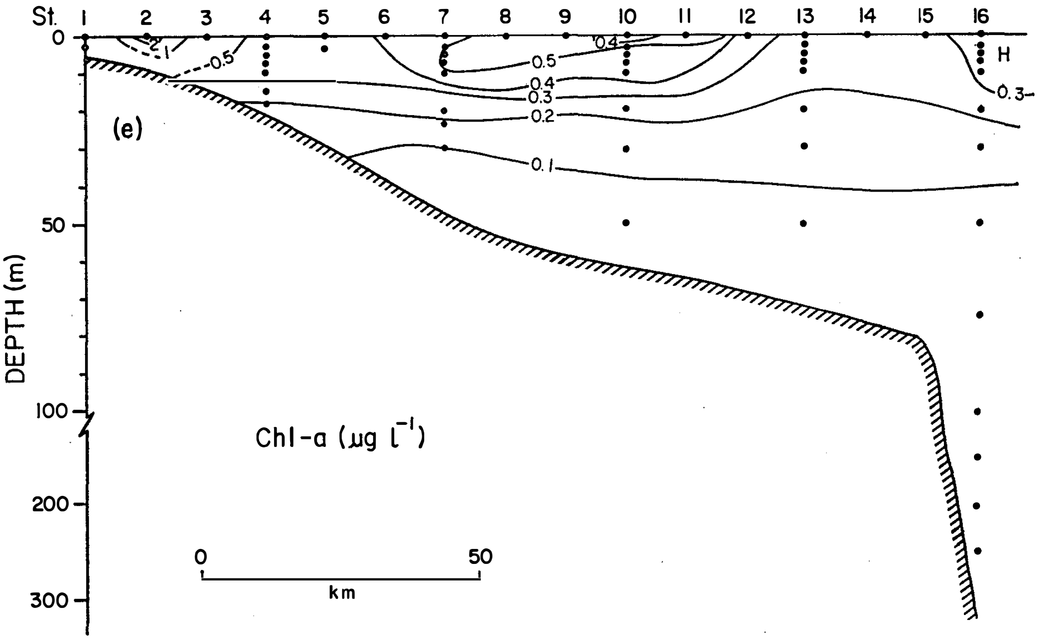

Fig. 2e. Chl-a.

above the pycnocline and in the near-bottom water over the Shelf; lower values were observed at mid-depths. Particulate concentration in the surface layer decreased sharply between Stns. 1 and 5 in the Mackenzie estuary. The highest SPM and POC concentrations were observed at the shallowest nearshore station where the water column was relatively well mixed (Figs. 2a–2d). The SPM and POC concentrations were 181 mg l^{-1} and 2290 μgCl^{-1} at 0 m, and 225 mg l^{-1} and 3650 μgCl^{-1} at 3 m depths respectively. These values are an order of magnitude higher than SPM and POC concentrations observed at Stn. 2 and yet several times higher than those found within the Mackenzie River itself (ERICKSON and FOWLER, 1986). This turbidity maximum cannot be explained by simple mixing, but requires an additional source of particulates or a mechanism for particle recycling. It is likely that bottom resuspension (forced by winds and tides) maintains high suspended load concentration in this nearshore zone.

Tidal flow often controls vertical mixing in estuaries (ROMAN and TENORE, 1978; SINCLAIR *et al.*, 1981). However, shallow depths over an extensive area and a long fetch in late summer combine in the Mackenzie estuary to make wind-generated waves potentially more important. Indeed, it has been estimated that inside the 5 m isobath waves may resuspend bottom material over 50% of the time during open water season (HARPER and PENLAND, 1982). This has been observed in other estuaries (FANNING *et al.*, 1982; GABRIELSON and LUKATELICH, 1985) and for example, DEMERS *et al.* (1987) have related highly variable Chl-*a* concentrations in the littoral zone (2–6.5 m) of the St. Lawrence estuary with variations in wind field. They found that wind velocity exceeding 4 m s^{-1} resulted in significant resuspension of POC in the water column. During our sampling period, wind velocities exceeded 5 m s^{-1} at almost all stations, and were greater than 10 m s^{-1} at over half of them. Thus, the abnormally high particulate concentrations at Stn. 1 could easily be accounted for by induced resuspension of bottom sediments. Further, the organic carbon content of SPM at Stn. 1 (1.3–1.6%) was much lower than that associated with Mackenzie River SPM (8.7% in April; ERICKSON and FOWLER, 1986) and closer to the values found in bottom sediments (1.4–1.6%; PELLETIER, 1975).

