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Natural radionuclides in waters of the New York Bight

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The half removal time of ²²⁸Th from the surface waters by settling particles, t_c , does not change much with season, except in the winter when regenerated ²²⁸Th as well as ²¹⁰Pb and ²¹⁰Po were transported back to the surface water from the bottom water and/or near-shore sediments. The removal of ²²⁸Th and ²¹⁰Pb from the surface waters of New York Bight by phytoplankton–zooplankton–fecal pellet route is not important in the shelf but is important in the slope areas. The removal of ²¹⁰Po is almost entirely associated with the phytoplankton–zooplankton–fecal pellet pathway throughout the New York Bight.

1. Introduction

Li et al [1] have discussed the radioactive disequilibrium between ²²⁸Th and ²²⁸Ra (daughter-parent pair with $t_{1/2} = 1.91$ and 5.75 years, respectively) in New York Bight waters during the summer and fall seasons when density stratification of the water column is strong. We present here the ²²⁸Th–²²⁸Ra results from the winter (January 5 to 21, 1976, R.V. “Conrad” 19-05 cruise) and spring (April 29 to May 8, 1977, R.V. “Cape Henlopen” 77-01 cruise) seasons when density stratification of the shelf water is either absent or weak. In addition, we discuss the ²¹⁰Po–²¹⁰Pb measurements ($t_{1/2} = 138$ days and 21.4 years, respectively) from the above-mentioned cruises. The ^{239,240}Pu results from these cruises are given

elsewhere [2]. The ²³⁴Th–²³⁸U results along with the ²²⁸Th–²²⁸Ra data from the “Cape Henlopen” 77-01 cruise are presented separately in Kaufman et al. [3]. The purpose of this paper is to show (1) how the ²²⁸Th/²²⁸Ra activity ratio, which is a measure of the removal rate of ²²⁸Th from the water column [1], changes with season; (2) what factors may control the ²²⁸Th/²²⁸Ra ratio in the water column; and (3) how the removal of ²¹⁰Pb and ²¹⁰Po is related to that of ²²⁸Th.

The sampling and analytical methods for ²²⁸Th and ²²⁸Ra were described in Li et al. [1] and Kaufman et al. [3]. The analytical methods for ²¹⁰Po and ²¹⁰Pb (in 20-liter seawater samples) are described in Benninger [4,5].

2. Results and discussion

2.1. ²²⁸Th and ²²⁸Ra

The ²²⁸Th and ²²⁸Ra concentrations of unfiltered water samples (mostly from the surface) from the winter and spring cruises are summarized in Tables 1 and 2, along with other pertinent in-

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TABLE 1

Concentration of Ra and Th isotopes (dpm/100 kg) in water samples from the New York Bight area (R.V. "Conrad" cruise 19-05, January 1976)

Ship station No.	Lat. N.	Long. W.	S (‰)	T (°C)	²²⁸ Th	²²⁸ Ra/ ²²⁶ Ra	²²⁶ Ra	²²⁸ Ra	²²⁸ Th/ ²²⁸ Ra
76	40°20.2'	73°10.4'	32.249	7.53	0.68 ± 0.07	—	10.0	(13.2)	(0.052)
77	40°26.6'	72°47.3'	32.170	7.61	0.47 ± 0.05	1.45 ± 0.14	10.0	14.5 ± 1.4	0.032 ± 0.005
79	40°42.4'	71°46.6'	32.580	8.22	0.36 ± 0.14	1.21 ± 0.15	10.0	12.1 ± 1.5	0.030 ± 0.015
83	40°23.2'	71°34.3'	33.338	9.79	0.65 ± 0.08	0.82 ± 0.09	10.0	8.2 ± 0.9	0.079 ± 0.014
85	40°28.3'	71°11.2'	32.976	9.08	0.54 ± 0.11	0.92 ± 0.10	10.0	9.2 ± 1.0	0.059 ± 0.014
90	40°28.4'	70°27.7'	32.488	7.39	0.34 ± 0.15	1.13 ± 0.12	10.0	11.3 ± 1.2	0.030 ± 0.014
92 (46 m)	40°27.8'	70°08.4'	32.536	7.62	0.34 ± 0.33	1.00 ± 0.10	10.0	10.0 ± 1.0	0.034 ± 0.033
95	41°00.2'	71°30.1'	31.511	6.36	0.97 ± 0.11	1.61 ± 0.16	10.0	16.1 ± 1.6	0.060 ± 0.009
100 (32 m)	40°26.6'	72°05.2'	32.570	8.26	0.51 ± 0.07	1.20 ± 0.13	10.0	12.0 ± 1.3	0.043 ± 0.008
100	40°26.1'	72°09.0'	32.836	8.51	0.58 ± 0.08	—	10.0	(10.8)	(0.054)
104 (27 m)	39°58.3'	71°43.4'	33.111	9.20	0.65 ± 0.06	0.95 ± 0.10	10.0	9.5 ± 1.0	0.068 ± 0.010
104	39°58.1'	71°43.4'	33.111	9.20	0.61 ± 0.06	0.88 ± 0.08	10.0	8.8 ± 0.8	0.069 ± 0.010
108	39°39.4'	71°25.3'	34.368	11.69	0.65 ± 0.09	0.67 ± 0.07	10.0	6.7 ± 0.7	0.097 ± 0.016
109	39°30.0'	71°24.4'	35.016	12.67	0.82 ± 0.09	0.59 ± 0.06	9.6	5.7 ± 0.6	0.144 ± 0.022
110	39°20.8'	71°18.6'	35.554	14.31	0.94 ± 0.11	0.47 ± 0.05	9.2	4.4 ± 0.4	0.214 ± 0.033
112	39°27.2'	71°43.0'	34.432	11.25	0.74 ± 0.07	0.71 ± 0.08	10.0	7.1 ± 0.8	0.104 ± 0.015
113	39°28.8'	71°53.7'	34.068	10.53	0.84 ± 0.07	0.80 ± 0.08	10.0	8.0 ± 0.8	0.105 ± 0.014
113 (80 m)	39°29.1'	72°00.3'	35.643	14.57	0.76 ± 0.09	0.73 ± 0.09	9.2	6.7 ± 0.9	0.113 ± 0.019
116	39°07.7'	71°54.0'	35.421	13.69	0.84 ± 0.07	0.40 ± 0.04	9.4	3.8 ± 0.4	0.221 ± 0.029
121	39°17.7'	72°37.7'	34.594	11.94	0.71 ± 0.05	—	10.0	(5.9)	(0.120)
122	39°12.2'	72°29.6'	34.179	10.90	0.68 ± 0.07	0.69 ± 0.07	10.0	6.8 ± 0.7	0.100 ± 0.015
122 (80 m)	39°11.5'	72°32.9'	35.112	13.08	1.07 ± 0.13	0.53 ± 0.06	9.6	5.0 ± 0.6	0.214 ± 0.037
125	38°45.8'	71°57.4'	35.347	13.43	0.74 ± 0.08	0.48 ± 0.06	9.4	4.5 ± 0.5	0.164 ± 0.028
128	39°16.6'	73°27.0'	32.988	8.07	0.57 ± 0.06	1.16 ± 0.14	10.0	11.6 ± 1.4	0.049 ± 0.006
128 (37 m)	39°15.3'	73°27.6'	32.996	8.07	0.45 ± 0.06	1.17 ± 0.11	10.0	11.7 ± 1.1	0.038 ± 0.006
129	39°23.8'	73°44.0'	32.755	6.92	0.78 ± 0.07	1.32 ± 0.12	10.0	13.2 ± 1.2	0.059 ± 0.008
131	39°39.5'	73°42.6'	32.415	5.97	0.59 ± 0.17	—	10.0	(12.4)	(0.048)
132	39°45.1'	73°22.8'	32.736	7.06	0.47 ± 0.06	1.16 ± 0.13	10.0	11.6 ± 1.3	0.041 ± 0.007
136	40°10.6'	73°42.7'	32.071	6.08	0.77 ± 0.07	1.34 ± 0.14	10.0	13.4 ± 1.4	0.057 ± 0.006
137	40°13.3'	73°29.8'	32.045	5.59	0.76 ± 0.08	1.45 ± 0.14	10.0	14.5 ± 1.4	0.052 ± 0.007
141	39°42.9'	73°14.3'	32.814	7.17	0.46 ± 0.06	1.18 ± 0.11	10.0	11.8 ± 1.1	0.039 ± 0.006
144	40°08.6'	72°46.0'	32.640	7.40	0.64 ± 0.05	1.23 ± 0.12	10.0	12.3 ± 1.2	0.052 ± 0.006
145	40°02.9'	72°28.7'	33.220	8.75	0.50 ± 0.05	0.95 ± 0.10	10.0	9.5 ± 1.0	0.053 ± 0.008
147	39°42.6'	72°53.2'	33.172	8.14	0.38 ± 0.15	0.99 ± 0.10	10.0	9.9 ± 1.0	0.038 ± 0.016
147 (55 m)	39°41.5'	72°53.3'	33.445	9.08	0.55 ± 0.09	1.33 ± 0.16	10.0	13.3 ± 1.6	0.041 ± 0.008
148	39°34.0'	73°03.1'	32.807	7.21	0.55 ± 0.04	1.17 ± 0.13	10.0	11.7 ± 1.3	0.047 ± 0.006
152	39°51.7'	72°19.8'	33.855	10.14	0.63 ± 0.05	0.70 ± 0.07	10.0	7.0 ± 0.7	0.090 ± 0.012
165	39°26.9'	72°23.1'	33.843	9.98	0.46 ± 0.18	0.71 ± 0.10	10.0	7.1 ± 1.0	0.065 ± 0.027
166	39°21.7'	72°32.4'	33.874	9.90	0.74 ± 0.07	0.68 ± 0.07	10.0	6.8 ± 0.7	0.109 ± 0.015

