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Preliminary study on particulate organic carbon export fluxes in the Bering Sea

Ma Hao(马 豪)[1,2], Zeng Zhi(曾 志)[1], He Jianhua(何建华)[2], Yin Mingduan(尹明端)[2], Chen Liqi(陈立奇)[2] and Zeng Shi(曾 实)[1]

1 Department of Engineering Physics, Tsinghua University, Beijing 100084, China; 2 Key Laboratory of Global Change and Marine-Atmospheric Chemistry, State Oceanic Administration, Xiamen 361005, China

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Abstract During the Second Chinese National Arctic Expedition (CHINARE) from July to September 2003, depth profiles of dissolved and particulate ^{234}Th in upper water columns were collected at two stations of BR03 and BR24 in the Bering Sea. ^{234}Th was sampled by using a traditional $Fe(OH)_3$ co-precipitation technique, which is a reliable approach to ^{234}Th measurement. We observed ^{234}Th excess at station BR03 below the euphotic zone, which was possibly due to the intensive remineralization of particulate matter. Particulate organic carbon (POC) export fluxes were estimated from a one-dimensional irreversible steady state model of ^{234}Th fluxes together with measurements of the POC/^{234}Th ratio on the suspended particles. The POC export fluxes from the euphotic zone were 11.66 and 11.69 mmol C m^{-2} d^{-1} at BR03 and BR24 stations, respectively. The ratios of POC fluxes to primary production at the two stations were about 0.5 and 0.59, respectively, probably due to the presence of large phytoplankton (in particular diatoms).

Key words $^{234}Th/^{238}U$ disequilibria, euphotic zone, particulate organic carbon, Bering Sea

1 Introduction

The euphotic zone is an active water layer in the ocean for marine phytoplankton to convert inorganic carbon into organic carbon, resulting in a CO_2 exchange across the atmosphere/ocean interface. Moreover, it is an important layer for the production of biogenic matter and for the vertical transport of particles to the deep sea. Export flux of particulate organic carbon (POC) from the euphotic zone to the deep ocean is regarded as a critical index of the efficiency of biological pump and it has often been used as a necessary measurement to determine the biogeochemical cycling rates of particle-reactive elements and constituents in the ocean[1-2].

The estimation of POC export fluxes in the ocean is based on two main approaches including sediment trap deployment and the radioactive isotope tracing method. In the upper ocean, the quantity and quality of sinking materials collected by sediment traps are largely based on the hydrodynamic situation and often involve "swimmer" related issues[2]. Re-

cently, the Neutrally Buoyant Sediment Trap has improved hydrodynamic problems and can be used to determine the POC flux in the upper ocean. However, the instrument is too expensive to be densely deployed in the investigated area and be widely used.

Natural radioactive isotope tracing is an alternative method to determine POC export fluxes, and the $^{234}Th/^{238}U$ disequilibrium is the most widely used approach. ^{234}Th is a radioactive nuclide with very high particle reactivity, produced *in-situ* from the decay of its parent ^{238}U with a steady rate in the ocean. ^{234}Th can be scavenged and removed rapidly with sinking particulate matter, resulting in disequilibrium between ^{234}Th and ^{238}U, especially in the upper water column. The deficiency of ^{234}Th with respect to ^{238}U reflects the cycle, export and remineralization of particles. Due to the relatively short half-life of ^{234}Th (24.1d), it is well suited for tracing biogeochemical processes in the timescale similar to particle dynamics in the upper ocean[3]. As reported by Buesseler *et al*.[4], the ^{234}Th-^{238}U disequilibrium technique is proved to be a robust method in the estimation of particle export fluxes from the euphotic zone in the ocean. Fukuchi *et al*. estimated the POC export flux from the euphotic zone of the Bering Sea using sediment traps in the ISHTAR (Inner Shelf Transfer And Recycling) Project which concerned biological processes in the seasonal sea ice region of the north Bering Sea[5]. Chen *et al*. first estimated POC export fluxes at three stations in the southwestern Bering Sea from $^{234}Th/^{238}U$ disequilibria[6]. To our knowledge, there are few reports on POC export fluxes in the Bering Sea. Here we report export fluxes of POC from the euphotic zone in the Bering Sea based on ^{234}Th-^{238}U disequilibrium data and a steady state box model.