Chlorophyll-*a* distribution along this transect did not coincide with those of SPM or POC. Highest Chl-*a* concentration (2.3 mg m^{-3}) was found in the surface layer at Stn. 2. Elsewhere Chl-*a* concentrations at the surface were relatively low (0.21–0.87 mg m^{-3}) and without systematic trends. Highest values at a station were usually found in the upper 10 m; at 50 m and deeper, Chl-*a* levels were less than 0.1 mg m^{-3}.

3.2. *Salinity-particulate relationship*

Figures 3a and 3b show the relationship between salinity and particulates (SPM and POC). At depth, where salinity exceeds 30‰, SPM and POC tended to be uniformly low except where there has been bottom resuspension (dashed envelope on Figs. 3a and 3b). It is clear that surface SPM concentrations at most nearshore stations were anomalously high and considerably variable compared with those of offshore stations in the same salinity range.

The scatter plot of salinity *vs.* SPM for offshore stations (see Fig. 3a) shows curvature which infers SPM removal from the surface layer. Such non-conservative behaviour requires particle loss by settling in addition to a simple dilution. MATSUMOTO and WONG (1977) found similar behaviour of suspended particulates (measured by Coulter Counter), although they did not sample a turbidity maximum such as we found at Stn. 1 during our cruise. Several factors complicate the relationship between salinity and particulates; differential settling of particles as affected by size, density and organic composition, production of particles by phytoplankton, grazing by zoo-