formation. The uncertainty represents 1 σ counting error. The ²²⁶Ra concentration (as a natural yield tracer for the ²²⁸Ra analysis) in Table 1 was estimated by the salinity vs. ²²⁶Ra relationship in New York Bight waters ([6] and unpublished data). The ²³²Th concentration data from the winter cruise are not given in Table 1 because the un-

certainty is too large (caused by generally lower yields).

2.1.1. Winter season

During the winter the shelf water was more-or-less well mixed vertically. Shelf water and surface slope water were produced by mixing of the inner

TABLE 2

Concentration of Ra and Th isotopes (dpm/100 kg) in the New York Bight (R.V. "Cape Henlopen", cruise 77-01, April 29 to May 8, 1977)

Ship station No.	Lat. N.	Long. W.	S (‰)	T (°C)	^{228}Th	^{228}Ra	$^{228}\text{Th}/^{228}\text{Ra}$	^{232}Th
1	39°31'	74°09'	30.27	8.98	0.39±0.03	13.3±1.1	0.029±0.004	0.08±0.03
2	39°27'	73°56'	31.39	9.55	0.38±0.03	13.9±1.1	0.027±0.003	0.03±0.01
4	39°15'	73°27'	33.63	9.79	0.66±0.06	10.3±1.5	0.064±0.010	0.01±0.01
4 (25 m)	39°15'	73°27'	34.09	5.90	0.52±0.03	9.4±1.1	0.055±0.008	0.03±0.02
7	39°04'	72°50'	33.80	8.97	0.36±0.03	7.1±1.4	0.051±0.011	0.01±0.01
8	39°02'	72°33'	35.01	12.7	0.36±0.03	5.8±0.7	0.062±0.009	0.01±0.01
9	38°31'	71°42'	35.80	13.6	0.48±0.03	6.4±0.9	0.075±0.012	0.01±0.01
10	38°47'	72°10'	35.47	13.58	0.49±0.03	5.1±0.7	0.095±0.014	0.01±0.01
14	39°18'	71°49'	35.07	13.33	0.41±0.03	5.1±0.7	0.080±0.013	0.02±0.01
14 (28 m)	39°18'	71°49'	35.76	13.48	0.57±0.03	5.8±0.8	0.098±0.015	0.01±0.01
16	39°33'	71°26'	~35.2	~13.3	0.49±0.03	5.3±0.7	0.092±0.013	0.01±0.01
17	39°40'	72°29'	33.30	9.84	0.45±0.04	12.4±1.5	0.036±0.005	0.02±0.01
18	39°39'	72°43'	33.15	10.1	0.37±0.03	13.5±1.5	0.028±0.004	0.01±0.01
19	39°53'	72°40'	32.79	9.03	0.51±0.03	-	-	0.02±0.01
20	39°46'	72°57'	32.53	8.95	0.51±0.03	18.2±1.5	0.028±0.003	0.02±0.01
22	39°55'	73°13'	32.54	9.09	0.40±0.03	17.1±1.5	0.023±0.003	0.01±0.01
22a	40°25'	73°53'	~28.0	~9.9	0.49±0.03	21.6±2.2	0.023±0.003	0.24±0.03
27	40°09'	73°11'	32.90	9.18	0.52±0.03	18.4±1.8	0.028±0.003	0.01±0.01
29	40°23'	73°02'	31.45	9.4	0.42±0.04	19.9±2.0	0.021±0.003	0.04±0.01
30	40°30'	72°37'	31.81	8.96	0.42±0.03	18.8±1.5	0.022±0.002	0.04±0.01
31	40°47'	72°29'	31.34	9.36	0.46±0.03	19.5±1.8	0.024±0.003	0.05±0.01
32	40°41'	72°20'	30.94	9.09	0.46±0.03	22.9±2.2	0.020±0.002	0.05±0.03
33	40°37'	72°13'	31.96	9.75	0.45±0.03	-	-	0.03±0.01
34	40°27'	72°05'	32.26	9.77	0.40±0.06	16.8±1.1	0.024±0.003	0.02±0.01
34 (21 m)	40°27'	72°05'	33.27	4.05	0.57±0.03	35.4±4.3	0.022±0.004	0.02±0.01
35	40°19'	71°58'	33.30	9.12	0.55±0.03	-	-	0.01±0.01
35 (40 m)	40°19'	71°58'	33.61	4.52	0.48±0.07	20.5±2.3	0.023±0.007	0.02±0.01
36	40°12'	71°53'	33.30	9.30	0.38±0.03	15.4±1.5	0.025±0.003	0.01±0.01
36 (45 m)	40°12'	71°53'	33.62	4.51	0.40±0.03	25.9±3.0	0.015±0.002	0.02±0.01
37	40°02'	71°50'	33.45	9.97	0.49±0.08	14.3±2.6	0.034±0.008	0.02±0.01
42	40°00'	71°44'	33.31	9.62	0.44±0.11	12.0±1.4	0.037±0.008	0.02±0.01
43	39°51'	71°32'	33.73	10.9	0.39±0.03	11.1±1.0	0.035±0.004	0.01±0.01
47 (50 m)	39°50'	71°30'	35.50	12.50	0.59±0.03	6.1±1.0	0.096±0.016	0.01±0.01