2 Study area

Bering Sea is the most northern marginal sea of the Pacific Ocean bounded by Siberia, Alaska and the Aleutian Islands with an area of 2.3×10^6 km^2. The northern portion is connected to Arctic Ocean by Bering Strait which is 80km wide and 50m deep. The warm water flows from the northern Pacific Ocean to the Arctic Ocean through the Bering Sea and Bering Strait. The Bering Sea is in triangular form and can be divided into three portions: the northern portion of the Bering Sea is characterized by broad continental shelf (accounting for 44% of the total Bering Sea area); the central and western portion consist of deep basins (accounting for 43% of the total Bering Sea area); the remaining is characterized by the continental slope[7-9].

Samples were collected at two stations (BR24: 170.78° E, 53.97° N and BR03: 176.18° E, 57.99° N) onboard R/V 'Xuelong' during the second Chinese National Arctic Expedition (CHINARE) from July to September 2003. At each station, 20L of seawater for each sample was collect-

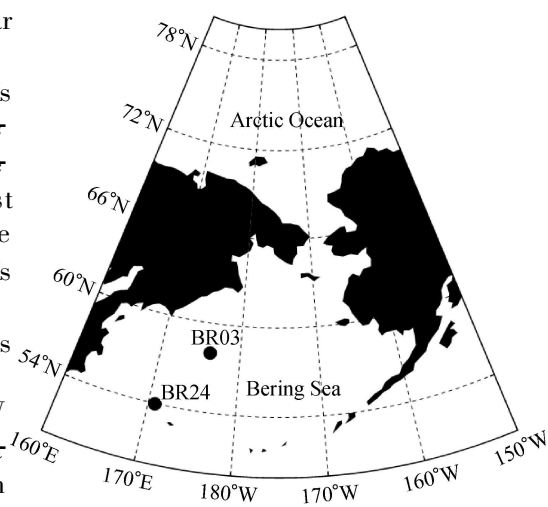

Fig. 1 Sampling stations

ed using Niskin bottles in each water depth (i.e. 0m, 10m, 30m, 50m, 75m, 100m, 150m and 200m).

3 Sample analysis

Upon sample collection, a 1 L portion of each sample was filtered through 0.7μm glass fiber filters (Whatman™ GF/F), dried and brought back to the laboratory for POC analysis. The remaining 19 liters of seawater were filtered through a 0.45μm membrane filer to obtain samples of water and particles. After that, the water samples were co-precipitated with $Fe(OH)_3$[10]. Finally the beta/alpha sources were prepared with electrodeposition and the radioactivity of ^{228}Th and ^{234}Th were detected with low-level α-spectrum/β-counter. In other studies, activities of ^{234}Th and its yield tracer ^{228}Th (or ^{229}Th, ^{230}Th) were usually measured using a β-counter and α-spectrometer, respectively, so the detector inter-calibration was necessary for the results. In the present study, only one detector was used to measure the activities of ^{234}Th and ^{228}Th simultaneously so the detector inter-calibration between α-spectrometer and β-counter was avoided and the measurement error was then reduced[11]. For the short half life, ^{234}Th activities were determined on board by the mentioned procedure above, while ^{238}U activities were calculated with the relationship between ^{238}U and salinity (S): $^{238}U\ (dpm \cdot L^{-1}) = 0.07081 \times S$[12]. Temperature and salinity were determined by shipborne CTD system.