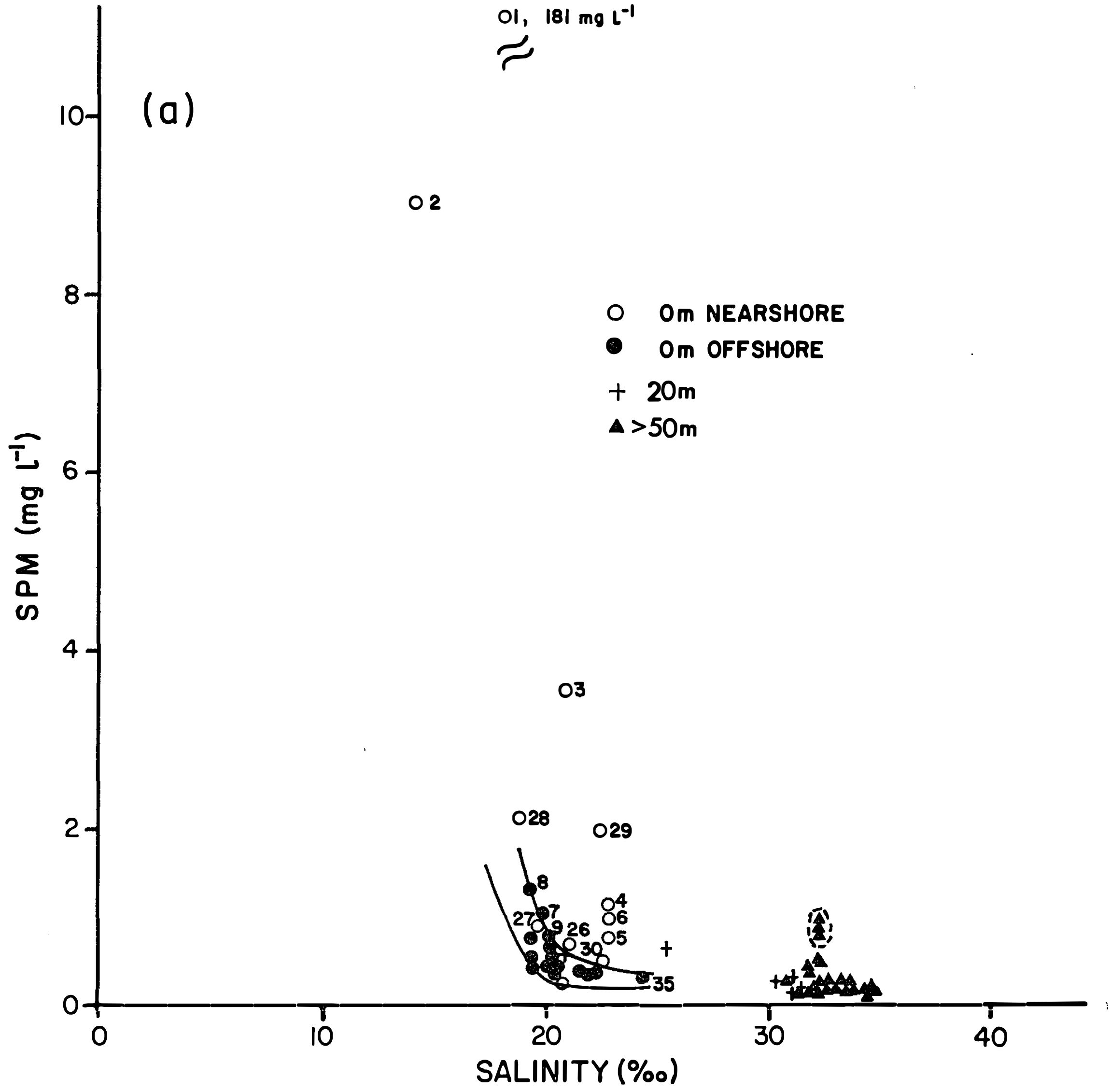

Fig. 3a. Relation between salinity and SPM in the surface water from all stations.

plankton, and discontinuity of water masses caused by physical processes and more than one source zone. In this preliminary overview we have not attempted to resolve these factors.

The nearshore is particularly prone to large fluctuations in SPM and POC concentrations since the Mackenzie River impinges on this zone and bottom resuspension can occur readily. Since the particulates will be important transport agents for pollutants from industrial activity, it becomes crucial to separate the particle sources to understand how they are passed through the estuary; C content appears to be one of the important identifiers.

3.3. Light transmission profiles

The light transmission profiles (Fig. 4) showed, in general, low percent transmission in surface and near-bottom water with a minimum in water of mid depth. Comparison between Figs. 4a and 4b indicates that transmissivity in the estuary was

