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Variability in the flux of rapidly sinking particles at the Chirikov Basin of the northern Bering Sea in summer 1988[*]

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Abstract: A time-series sediment trap was deployed at 13 m above the bottom at the Chirikov depocenter (about 50 m depth) of the northern Bering Sea from 20 June, 1988 to 24 September, 1988. Twelve consecutive samples were collected with a time interval of 8 days. According to the physical conditions (temperature, current speed and direction) around the trap site, the deployment period can be separated into three distinct short periods, phase I (from 20 June to 7 August), phase II (from 7 August to 31 August) and phase III (from 31 August to 24 September). Averaged daily carbon flux was higher in phase I (490 mgC m^{-2}) than those in phase II (425 mgC m^{-2}) and in phase III (439 mgCm^{-2}). In phase I, northward flowing and cold Bering Shelf Anadyr Water (BSAW) induced to produce autochthonous large sinking particles (LG) around the trap site and also carried allochthonous small particles (SM) from the south. In phase II, when the cold BSAW and warm Alaskan Coastal Water (ACW) occurred alternatively, LG fraction decreased possibly due to the less influence of BSAW. In phase III, BSAW replaced ACW, and LG fraction increased again, though the fecal pellet composition of LG were quite different from that in Phase I. The LG increase in phase III was primarily attributed to a fall phytoplankton bloom and intensified herbivorous grazing acitivities.

1. Introduction

The continental shelf of the northern Bering Sea has been recognized as an area of high marine production at several trophic levels (MCROY *et al.*, 1972; SAMBROTTO *et al.*, 1984), because the advection of oceanic water from the basin of the Bering Sea is primarily responsible for the high biomasses of the shelf area (SPRINGER and ROSENEAU, 1985; SPRINGER *et al.*, 1989; GREBMEIER *et al.*, 1988). The benthic biomass, in particular, at the Chirikov Basin of the northern Bering Sea is extremely high, which indicates the close coupling between pelagic sedimentation of organic matter and high abundance and biomass of benthic fauna (GREBMEIER *et al.*, 1988; GREBMEIER *et al.*, 1989; GREBMEIER and MCROY, 1989). This has been verified by sediment trap studies in this area (FUKUCHI *et al.*, 1993).

A preliminary report of the last study with a time-series sediment trap (96-day deployment) showed that considerable amount of organic particles sank onto the bottom, and the high flux continued for about 3 months in summer. From the data of a short-term trap deployment (1 day), sinking particles were dominated by zooplankotn fecal pellets, marine snow-like particles and diatom cells (FUKUCHI *et al.*, 1993).

In summer season, physical oceanographic regime in the northern Bering Sea includes 3 water masses; Anadyr Water (AW), Bering Shelf Water (BSW) and Alaskan Coastal Water (ACW). These water masses are defined by T/S profiles and were characterized following bottom water properties: AW ($S > 32.5$, $T = -1.0$ to 1.5℃) on the western side of the Sea,