4 Results and discussion

4.1 hydrologic parameters

The depth profiles of temperature and salinity were listed in table 1. The mixed layer at BR24 and Br03 station could extend to a depth of 50m with main thermocline and halocline located in the range of 20 to 50m depth. As a marginal sea of North Pacific Ocean, the southern part of Bering Sea was connected with the Pacific Ocean. BR03 station lay in the Bering Basin and was characterized by typical vertical profiles of temperature and salinity in the Bering Sea: the warmer waters (> 7 ℃) could not extend more than 15m depth and intermediate colder waters (< 3 ℃) between 50 to 200m. The warm waters also existed at BR24, while the intermediate cold waters were heated by warm water from the North Pacific Ocean and showed a higher temperature than that of BR03.

4.2 Vertical profiles of ^{234}Th and POC concentrations

Vertical profiles of ^{234}Th and ^{238}U activities are given in Table 1 and Fig. 2. The particulate fraction accounted for 8% ~ 28% of total ^{234}Th activities. ^{234}Th activities showed an apparent deficiency to its parent ^{238}U in the euphotic zone due to the scavenged to and removed with marine particles. Below 100m, total ^{234}Th activities balanced with ^{238}U. At BR03, there was a significant excess of ^{234}Th at 200m, which might be due to intensive remineralization of particles.

Table 1. Vertical distributions of temperature, salinity, POC concentrations and ^{234}Th activities

Station	Depth (m)	T (℃)	S	A_{DTh} (dpm·L^{-1})*	A_{PTh} (dpm·L^{-1})	A_U (dpm·L^{-1})	POC (μmol·L^{-1})
	0	9.490	32.106	1.707±0.225	0.237±0.019	2.273	13.056
	10	9.490	32.707	1.375±0.076	0.316±0.025	2.316	9.250
BR24	20	6.431	32.904	1.224±0.071	0.412±0.022	2.330	8.500
Bottom	30	5.457	33.022	1.725±0.130	0.451±0.027	2.338	6.383
depth:	50	4.563	33.089	1.211±0.067	0.500±0.034	2.343	8.583
3100m	75	3.550	33.187	1.447±0.120	0.664±0.043	2.350	8.050
	100	4.050	33.623	1.646±0.077	0.331±0.024	2.381	11.528
	150	4.128	33.840	1.799±0.145	0.260±0.020	2.396	4.264
	0	10.488	33.054	1.146±0.087	0.646±0.054	2.341	12.167
	10	9.987	33.069	1.488±0.096	0.438±0.031	2.342	12.000
BR03	30	5.505	33.094	1.447±0.105	0.206±0.012	2.343	7.041
Bottom	50	2.258	33.193	1.329±0.086	0.347±0.023	2.350	4.771
depth:	75	1.754	33.207	1.533±0.074	0.214±0.019	2.351	3.073
3870m	100	1.744	33.236	1.748±0.125	0.480±0.038	2.353	2.300
	150	2.228	33.386	1.834±0.117	0.193±0.020	2.364	1.819
	200	3.523	33.740	2.215±0.139	0.307±0.024	2.389	3.438

* 1 dpm = 1/60 Bq

4.3 *Scavenging and removal rates of ^{234}Th*

Estimates of the scavenging and removal rates of ^{234}Th as well as the resident times of dissolved and particulate ^{234}Th can be determined from an irreversible steady state model of thorium scavenging in the water column using the following equation[13]:

$$\partial A_{Th}/\partial t = \lambda \cdot [A_U - (A_{DTh} + A_{PTh})] - P_{Th} + V \quad (1)$$

where A_U, A_{DTh} and A_{PTh} represent the activities (dpm·L^{-1}) of ^{238}U, dissolved ^{234}Th and particulate ^{234}Th, and λ is the ^{234}Th decay constant (0.02876 d^{-1}). The term P_{Th} (dpm·m^{-3}·d^{-1}) represents the removal rate of particulate ^{234}Th due to particle sinking and V, the contributions of advection and diffusion to the ^{234}Th fluxes.