shelf water and the top of the slope water (Fig. 1A). The slope-shelf front was at a salinity of about 33.5‰ (Figs. 1A and 2A). Interestingly, at the same salinity, the shelf water had a warmer temperature to the north than to the south of the Hudson Canyon (Fig. 1A).

The ^{228}Ra concentration increased from the slope toward the shore (Figs. 2B and 3A). A break in the ^{228}Ra vs. salinity plot (Fig. 3A) at the slope-shelf front indicates that ^{228}Ra had been injected from the shelf sediments, especially from the inner shelf sediments, to the shelf water. The

^{228}Th concentration as well as the $^{228}\text{Th}/^{228}\text{Ra}$ activity ratio decreased from the slope to the mid-shelf, then increased toward the shore (Fig. 2C and D). In contrast, the ^{228}Th concentration and $^{228}\text{Th}/^{228}\text{Ra}$ activity ratio decreased continuously from the slope shoreward during the summer and fall seasons [1]. It is not likely that the high ^{228}Th concentration and $^{228}\text{Th}/^{228}\text{Ra}$ ratios near shore during the winter were caused by high suspended particle concentrations, since the concentration of suspended particles increases from the slope toward the shore during all seasons [7,8]. Further-

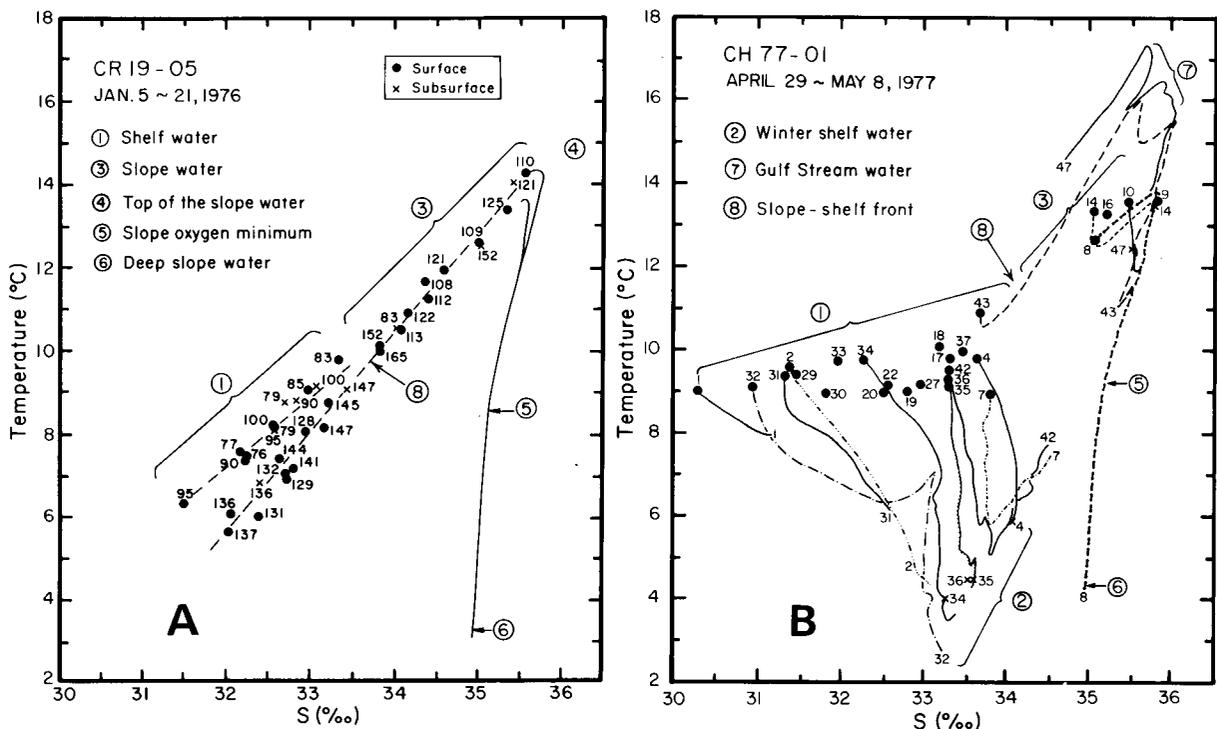


Fig. 1. Temperature-salinity diagrams in the New York Bight during (A) winter and (B) spring. Dots and crosses represent discrete surface and subsurface samples (respectively). The smooth curves were obtained from CTD probes.

more, a strong acid leachate of suspended particles from inner shelf waters collected by centrifugation during the same winter cruise gave $^{228}\text{Th} = 2.1 \pm 0.1$ dpm/g [1]. The concentration increase of suspended matter by about $200 \mu\text{g/l}$ from the mid-shelf shoreward [7] thus augments the total ^{228}Th concentration by only about 0.04 dpm/100 l, which is too small to explain the observed increase of total ^{228}Th toward the shore during the winter. A better explanation is that ^{228}Th in settling particles and/or in bottom sediments had been partially regenerated to the bottom water during the seasonal stratification and transported back to the surface water by vertical mixing during the winter. The regeneration of ^{228}Th is also indicated by $^{228}\text{Th}/^{228}\text{Ra}$ ratios of greater than one at a water depth of 200–350 m in the surface Atlantic Ocean [9].

The half removal time of ^{228}Th from a parcel of water by settling particles, t_c , can be estimated using the relationship:

$$t_c = (\ln 2) / \lambda_c = [(\ln 2) / \lambda_2] [R / (1 - R)] \quad (1)$$

where λ_c = the first-order removal rate constant of ^{228}Th , R = activity ratio of $^{228}\text{Th}/^{228}\text{Ra}$, and λ_2 = decay constant of ^{228}Th . Therefore, the minimum of $^{228}\text{Th}/^{228}\text{Ra}$ in the mid-shelf (Fig. 2D) corresponds to a t_c of about 22–29 days. The t_c of surface slope water ranged from 137 to 194 days, which is about twice as long as during the summer and fall but is still short when compared to a t_c of 350 ± 50 days in the surface Atlantic Ocean at a similar latitude [9].