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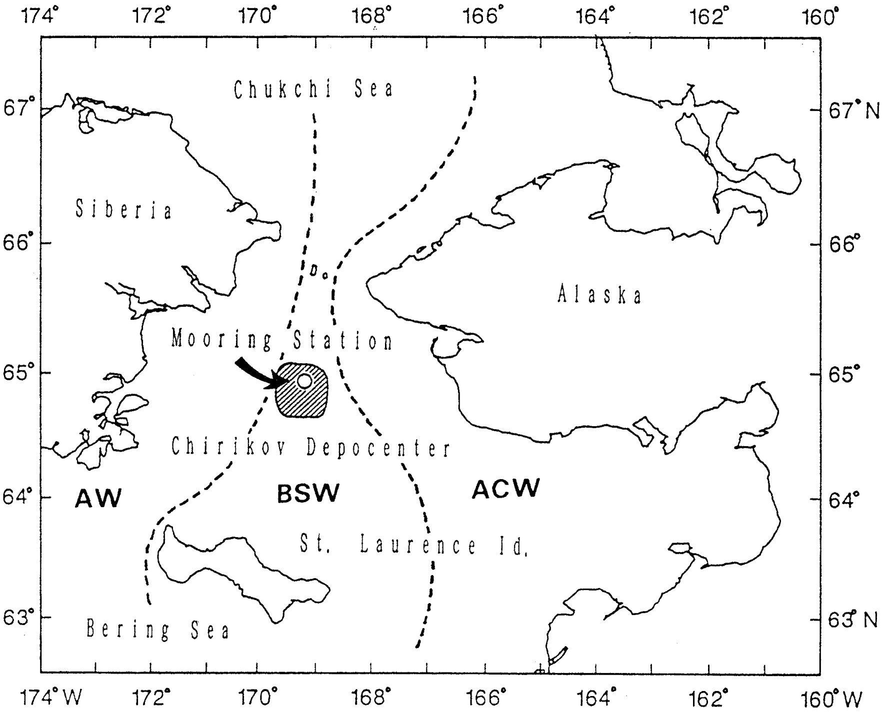

Fig. 1. Location of mooring station for time-series sediment trap experiment (64°58.62′ N, 169°10.08′ W) at the Chirikov Basin of the northern Bering Sea. Shaded area indicates the main depocenter of the Basin (GREBMEIER *et al.*, 1988).

BSW (S=31.8 to 32.5, T=0 to 1.5℃) in the middle region, and ACW ($S<31.8$, $T>4$℃) near the Alaska coast (COACHMAN *et al.*, 1975; GREB-MEIER *et al.*, 1988; DEAN, *et al.*, 1989). BSW and ACW are distinct in water properties and form a well-defined frontal zone, while AW and BSW are less distinct. The two water masses (AW and BSW) with a combined water properties is called as Bering Shelf-Anadyr Water (BSAW).

These complicated physical properties of waters in the northern Bering Sea can display a variability of biological processes over relatively small spatial and temporal scales. Thus, an understanding of frequencies, magnitude and spatial-temporal scales of particle flux variablity is important to model biological productivity with reference to physical and chemical water properties.

In the present study, a time-series sediment trap were deployed at the main depocenter of the Chirikov Basin of the northern Bering Sea in summer 1988. This experiment was conducted to understand the possible influences of physical water conditions on the sedimentation processes of particulate organic matter flux at the Chirikov Basin area. This paper deals primarily with variabilities of large sinking materials including fecal pellets and zooplankton captured in the trap at the main depocenter of the northern Bering Sea.

2. Materials and Methods

The experiments were conducted at a station (64°58.62′ N, 169°10.08′ W) located at the main depocenter of the Chirikov Basin in the northern Bering Sea at the depth of 49 m (Fig. 1), during the cruises of ISHTAR Leg I, 1988 of R/V T. G. Thompson and ISHTAR Leg IV, 1988 of R/V T. Washington. The moored time-series sediment trap, described by FUKUCHI *et al.* (1993), was situated 13 m above the bottom to reduce the influence of sediment resuspension. The trap was designed to collect 12 consecutive samples with a collection interval of 8 days from 20 June 1988 to 24 September 1988 (Table 1). Neutralized

Table 1. Sampling intervals of time-series sediment trap experiment conducted at the Chirikov Basin in the northern Bering Sea, 1988.

Sample No.	Sampling period	
	opening	closing
1	12:00 20 June	— 12:00 28 June
2	12:00 28 June	— 12:00 6 July
3	12:00 6 July	— 12:00 14 July
4	12:00 14 July	— 12:00 22 July
5	12:00 22 July	— 12:00 30 July
6	12:00 30 July	— 12:00 7 Aug.
7	12:00 7 Aug.	— 12:00 15 Aug.
8	12:00 15 Aug.	— 12:00 23 Aug.
9	12:00 23 Aug.	— 12:00 31 Aug.
10	12:00 31 Aug.	— 12:00 8 Sept.
11	12:00 8 Sept.	— 12:00 16 Sept.
12	12:00 16 Sept.	— 12:00 24 Sept.

formalin in filtered sea water (ca. 10% v/v) served for sample preservation during deployment.