Here, the contributions of advection and diffusion are neglected and Eq. (1) is rewritten for dissolved and particulate ^{234}Th in a steady state, respectively:

$$J_{Th} = \lambda \cdot (A_U - A_{DTh}) \quad (2)$$

$$P_{Th} = J_{Th} - \lambda \cdot A_{DTh} \quad (3)$$

$$\tau_D = A_{DTh}/J_{Th} \quad (4)$$

$$\tau_P = A_{PTh}/P_{Th} \quad (5)$$

where the term J_{Th} (dpm·m^{-3}·d^{-1}) represents the net scavenging rate of dissolved ^{234}Th onto particles. τ_D (d) and τ_P (d) are the residence times of ^{234}Th with respect to particle scavenging and removal, respectively.

The results calculated from the model mentioned above were given in Table 2. At BR24, J_{Th} ranged from 16.296 in the surface water to 32.550 dpm·m^{-3}·d^{-1} at the depth of 150m with an average of 23.705 dpm·m^{-3}·d^{-1}; PTh ranged from 4.673 dpm·m^{-3}·d^{-1} in the surface water to 19.962 dpm·m^{-3}·d^{-1} at the depth of 150m with an average

of 12.310 dpm·m^{-3}·d^{-1}; τ_D ranged from 37.2d in the surface water to 104.7d at the depth of 150m with an average of 70.916d; τ_P ranged from 17.588d in the surface water to 96.514d at the depth of 150m with an average of 42.357d.

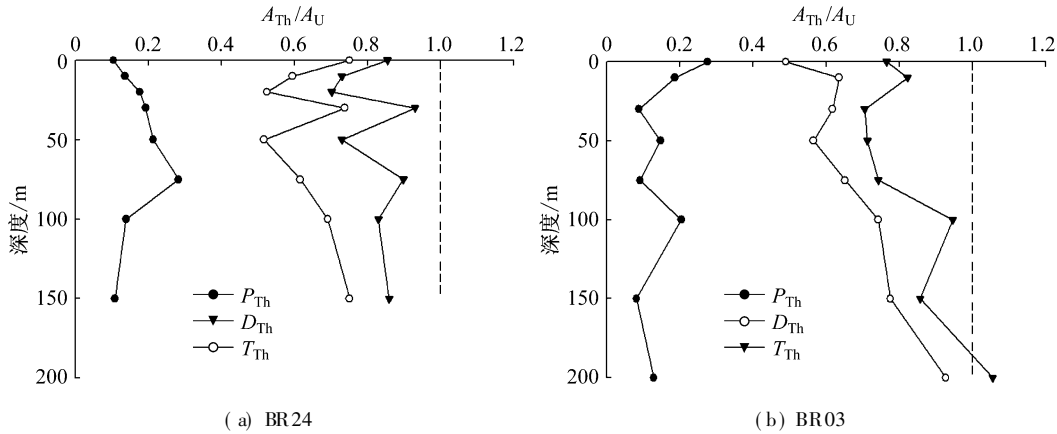

Fig. 2 Depth profiles of $^{234}Th/^{238}U$ activity ratios

At BR03, J_{Th} ranged from 5.013 in the surface water to 34.342 dpm·m^{-3}·d^{-1} 200m deep with an average of 21.907 dpm·m^{-3}·d^{-1}; P_{Th} ranged from -3.817 dpm·m^{-3}·d^{-1} in the surface water to 19.852 dpm·m^{-3}·d^{-1} 200m deep with an average of 11.735 dpm·m^{-3}·d^{-1}; τ_D ranged from 33.383d in the surface water to 441.799d 200m deep with an average of 115.378d; τ_P ranged from -80.440d in the surface water to 132.559d 200m deep with an average of 23.756d. We found some P_{Th} and τ_P had negative values at the depth of 200m, which was consistent with the excess of ^{234}Th mentioned above.