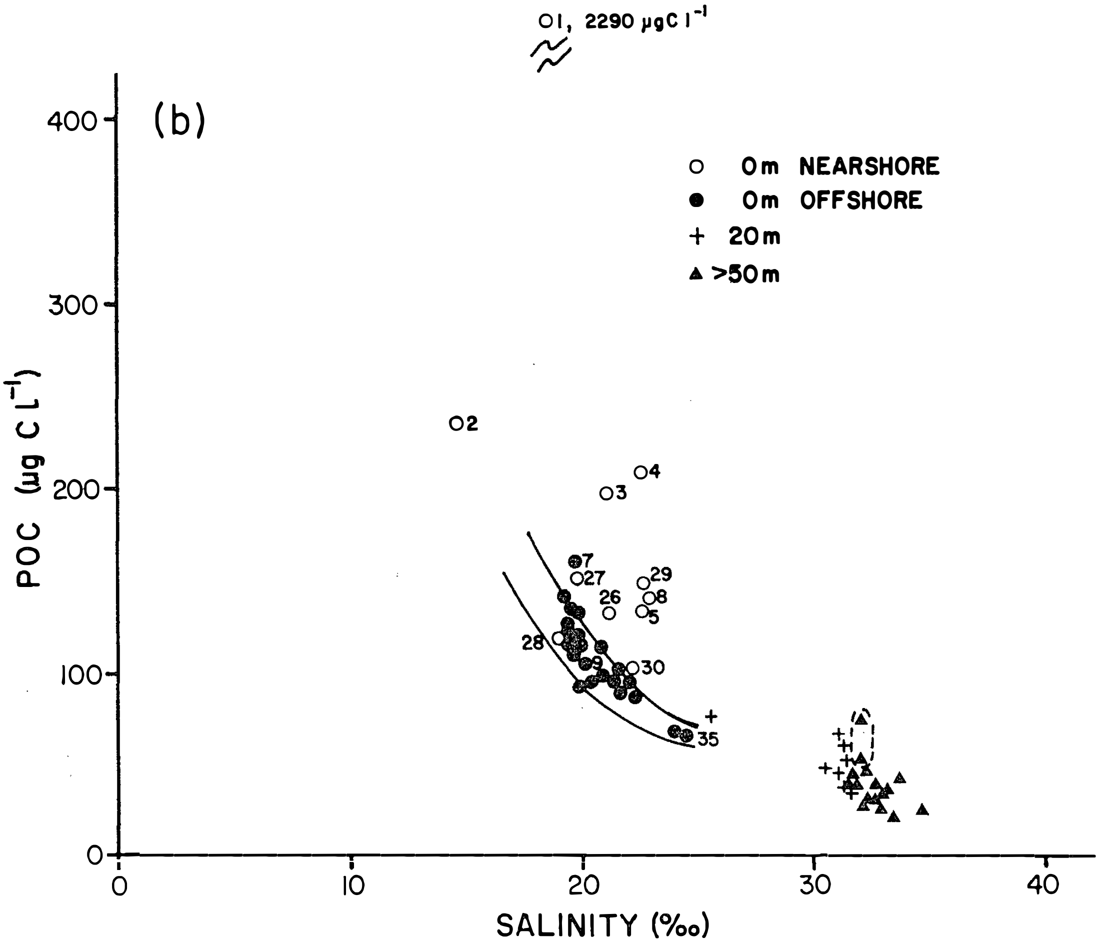

Fig. 3b. Relation between salinity and POC in the surface water from all stations.

more variable than the outer-shelf stations, in particular Stn. 10 to 14. The time-variability of inshore stations is represented by profiles 5 and 5′, 4 and 4′ which were taken at the same respective stations, but on different days. This dissimilarity is also evident in the other water properties, particularly in the surface layer (see Table 1); at Stn. 4, transmissivity and salinity in the surface both decreased dramatically from September 11 to 16. At Stn. 5 a similar positive correlation between light transmission and salinity can be seen, and we conclude that these observations are related directly to the extent of the Mackenzie plume. Detailed time series on particulate loading, salinity, currents and sedimentation (by trapping) will be required to identify representative water properties at the nearshore stations, and the particle transport by source through the zone. Of note, this region lies in the middle of the oil exploration sector which makes pollutant transport modelling difficult, but essential.

3.4. Comparison of POC in different Arctic regions

We have compared our POC observations over the Mackenzie Shelf and slope with those collected from stations from the Central Arctic Ocean (GORDON and CRANFORD, 1985), and the Chukchi Sea (HANDA and TANOUE, 1981; HATTORI, 1979). Generally, POC is found to be log-normally distributed with a water body (WANGERSKY, 1974; GORDON, 1977); therefore we have taken logarithms before doing calculating