Collected materials with the time-series sediment trap were splitted into two aliquots; one was used for batch analyses of organic carbon and nitrogen (FUKUCHI *et al.*, 1993), and the other for the size fractionation analyses of the present study. Particles in this study were further divided into two fractions, Large-sized particle fraction (LG), and Small-sized particle fraction (SM), according to a procedure as follows. Particles with a small volume of seawater (ca. 50 ml) was gently injected into a settling column (approximate size of 50mm × 500mm) with 3.2% NaCl solution. The particles were separated into two fractions, LG with higher sinking rates and SM with lower sinking rates, after a given period of time. The settling column was exposed to cold condition (about 4℃) in the laboratory.

The sinking rate to differentiate two particle fractions was calculated under the following assumptions. The maximum northward current speed (daily mean) near the station is 35 cm sec^{-1} (R. TRIPP, personal communication). The horizontal expansion of the main depocenter is about 50 km, which is roughly estimated from the distribution range of dense benthic biomass (GREBMEIER and MCROY, 1989). The approximate location of the trap mooring site was in the center part of the depocenter. Then, for large particles which start sinking at the outer edge of the depocenter to reach the bottom (ca. 50 m) at the mooring site, the minimum sinking rate is calculated to be approximately 60 m d^{-1}. The sinking rate of LG fraction is $>$60 m^{-1} and that of SM fraction $<$60 m^{-1}.

Although this separation procedure is quite preliminary, the LG fraction is expected to be an approximate indication of autochthonous particles in the water column above the depocenter. Since LG fraction represents the minimum estimate of the autochthonous materials, SM fraction probably include both of auto-chthonous and allochthonous materials, the latter of which would mostly come from the south with northward current.

Sample particles separated were used for Particulate Organic Carbon (POC) determinations, orgnic matter analyses (sterols), inorganic matter analyses, and microscopic examinations of fecal pellets, zooplankton and phytoplankton. The present study covers only results of POC, fecal pellets and zooplankton.

Zooplankton swimmers larger than about 1 mm were removed carefully from LG fractions and were examined for the species compositions and abundances. Aliquots of LG fractions were used for examinations of large fecal pellet (ca. $>$0.1mm) compositions and abundances under a disecting microscope. POC contributions of fecal pellets were estimated based on a conversion factor of pellet volume to carbon according to the data of JOHANNES and SATOMI (1966). Aliquots of LG and SM fractions were filtered through GF/F glass fiber filters and were analyzed for POC with a Infra-red gas analyzer (Horiba LIA-2) as described by SASAKI and NISHIZAWA (1989).

3. Results

Particulate flux

The POC flux at 13 m above the bottom of the depocenter revealed a relatively small fluctuation between sampling intervals, where a factor of about 1.7 difference was found (Fig. 2). Fluxes of LG fractions varied in the range of 127 to 271 mgC m^{-2}d^{-1} with a mean flux of 205 mgC m^{-2}d^{-1}. SM fluxes were in the range of 138 to 342 mgC m^{-2}d^{-1} with a mean flux of 257 mgC m^{-2}d^{-1}, being slightly larger than those of LG. The relative contribution of LG increased