2.1.2. Spring season

During our spring cruise, the thermocline was already well developed (Fig. 1B), although density stratification was still relatively weak. The remnant winter shelf water was cooler than usual (Fig. 1B). We also encountered a warm water ring (Gulf Stream water) at stations 43 and 47 (Fig. 1B). The surface shelf and slope waters were formed by the

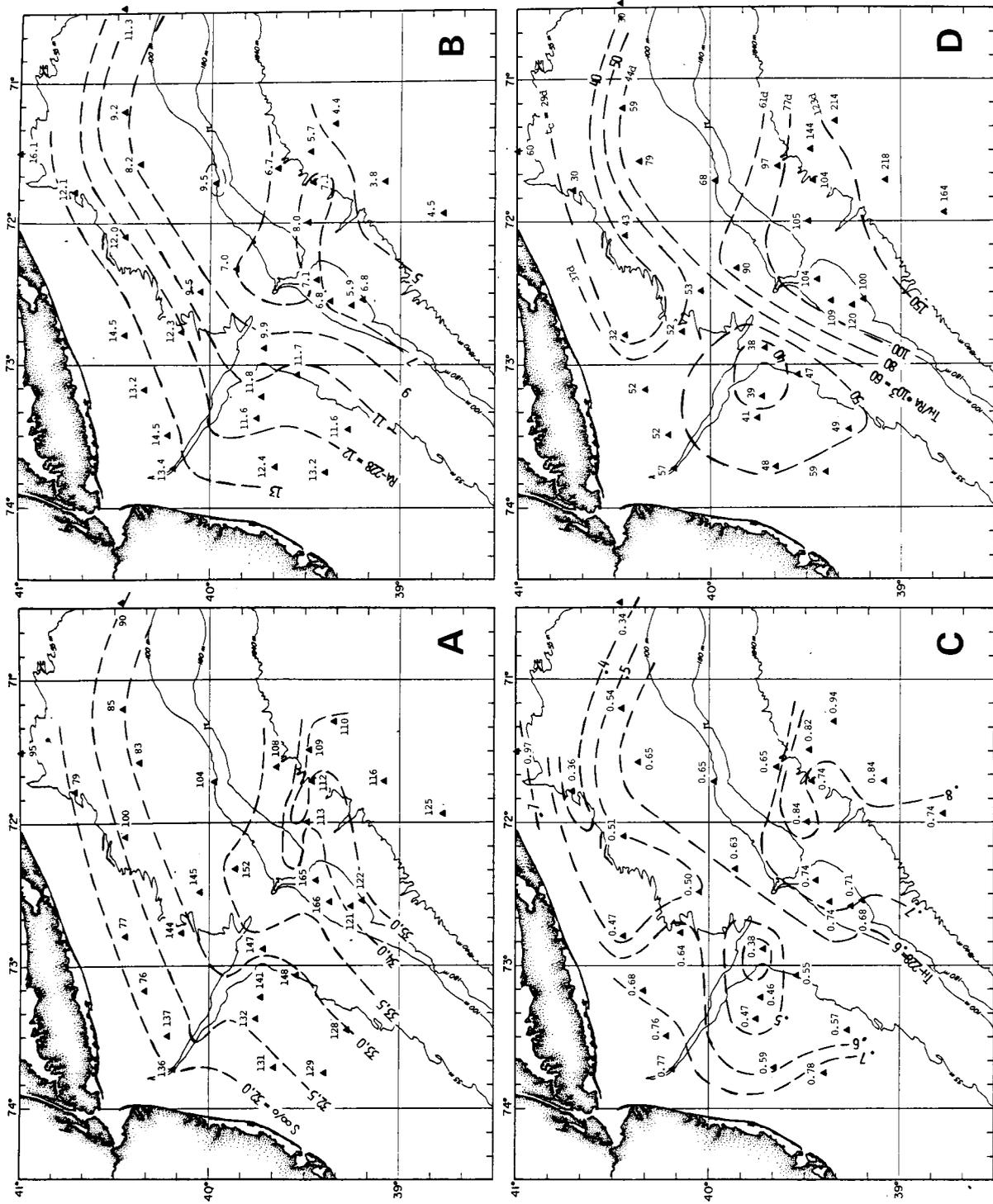


Fig. 2. Areal distributions of (A) stations (number) and salinity (contour), (B) ^{228}Ra (dpm/100 kg), (C) ^{228}Th (dpm/100 kg) and (D) $^{228}\text{Th}/^{228}\text{Ra}$ activity ratio during the winter cruise (R.V. "Conrad" cruise 19-05, January 5-21, 1976).

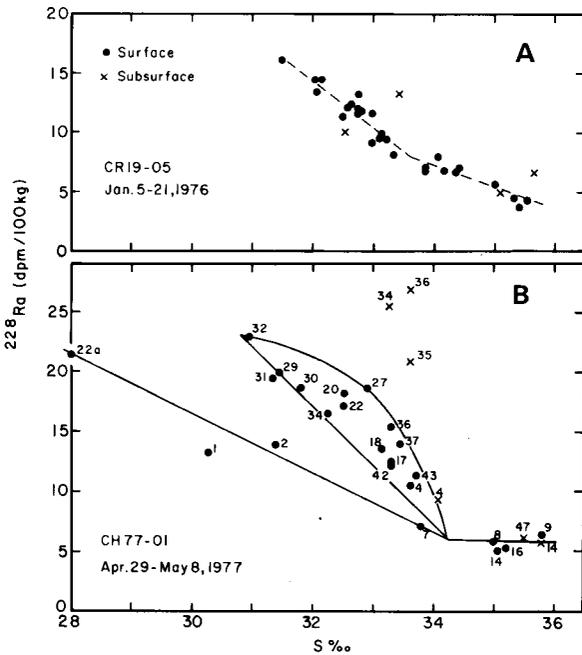


Fig. 3. ^{228}Ra concentration vs. salinity plots during (A) winter and (B) spring. Numbers beside the dots (surface samples) and crosses (subsurface samples) are station numbers.

mixing of the inner surface shelf waters, outer surface shelf water and the top of slope water. The slope-shelf break was at a salinity of about 34‰.

As usual, the ^{228}Ra concentration increased from the surface slope toward the shore (Figs. 3B and 4B). Interestingly, the shelf waters contained more ^{228}Ra to the north of the Hudson Canyon than to the south at the same salinity (Fig. 3B). The unusually high ^{228}Ra concentration in the shelf bottom waters north of Hudson Canyon (Fig. 3B, stations 34, 35 and 36) again indicates a ^{228}Ra source from the shelf sediments, probably from the fine-grained sediment deposit on the southern New England shelf (nicknamed "mud hole" or "mud patch") [8]. The details are discussed in Kaufman et al. [3].