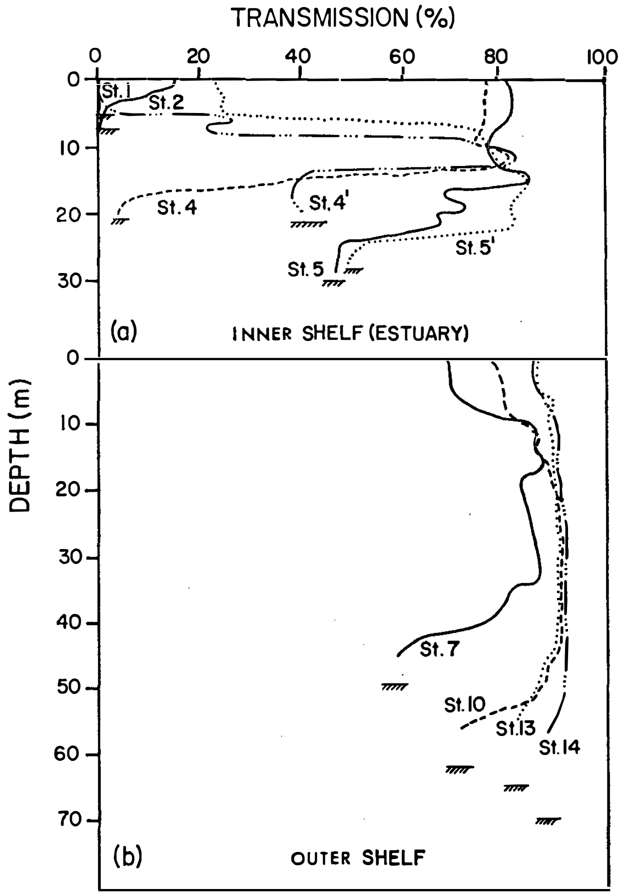

Fig. 4. Vertical profiles of light transmission observed over the Inner Shelf (estuary) and Outer Shelf (b).

Table 1. Temporal changes in temperature, salinity, and light transmission observed at estuarine stations.

Station	Bottom depth (m)	Type of water	Depth (m)	Temp. (°C)	Sal. (‰)	Trans. (%)	Date	Time
4	21	SL	3.0	5.08	22.89	75.3	Sep. 11, 1986	0116
		ICL	12.9	2.80	28.17	80.8		
		BTL	18.8	−0.04	30.67	5.3		
4′	22	SL	2.0	6.01	11.22	0.0	Sep. 16, 1986	0313
		ICL	11.4	2.06	26.10	80.3		
		BTL	19.8	−0.29	30.53	39.6		
5	31	SL	3.5	5.09	22.81	81.2	Sep. 11, 1986	1416
		ICL	14.4	3.33	27.23	86.6		
		BTL	29.0	−1.19	31.61	47.1		
5′	29	SL	2.5	5.39	17.39	24.7	Sep. 16, 1986	0436
		ICL	14.4	2.81	27.98	83.7		
		BTL	26.2	−1.14	31.35	48.2		

SL: surface layer, ICL: intermediate clear layer, BTL: bottom turbid layer.

Table 2. Comparison of POC concentrations ($\mu gC\,l^{-1}$) observed in different geographic conditions in the Arctic Ocean. Data sources are: Central Arctic, Gordon and Cranford (1985); Beaufort Sea, this paper; and Chukchi Sea, Handa and Tanoue (1981). Data are averaged according to water mass using definitions of Kinney et al. (1971) with exception of the surface layer (about 10 m) of the Southern Beaufort Sea which is strongly influenced by Mackenzie River water as shown in Figs. 2a and 2b.