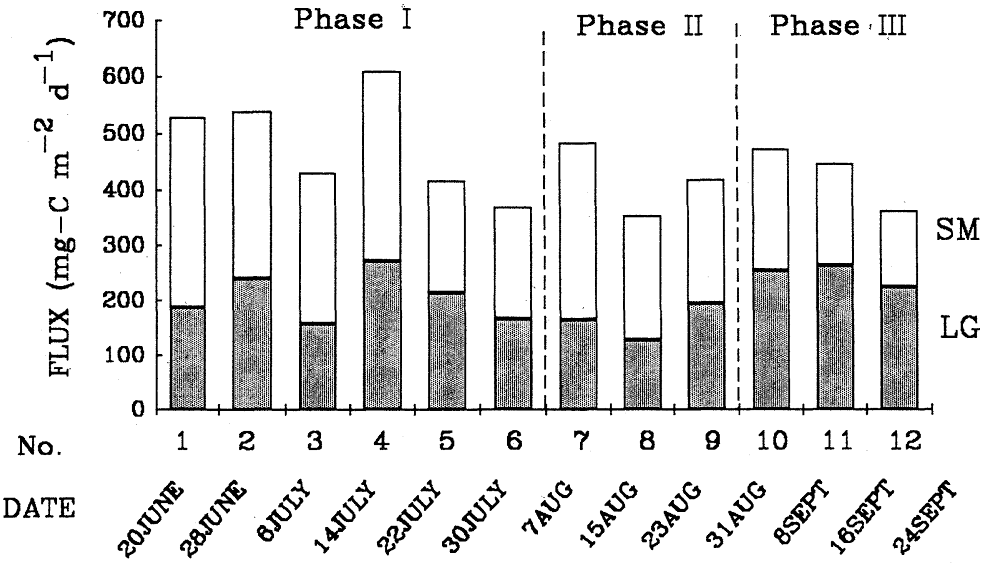

Fig. 2. Variability of downward flux of particulate organic carbon (POC) at the Chirikov depocenter. Trap-collected particles were classified into two groups: Large-sized particle fraction (LG) and Small-sized particle fraction (SM), according to their sinking rates.

towards the end of the mooring period.

Microscopic observations of LG showed that the dominant component were two different types of fecal pellets; cylindrical pellets and elliptical pellets. The fecal pellet fluxes in terms of POC were shown in Figs. 3-a & b. While the cylindrical pellets mostly occurred in the 1st half of the mooring period, the abundance of elliptical pellets increased towards the end of the period, particulary between 16 September and 24 September. In two fecal pellet types, large pellets (> 1 mm) predominated in carbon contribution to small pellets (0.1-1mm). Few fecal pellets and zooplankton swimmers were observed in the SM fractions which were dominated by diatoms (SASAKI *et al.*, 1992).

POC contributions of total fecal pellet (cylindrical and elliptical pellets) of LG fractions showed that the relative abundance of total pellets varied between a sampling interval (Fig. 3-c). In two periods of 14 July to 30 July and 16 September to 24 September, estimated carbon contributions of total pellet accounted for about 100% of the measured total LG carbon. In other periods, LG fractions were mainly composed of both fecal pellets and marine snow-like particles possibly derived from appendicularion houses as suggested by FUKUCHI *et al.* (1993). The averaged carbon contribution of fecal pellets to mean LG fraction were 49 % through the entire observation period.

Trap-collected zooplankton

Table 2 shows the list of zooplankton captured in LG fractions of the sediment trap. They were classified into four representative groups; oceanic species, coastal species, cosmopolite and others, according to SPRINGER *et al.*, (1989). Oceanic and coastal species were occupied by copepods. A predominant animal in numerical abundance was a small cosmopolite copepod, *Pseudocalanus* spp. Few benthic animals, such as Cumacea, were found in the trap samples.

Variabilities in abundance of trap-collected zooplankton other than cosmopolite copepod *Pseudocalanus* spp. are shown in Fig. 4. On the average, trap-collected zooplankton was dominated by oceanic copepods except for the period of 8 September to 24 September, and coastal copepods (*Calanus marshallae*) occurred as a low percentage of the total population through the period. A high relative abundance of the oceanic group possibly indicates an occurrence of water mass transported from the southern Bering Sea where the oceanic copepods originally inhabited.