South of the Hudson Canyon, the ^{228}Th concentration decreased slightly from the slope toward the shore except for two stations (1 and 22a) nearest to the shore (Fig. 4C), where the concentration of suspended particles and of ^{232}Th was the highest (Table 2). However, after subtracting the detrital component of ^{228}Th from these two

stations (by assuming a $^{228}\text{Th}/^{232}\text{Th}$ ratio of one in the suspended particles near shore and that all ^{232}Th in the water samples is detrital), the ^{228}Th concentrations and $^{228}\text{Th}/^{228}\text{Ra}$ ratios in these two stations became the lowest, as shown by the numbers in brackets in Fig. 4C and by the arrows in Fig. 5A. In contrast, the ^{228}Th concentration north of the Hudson Canyon decreased slightly from the slope to the outer shelf, then increased slightly in the mid- and inner-shelf areas (Fig. 4C), again indicating small regenerational inputs of ^{228}Th from the bottom water and/or shelf sediments. Nonetheless, the $^{228}\text{Th}/^{228}\text{Ra}$ ratio decreased from the slope toward the shore on either side of the Hudson Canyon (Fig. 4D). The t_c of 20 ± 7 days in the surface shelf water and 70 ± 10 days in the surface slope water (Fig. 4D) are in the same range as observed in the summer and fall seasons [1].

As shown in Fig. 5C, the chlorophyll-a concentration (a measure of the living phytoplankton biomass; data were provided by T. Malone and E. Cosper) was highest in the inner shelf and slope areas, mainly caused by the high nutrient levels there. In the spring of 1976, the zooplankton each day consumed about 6% and 40% of the phytoplankton biomass in the region of the inshore and offshore chlorophyll-a maxima, respectively [10]. The phytoplankton biomass was about $500 \mu\text{g}/\text{l}$ (dry weight) inshore and $300 \mu\text{g}/\text{l}$ offshore in the spring of 1977 (Fig. 5C, phytoplankton dry weight = $100 \times$ chlorophyll-a in the New York Bight: T. Malone, personal communication). The ^{228}Th concentration of a mixed plankton sample (largely phytoplankton) obtained during the same time was about $0.7 \text{ dpm}/\text{g}$ (^{232}Th was about $0.1 \text{ dpm}/\text{g}$). If one assumes similar conditions in spring of 1977 as in spring of 1976, and if, during the grazing of phytoplankton by zooplankton, ^{228}Th does not significantly redissolve back to the water column but mostly settles to the bottom sediments as fecal pellets or fecal aggregates, then the maximum removal rates of ^{228}Th by the phytoplankton-zooplankton-fecal pellet route should be about $21 \times 10^{-6} \text{ dpm}/\text{l day}$ ($= 0.06 \text{ day}^{-1} \times 500 \times 10^{-6} \text{ g}/\text{l} \times 0.7 \text{ dpm}/\text{g}$) inshore and $84 \times 10^{-6} \text{ dpm}/\text{l day}$ offshore. On the other hand, taking a half removal time of ^{228}Th by settling

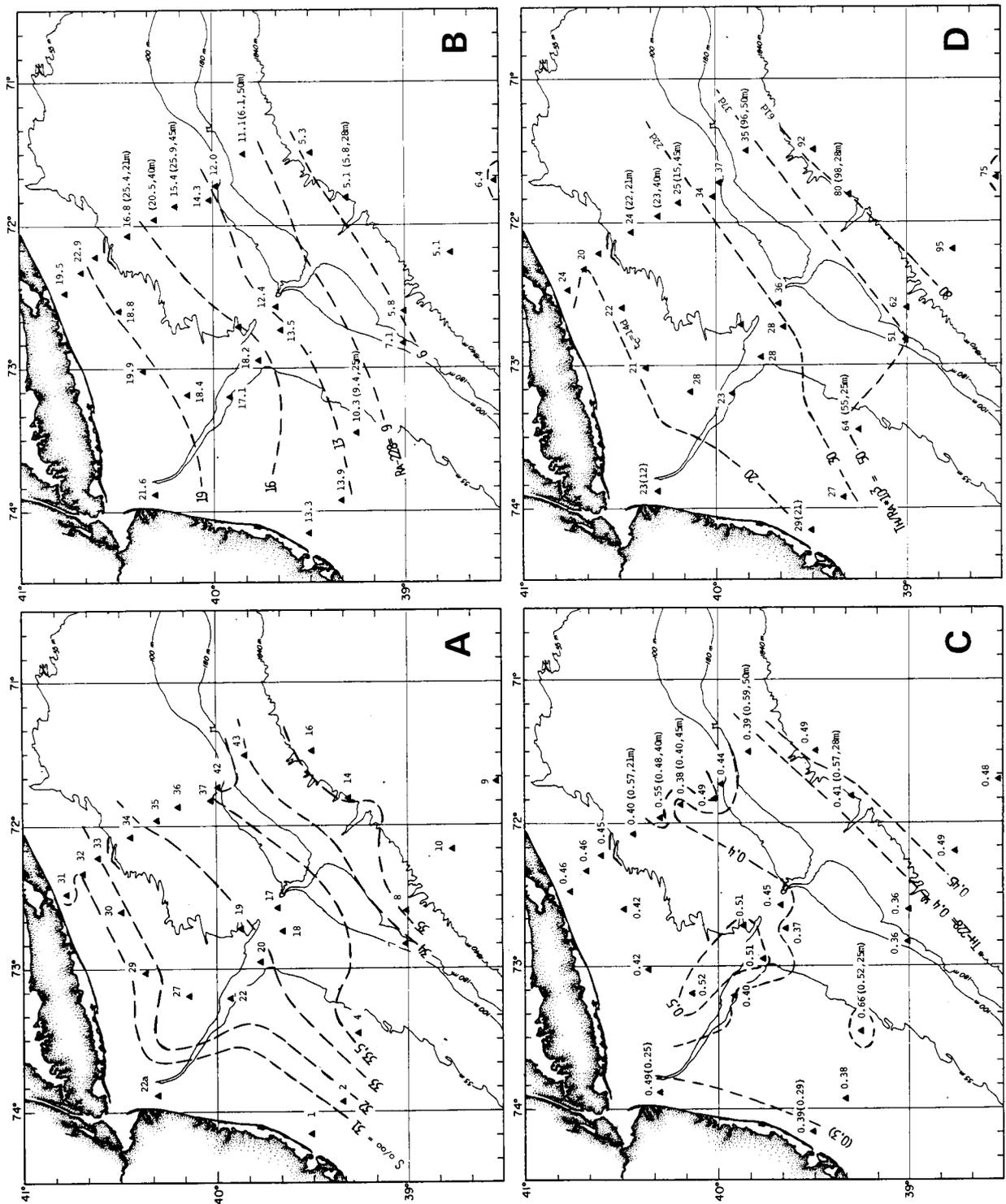


Fig. 4. Areal distributions of (A) stations (numbers) and salinity (contour), (B) ^{228}Ra (dpm/100 kg) and salinity (contour), (C) ^{228}Ra (dpm/100 kg) and salinity (contour), and (D) ^{228}Ra activity ratio during the spring cruise (R.V. "Cape Henlopen" cruise 77-01, April 29 to May 8, 1977).