Water mass	Depth (m)	Central Arctic Ocean (Apr. 1983)			Beaufort Sea (Sep. 1986)			Chukchi Sea* (July 1978)		
		GM	Range	n	GM	Range	n	GM	Range	n
Arctic surface water	0–50	13.8	(5.8–30.2)	10	58.5	(33.8–233.1)**	126	200	(91.4–418)	9
Bering Strait-Chukchi Sea water	51–200	4.8	(2.4–18.1)	19	31.3	(17.0–97.4)	19	—	—	—
Intermediate water	201–350	5.1	(2.9–11.2)	12	33.7	(21.6–50.3)	7	—	—	—
Atlantic water	351–900	3.4	(1.7–8.3)	20	26.0	(25.3–26.6)	2	—	—	—
Arctic deep water	>900	2.5	(0.7–5.6)	41	—	—	—	—	—	—

* Recalculated from original data report (Hattori, 1979) from which resuspended POC concentrations were excluded.

** Abnormally high values at Stn. 1 were omitted for calculation.

averages reported in Table 2. Further, data were averaged for each water mass following the method used by Kinney *et al.* (1971), and Gordon and Cranford (1985). However, it should be noted that the surface layer (about 10 m) of the Southern Beaufort Sea is strongly influenced by fresh water from the Mackenzie River (Figs. 2a and 2b).

Despite considerable scatter due to spatial patchiness, our Beaufort Sea data tend to fall between the high values reported for the Chukchi Sea and the low values for the Central Arctic Ocean (see Table 2). At all depths, the POC concentrations over the shelf and slope exceeded those from respective depths in the Central Arctic (Admittedly we have only very few data from the Atlantic layer of water). Melnikov and Pavlov (1978) reported low concentrations of POC in winter (5–10 $\mu g\,l^{-1}$ above 50 m, and less than 5 $\mu g\,l^{-1}$ below 250 m) with POC subsequently increasing in the top 50 m (25–45 $\mu g\,l^{-1}$) in summer (greater solar radiation with associated potential enhancement in productivity). Our observations were conducted late in the open-water season for the Beaufort Sea so that we expect seasonally higher production which may effect the contrast in POC between the shelf and the central Arctic Ocean. This has also a parallel in the Chukchi Sea data where highest POC levels were observed in summer (July).

Therefore, we suggest that productivity contributes a seasonal signal in POC over the Mackenzie Shelf. Although the production takes place at the surface, its influence on POC is felt throughout the water column. However, it is clear that productivity is not the only control on POC over the Mackenzie Shelf nor perhaps the most important since this area has a low annual new production relative to temperate coastal areas (about 20 gC m^{-2} y^{-1}, Macdonald *et al.*, 1987; Subba Rao and Platt, 1984) and receives a large quantity of allochthonous inorganic and organic matter from the Mackenzie River, especially in spring–summer. Thus the high POC concentration we measured over the shelf probably has the Mackenzie River as its primary source, and this has been augmented by summer production followed by settling to depth. To understand material budgets for this region, therefore, it is important to be able to distinguish between the above two POC sources and how they affect the observed POC load at a given time and place.

Further work on the seasonality and source of suspended particulate matter, primary production, and sedimentation is being carried out under NOGAP Beaufort Sea Oceanography. We plan to use inorganic composition, and isotopic and elemental abundances to unravel the timing, sources and sinks of the various particulate contributors.

Acknowledgements

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References

Bornhold, B. D. (1975): Suspended matter in the Southern Beaufort Sea. Beaufort Sea Tech. Rep., **256**, 23 p.

Demers, S., Therriault, J.-C., Bourget, E. and Bah, A. (1987): Resuspension in the shallow sublittoral zone of a macrotidal estuarine environment; Wind influence. Limnol. Oceanogr., **32**, 327–339.

Erickson, P. and Fowler, B. (1986): The flux of suspended particulates, petroleum related hydrocarbons, trace metals and nutrients from the Mackenzie River during the winter season; A pilot study of the east channel. A report prepared for Department of Indian Affairs and Northern Development, Ottawa, Ontario, under DSS contract IST84-00504. 123 p.

Erickson, P., Thomas, D., Pett, R. and deLange Boom, B. (1983): Issungnak Oceanographic Survey, Part A; Oceanographic properties. A report prepared for Esso Resources Canada Ltd., Gulf Canada Resources Inc., Dome Petroleum Ltd. by Arctic Laboratories Ltd., Inuvik, Northwest Territories, 194 p.