Table 2 Estimated resident times, scavenging and removal rates

Station	Depth (m)	J_{Th} (dpm m^{-3} d^{-1})	P_{Th} (dpm m^{-3} d^{-1})	τ_D (d)	τ_P (d)
BR24	0	16.296	9.483	104.740	24.978
	10	27.049	17.963	50.851	17.588
	20	31.814	19.962	38.466	20.645
	30	17.635	4.673	97.823	96.451
	50	32.550	18.181	37.212	27.480
	75	25.968	6.878	55.724	96.514
	100	21.136	11.619	77.872	28.481
	150	17.188	9.719	104.643	26.721
BR03	0	34.342	15.775	33.383	40.923
	10	24.545	11.958	60.629	36.601
	30	25.782	19.852	56.121	10.387
	50	29.380	19.410	45.230	17.860
	75	23.541	17.384	65.116	12.313
	100	17.412	3.618	100.393	132.559
	150	15.237	9.701	120.378	19.846
	200	5.013	-3.817	441.779	-80.440

4.4 POC export flux

The euphotic zone could extend to 50m depth at BR24 and BR03 in the Bering Sea, so we chose the depth of 50m as the export layer in the scavenging model to estimate POC export fluxes[14]:

$$F^B = F_{PTh} \cdot POC/A_{PTh} \quad (6)$$

where F^B, F_{PTh} and POC/A_{PTh} represent POC export fluxes, ^{234}Th export fluxes and POC to particulate ^{234}Th ratio, respectively. The results are listed in Table 3.

For limited ship time, we did not use pump to get large volume of sea water (i.e. 200 ~ 300L) on board so as to obtain size-fractionated particles, so the POC/A_{PTh} ratios we used in this paper to estimate POC fluxes were ratios in the suspended particles rather than really sinking matters. The POC export fluxes were 11.66 mmol C m^{-2} d^{-1} at BR24 and 11.69 mmol C m^{-2} d^{-1} at BR03, respectively. The data lay in the range of results (about 10– 15 mmol C m^{-2} d^{-1}) in the neighboring sea area reported by Chen *et al.*[6] However, they were much less than those in the northern Bering Sea due to different biological conditions. Moreover, Fukuchi used sediment traps to determine POC fluxes[5], which often differs from the ^{234}Th data reported by Buesseler[15].

Table 3. Estimated resident times in the euphotic zone and POC export fluxes

Station	Export layer (m)	τ_D (d)	τ_P (d)	POC/A_{PTh} (μmol dpm^{-1})	F_{PTh} (dpm m^{-2} d^{-1})	F^B (mmol C m^{-2} d^{-1})
BR24	50	57.5	29.8	17.18	678.6	11.66
BR03	50	52.1	20.5	13.76	849.4	11.69

The primary productivity of the euphotic zone in the Bering Sea was 19.8 mmol C m^{-2} d^{-1}[16], so 50% at BR24 and 59% at BR03 of the organic carbon produced by phytoplankton were exported from the euphotic zone. Such high ratios might be because of the existence of large phytoplankton biomass, especially diatoms[2].

4.5 Conclusion

The ^{234}Th-^{238}U disequilibria in the upper ocean were used to estimate the resident times and export fluxes of ^{234}Th as well as POC export fluxes in summer of the Bering Sea. At BR24, the resident times of dissolved and particulate ^{234}Th were 57.5d and 29.8d respectively, and POC export flux was 11.66 mmol C m^{-2} d^{-1}. At BR03, the resident times of dissolved and particulate ^{234}Th were 52.1d and 29.8d respectively, and POC export flux was 11.69 mmol C m^{-2} d^{-1}. And ^{234}Th activities were excess to ^{238}U at the depth of 200m, which may be because of intensive remineralization of particles. POC export from the euphotic zone accounted for 50% and 59% of primary productivity, due to the existence of large phytoplankton in the high latitude seas. The results can be a reference for further understanding the role of the Bering Sea in global carbon cycle.

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