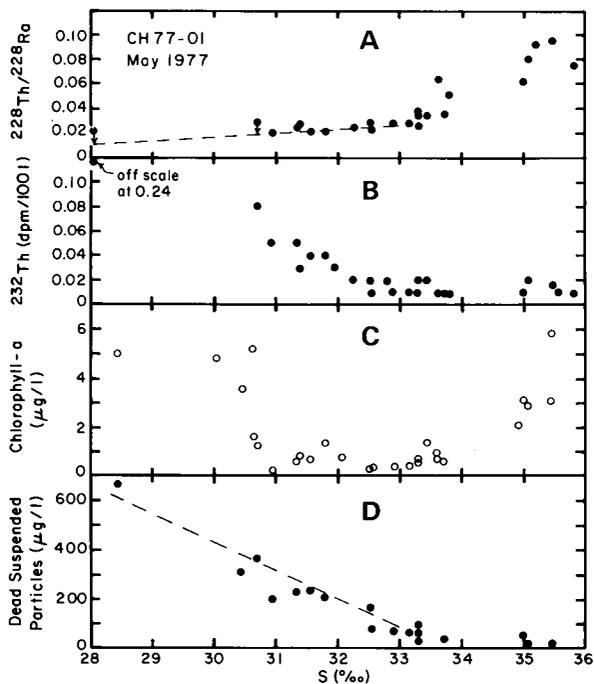


Fig. 5. Plots of salinity vs. (A) $^{228}\text{Th}/^{228}\text{Ra}$ activity ratio, (B) ^{232}Th concentration, (C) chlorophyll-a concentration and (D) non-living suspended particles during the spring cruise. In A, the arrows point to values which are corrected for detrital contributions (see text).

particles of 20 days inshore and 70 days offshore and a ^{228}Th concentration of 0.4 dpm/100 l inshore and 0.5 dpm/100 l offshore (Fig. 4C and D), the total removal rates of ^{228}Th by settling particles can be calculated as $(100-210) \times 10^{-6}$ dpm/l day inshore ($= \ln 2/20 \pm 7$ days $\times 0.4$ dpm/100 l) and $(50 \pm 7) \times 10^{-6}$ dpm/l day offshore. It is evident from the above calculations that the phytoplankton-zooplankton-fecal pellet route is probably not an important removal pathway of ^{228}Th from the shelf surface water, but it could be important in the slope surface water during the spring. In September 1976, the zooplankton grazing rate was as high as 0.53 day^{-1} and the phytoplankton biomass was about $100 \mu\text{g/l}$ inshore [10]. Thus the maximum removal rate of ^{228}Th by the phytoplankton-zooplankton-fecal pellet route would be about 37×10^{-6} dpm/l day ($= 0.53 \text{ day}^{-1} \times 100 \times 10^{-6} \text{ g/l} \times 0.7 \text{ dpm/g}$), which is still relatively small compared to that by settling particles.

The non-living suspended particles (both organic and inorganic particles) can be removed from the water column by (1) direct gravitational settling, and (2) by zooplankton grazing and subsequent settling as fecal pellets. The relative importance of the above two removal mechanisms cannot be estimated at this time and warrants further study. However, by measuring the fecal pellet flux, Adler et al. [11] demonstrated that the removal of particle-reactive trace metals such as Th from the waters of Narragansett Bay is not controlled by the grazing activity of zooplankton during the warm season.

The $^{228}\text{Th}/^{228}\text{Ra}$ ratio is inversely correlated with the concentrations of ^{232}Th and non-living suspended particles (compare Fig. 5A, 5B and 5D). The concentration of non-living suspended particles was obtained by subtracting the living phytoplankton biomass from the total concentration of suspended particles (data provided by P. Biscaye). This implies that the fast removal of ^{228}Th from the surface shelf waters is mainly through adsorption of ^{228}Th onto non-living particles and their subsequent settling to the bottom. The non-living suspended particles are continuously provided by the resuspension of bottom sediments near shore and from river inputs [7,8]. The correlation of ^{232}Th with the concentration of non-living suspended particles gives $2.2 \text{ dpm } ^{232}\text{Th}$ per gram (dry weight) which is similar to the value we found in the fine-grained surface sediments of the "mud hole" area [2].

2.2. ^{210}Po and ^{210}Pb

The ^{210}Po and ^{210}Pb concentrations of unfiltered water samples from the winter and spring cruises are summarized in Table 3.

In the winter, both ^{210}Pb and ^{210}Po concentrations decreased from the slope (high salinity) to the mid-shelf, then increased drastically toward the shore (low salinity) as shown in Fig. 6, in close resemblance to the ^{228}Th distribution pattern (Fig. 2C). The high ^{210}Pb and ^{210}Po concentrations near shore again indicate regenerational inputs from the bottom water and/or sediments. A $^{210}\text{Po}/^{210}\text{Pb}$ activity ratio of greater than one throughout the New York Bight surface water

TABLE 3

Concentrations of ^{210}Pb and ^{210}Po (dpm/100 kg) in water samples from the New York Bight area