Fanning, K. A., Carder, K. L. and Betzer, P. R. (1982): Sediment resuspension by coastal waters; A potential mechanism for nutrient re-cycling on the ocean's margins. Deep-Sea Res., **29**, 953–965.

Gabrielson, J. O. and Lukatelich, R. J. (1985): Wind-related resuspension of sediments in the Peel-Harvey estuarine system. Est. Coast Shelf Sci., **20**, 135–145.

Gordon, D. C., Jr. (1977): Variability of particulate organic carbon and nitrogen along the Halifax-Bermuda section. Deep-Sea Res., **24**, 257–270.

Gordon, D. C., Jr. and Cranford, P. J. (1985): Detailed distribution of dissolved and particulate organic matter in the Arctic Ocean and comparison with other oceanic regions. Deep-Sea Res., **32**, 1221–1232.

Handa, N. and Tanoue, E. (1981): Organic matter in the Bering Sea and adjacent areas. The Eastern Bering Sea Shelf: Oceanography and Resources, ed. by D. W. Hood and J. A. Calder. Seattle, Office of Marine Pollution Assessment, 359–381.

Harper, J. and Penland, S. (1982): Beaufort Sea Sediment Dynamics, Unpublished Manuscript.

Hattori, A. ed. (1979): Preliminary Report on the Hakuhō Maru Cruise KH-78-3. Tokyo, Ocean Res. Inst., Univ. Tokyo, 87 p.

Karickoff, S. W., Brown, D. S. and Scott, T. A. (1979): Sorption of hydrophobic pollutants on natural sediments. Water Res., **13**, 241–248.

KINNEY, P. J., LODER, T. C. and GROVES, J. (1971): Particulate and dissolved organic matter in the Amerasian Basin of the Arctic Ocean. Limnol. Oceanogr., **16**, 132–137.

MACDONALD, R. W., WONG, C. S. and ERICKSON, P. E. (1987): The distribution of nutrients in the southeastern Beaufort Sea; Implications for water circulation and primary production. J. Geophys. Res., **92**, 2939–2952.

MATSUMOTO, E. and WONG, C. S. (1977): The distribution of suspended particles in the southern Beaufort Sea. J. Oceanogr. Soc. Jpn., **33**, 227–232.

MELLING, H. and LEWIS, E. L. (1982): Shelf drainage flows in the Beaufort Sea and their effect on the Arctic Ocean pycnocline. Deep-Sea Res., **29**, 967–985.

MELNIKOV, I. A. and PAVLOV, G. L. (1978): Characteristics of organic carbon distribution in the water and ice of the Arctic Basin. Oceanology, **18**, 163–167.

PELLETIER, B. R. (1975): Sediment dispersal in the southern Beaufort Sea. Beaufort Sea Tech. Rep., **25a**, 80 p.

ROMAN, M. R. and TENORE, K. R. (1978): Tidal resuspension in Buzzards Bay, Massachusetts. I. Seasonal changes in the resuspension of organic carbon and chlorophyll-*a*. Est. Coast. Mar. Sci., **6**, 37–46.

SINCLAIR, M., SUBBA RAO, D. V. and COUTURE, R. (1981): Phytoplankton temporal distributions in estuaries. Oceanol. Acta, **1**, 239–246.

SUBBA RAO, D. V. and PLATT, T. (1984): Primary production of Arctic waters. Polar Biol., **3**, 191–201.

THOMAS, D. J., MACDONALD, R. W. and CORNFORD, A. B. (1986): Geochemical mass balance calculations for the coastal Beaufort Sea, N. W. T., Canada. Rapp. P. V. Reun. Cons. Int. Explor. Mer, **186**, 159–178.

WANGERSKY, P. J. (1974): Particulate organic carbon; Sampling variability. Limnol. Oceanogr., **19**, 980–984.

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