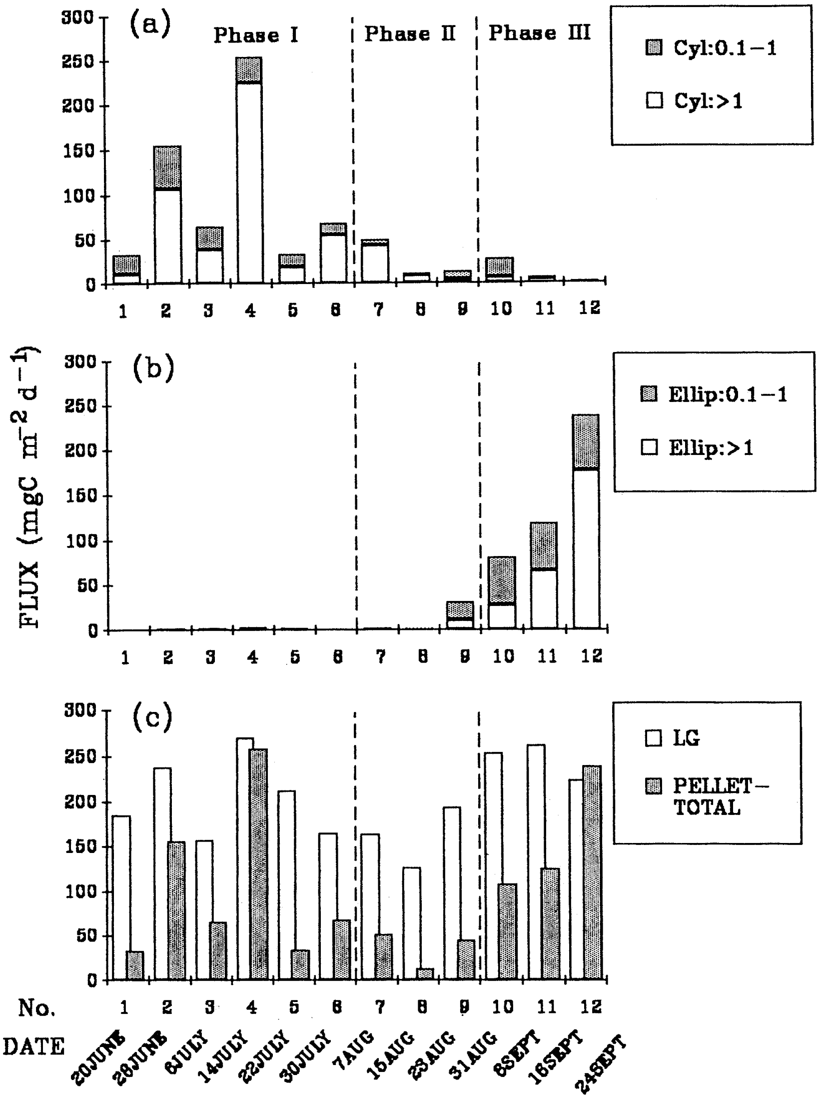

Fig. 3. Variability of zooplankton fecal pellet fluxes of the LG fraction in terms of POC (mg m^{-2} d^{-1}). (a): Estimated fluxes of cylindrical fecal pellets (Cyl) for two different size groups (0.1–1 mm and > 1 mm), (b): estimated fluxes of elliptical fecal pellets (Ellip) for two different sizes (0.1–1 mm and > 1 mm), (c): sum of cylindrical and elliptical fecal pellet fluxes (PELLET-TOTAL), and measured fluxes of LG fraction (LG).

Typical oceanic copepods, primarily *Neocalanus cristatus*, *N. flemingeri*, *Eucalanus bungii* were abundant (> 50% of total zooplankton) from the end of June to middle of August. However, the copepod abundance obtained in this study (inds. sample^{-1}) may not show the exact animal density in the water mass, primarily because of the avoidance of animals from the trap, and the degree of influence of northward current on the advective particle transportation can not be quantitatively estimated.

Current flow

The eight-day mean current flow at 24 m depth near the sediment trap site at the Chirikov basin was generally northward along the axis in the range from 5 to 19 cm^{-1} (Fig. 5-b; R. TRIPP, personal communication). The 8 day

Table 2. Representative species of four groups of zooplankton communities in the LG fractions of trap samples.