Station No.	^{210}Pb	^{210}Po	$^{210}\text{Po}/^{210}\text{Pb}$
<i>R. V. "Conrad" cruise 19-05, January 1976</i>			
83	—	3.6 ± 0.6	—
85	3.1 ± 0.8	—	—
106 *	2.1 ± 0.4	2.3 ± 0.6	1.1 ± 0.3
108	1.7 ± 0.4	4.3 ± 0.6	2.6 ± 0.7
110	2.8 ± 0.5	4.6 ± 0.7	1.7 ± 0.4
125	4.0 ± 0.8	5.2 ± 0.8	1.3 ± 0.3
129	4.2 ± 0.7	—	—
137	6.8 ± 0.7	9.0 ± 1.5	1.3 ± 0.3
141	5.5 ± 0.6	7.5 ± 0.9	1.4 ± 0.2
144	7.0 ± 1.1	7.4 ± 0.9	1.1 ± 0.2
145	5.2 ± 0.6	6.2 ± 0.7	1.2 ± 0.2
152	—	3.0 ± 0.5	—
<i>R. V. "Cape Henlopen" cruise 77-01, April 29 to May 8, 1977</i>			
1	5.6 ± 0.3	2.7 ± 0.2	0.49 ± 0.05
2	6.4 ± 0.3	2.2 ± 0.3	0.34 ± 0.04
4	4.2 ± 0.2	2.2 ± 0.2	0.52 ± 0.05
4 (25 m)	2.5 ± 0.2	3.4 ± 0.2	1.35 ± 0.12
7	3.5 ± 0.2	2.1 ± 0.2	0.60 ± 0.07
8	7.4 ± 0.4	4.3 ± 0.4	0.59 ± 0.05
9	8.7 ± 0.4	5.0 ± 0.5	0.57 ± 0.06
10	8.0 ± 0.4	7.9 ± 0.5	0.99 ± 0.07
14	6.8 ± 0.3	4.9 ± 0.3	0.71 ± 0.05
14 (28 m)	4.6 ± 0.2	3.4 ± 0.2	0.74 ± 0.06
16	7.6 ± 0.3	7.8 ± 0.4	1.04 ± 0.06
17	4.3 ± 0.2	2.6 ± 0.3	0.61 ± 0.07
18	4.1 ± 0.2	2.2 ± 0.2	0.53 ± 0.05
19	4.0 ± 0.2	2.7 ± 0.2	0.67 ± 0.07
20	4.0 ± 0.2	3.7 ± 0.3	0.93 ± 0.10
22	4.1 ± 0.2	1.9 ± 0.2	0.47 ± 0.05
22a	4.8 ± 0.3	2.4 ± 0.2	0.50 ± 0.06
27	5.9 ± 0.3	2.3 ± 0.2	0.39 ± 0.04
29	5.6 ± 0.3	3.5 ± 0.3	0.63 ± 0.06
30	7.4 ± 0.3	4.0 ± 0.4	0.54 ± 0.05
31	5.7 ± 0.3	3.4 ± 0.3	0.60 ± 0.06
32	8.0 ± 0.4	4.2 ± 0.4	0.52 ± 0.05
33	6.4 ± 0.3	3.8 ± 0.3	0.60 ± 0.05
34	7.7 ± 0.4	3.1 ± 0.3	0.40 ± 0.04
34 (21 m)	2.8 ± 0.2	4.6 ± 0.3	1.64 ± 0.16
35	5.7 ± 0.3	2.6 ± 0.2	0.46 ± 0.05
35 (40 m)	3.9 ± 0.2	3.7 ± 0.3	0.96 ± 0.10
36	3.5 ± 0.2	1.5 ± 0.1	0.43 ± 0.05
36 (45 m)	2.6 ± 0.2	3.0 ± 0.3	1.17 ± 0.13
37	3.9 ± 0.2	1.4 ± 0.2	0.36 ± 0.05
42	5.5 ± 0.3	1.7 ± 0.3	0.31 ± 0.03
43	5.1 ± 0.2	1.8 ± 0.2	0.34 ± 0.03
47 (50 m)	6.9 ± 0.3	7.2 ± 0.6	1.06 ± 0.09

* Location: $39^{\circ}49'N$, $71^{\circ}35'W$; $S=33.276\%$, $T=9.39^{\circ}C$.

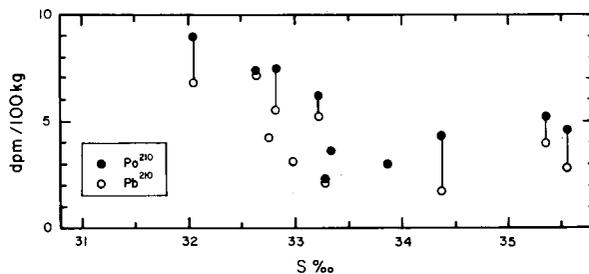


Fig. 6. Plot of salinity vs. the concentrations of ^{210}Pb and ^{210}Po during the winter cruise.

during the winter (Table 3 and Fig. 6) suggests that ^{210}Po is preferentially regenerated back to the water column as compared to ^{210}Pb in the coastal marine environment.

In the spring, the ^{210}Pb and ^{210}Po concentrations decreased from the slope to the mid-shelf, then increased again toward the shore, especially on the shelf north of the Hudson Canyon (Fig. 7B and C), resembling the ^{228}Th distribution pattern (Fig. 4C). The $^{210}\text{Po}/^{210}\text{Pb}$ activity ratio in the surface waters was always less than one, and in the bottom shelf water always greater than one (Table 3 and Fig. 6D). This fact suggests that ^{210}Po was preferentially taken up compared to ^{210}Pb by certain suspended particles (most likely plankton) in the surface water, and regenerated back to the bottom water when the particles settled, most likely as planktonic debris and/or fecal pellets. As shown by many earlier works (e.g., [12–14]), the $^{210}\text{Po}/^{210}\text{Pb}$ activity ratios are much higher than one in marine plankton, suspended particles and zooplankton fecal pellets. The preferential regeneration of ^{210}Po over ^{210}Pb is also indicated by a $^{210}\text{Po}/^{210}\text{Pb}$ ratio of greater than one for filtered seawater at depths between 100 and 800 m in the Atlantic Ocean [13].

If we assume that the concentrations of ^{210}Pb and ^{210}Po in the surface mixed layer of the New York Bight (nearshore areas excluded) are maintained at steady state, then the production rate of ^{210}Pb (or ^{210}Po) from the decay of the mother nuclide ^{222}Rn (or ^{210}Pb) plus the atmospheric input rate of ^{210}Pb (or ^{210}Po) is balanced by the radioactive decay rate plus the removal rate by

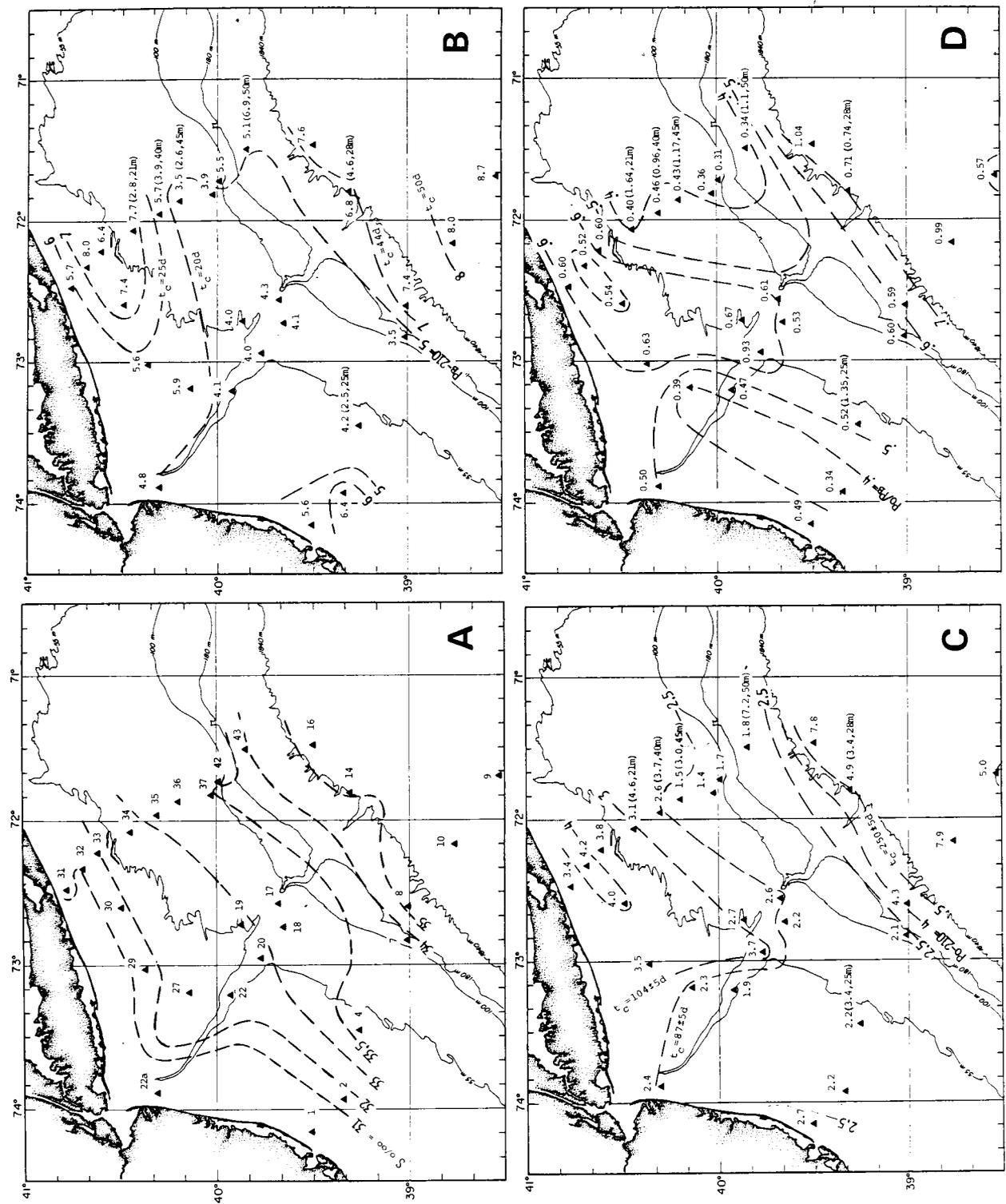


Fig. 7. Areal distributions of (A) stations (numbers) and salinity (contour), (B) ^{210}Po (dpm/100 kg) and (D) ^{210}Po / ^{210}Pb activity ratio during the spring cruise.

settling particles, i.e.:

$$\lambda_2 \cdot A_1 + I_2/h = \lambda_2 \cdot A_2 + \lambda_c A_2 \quad (2a)$$

where λ_2 = decay constant of daughter nuclide; I_2 = atmospheric input rate of daughter nuclide; A_1 and A_2 = activities of parent and daughter nuclides, respectively; λ_c = first-order removal rate constant of daughter from the water; and h = mean depth of the surface mixed layer. Rearranging the above equation, one obtains t_c :

$$t_c = \frac{\ln 2}{\lambda_c} = \frac{\ln 2 \cdot A_2}{\lambda_2(A_1 - A_2) + I_2/h} \quad (2b)$$

A similar approach was used by Turekian et al. [15], in discussing these nuclides in surface seawater.

During the spring cruise, the mean depth of the surface mixed layer (h) was about 15 ± 5 m in the shelf area and about 23 ± 5 m in the slope area. The ^{222}Rn concentration in the surface mixed layer was about 8 ± 1 dpm/100 l throughout the New York Bight (S. Carson, personal communication). Therefore, if one assumes that the atmospheric input rates of ^{210}Pb and ^{210}Po in the New York Bight are similar to those measured by Benninger for New Haven (i.e., 0.93 ± 0.34 dpm $^{210}\text{Pb}/\text{cm}^2$ yr and 0.10 ± 0.05 dpm $^{210}\text{Po}/\text{cm}^2$ yr [4]), the t_c for ^{210}Pb and ^{210}Po in the New York Bight waters can be calculated by equation (2b). The $\lambda_2(A_1 - A_2)$ term in equation (2b) is always negligibly small as compared to the I_2/h term for ^{210}Pb and is not greater than 15% of I_2/h for ^{210}Po . The corresponding t_c values for different concentrations of ^{210}Pb and ^{210}Po are shown in Fig. 7B and C.

The similarity in t_c values between ^{210}Pb and ^{228}Th (compare Figs. 7B and Fig. 4D, excluding nearshore areas where the regenerational input of ^{210}Pb is high) suggests that the removal pathway of ^{210}Pb from surface water is closely coupled to that of ^{228}Th , i.e., adsorption onto suspended particles and subsequent settling to the bottom.

The longer t_c of ^{210}Po than ^{210}Pb (or ^{228}Th) in the spring indicates that ^{210}Po is removed from the surface water much more slowly than ^{210}Pb , due to a higher recycling efficiency of ^{210}Po , probably caused by a coupling of the cycles of ^{210}Po to those of organic carbon [13].

The removal rate of ^{210}Po from the surface waters by the phytoplankton–zooplankton–fecal pellet route was estimated to be about 330×10^{-6} dpm/l day inshore and 1320×10^{-6} dpm/l day offshore in the spring (using the same parameters as in the ^{228}Th calculation, and a ^{210}Po concentration in the mixed plankton sample of 11.1 ± 0.7 dpm/g). The total removal rate of ^{210}Po by settling particles is about 200×10^{-6} dpm/l day inshore ($= \ln 2/87$ days $\times 2.5$ dpm/100 l, excluding the area north of the Hudson Canyon) and 140×10^{-6} dpm/l day offshore ($\ln 2/250$ days $\times 5$ dpm/100 l). Therefore, the removal rates of ^{210}Po by the phytoplankton–zooplankton–fecal pellet route are more than enough to account for the total removal rates by settling particles and again suggest the regeneration of ^{210}Po within the surface waters. Unfortunately, a similar calculation for ^{210}Pb cannot be performed due to loss of the ^{210}Pb fraction during analysis of the mixed plankton sample.

3. Summary and conclusions

(1) During spring, summer and fall when the water column is stratified, the half removal time of ^{228}Th from the surface waters by settling particles, t_c , does not change much with season. The decrease of t_c from the slope ($= 70 \pm 10$ days) toward the shelf ($= 20 \pm 7$ days) correlates with the general trend of increasing suspended sediment particle concentrations toward the shore throughout the year. The most likely removal mechanism of ^{228}Th from the shelf surface water is the adsorption of ^{228}Th onto suspended particles (both organic and inorganic) and subsequent settling to the bottom. In contrast, the removal of ^{228}Th in the slope surface water and the open ocean is mainly through the phytoplankton–zooplankton–fecal pellet route.

(2) The increase of the ^{228}Ra concentration from the slope toward the shore throughout the year is caused mainly by the desorption of ^{228}Ra from the bottom sediments, especially the fine-grained sediments near the shore and the “mud hole” area on the southern New England shelf.

(3) The similar half removal times of ^{228}Th and

^{210}Pb from the New York Bight waters suggest a close coupling of their removal pathways. The removal of ^{210}Po appears to be coupled with organic carbon cycles, causing it to be removed more slowly due to recycling through the water column.

(4) The high concentrations of ^{228}Th , ^{210}Pb and ^{210}Po in the nearshore waters during the winter and, to a lesser extent, the spring season, suggest that these nuclides in the settling particles and/or in the bottom sediment have been regenerated to the bottom water during the seasonal stratification and transported back to the surface water during the winter mixing.

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