GROUP	SPECIES
OCEANIC SPECIES	*Neocalanus cristatus* *N. plumchrus* *Eucalanus bungii* *Metridia pacifica*
COASTAL SPECIES	*Calanus marshallae*
COSMOPOLITE	*Pseudocalanus* spp.
OTHERS	Polychaeta Chaetognatha Cirripedia Cumacea Amphipoda(Gammaridea) Decapoda larvae Appendicularia Copepoda *Scorecithricella minor* *Acartia tumida* *Oithona* spp. *Euterpina* spp. unidentified

mean current speeds are inevitably smaller than the daily maximum speed mentioned before (35 cm^{-1}). The period of 8 day corresponds to the collection interval of the sediment trap. The eight-day mean water temperature were in the range of 0.4 to 5.1℃ (Fig. 5-a). The current speed, direction and water temperature data show a marked fluctuation between the sampling interval, which may be related to the passage of a frontal zone between BSAW and ACW.

4. Discussions

Rapidly sinking particles should represent the agents transported vertically from the upper productive layers to depths as forms of relatively large fecal pellets and marine snow (e.g. ANGEL, 1984; FOWLER and KNAUER, 1986). However abundances, qualities and variabilities of particles transported with advective water movements (allochthonous particles) can not be related to biological processes in the upper layers. Since the Chirikov basin area is in very complicated water conditions, it is necessary for trap-collected particles to be primarily separated as autochthonous rapidly sinking particles (LG in this case) and allochthonous small particles (SM).

The current data (Fig. 5) showed that the waters at the trap site during the period of sample Nos. 1 through 6 (from 20 June to 7 August) is in low temperature, and in continuous and strong northward current which is possibly

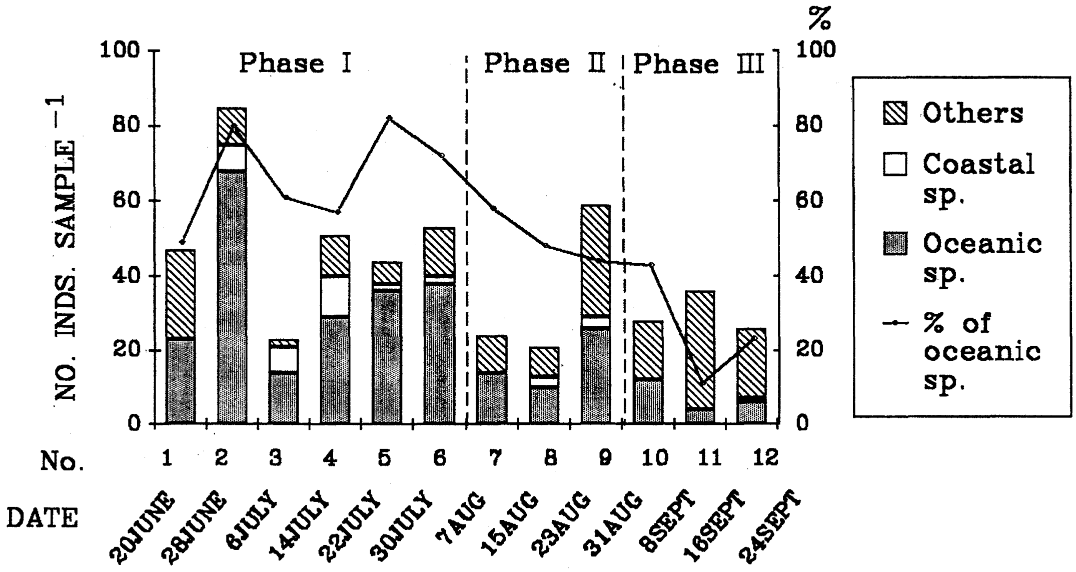

Fig. 4. Variability of zooplankton abundance collected in the LG fractions, and contributions of oceanic copepods to total zooplankton. Total zooplankton includes oceanic copepods (Oceanic sp.), coastal copepods (Coastal sp.) and other zooplankton (Others) (see Table 2).

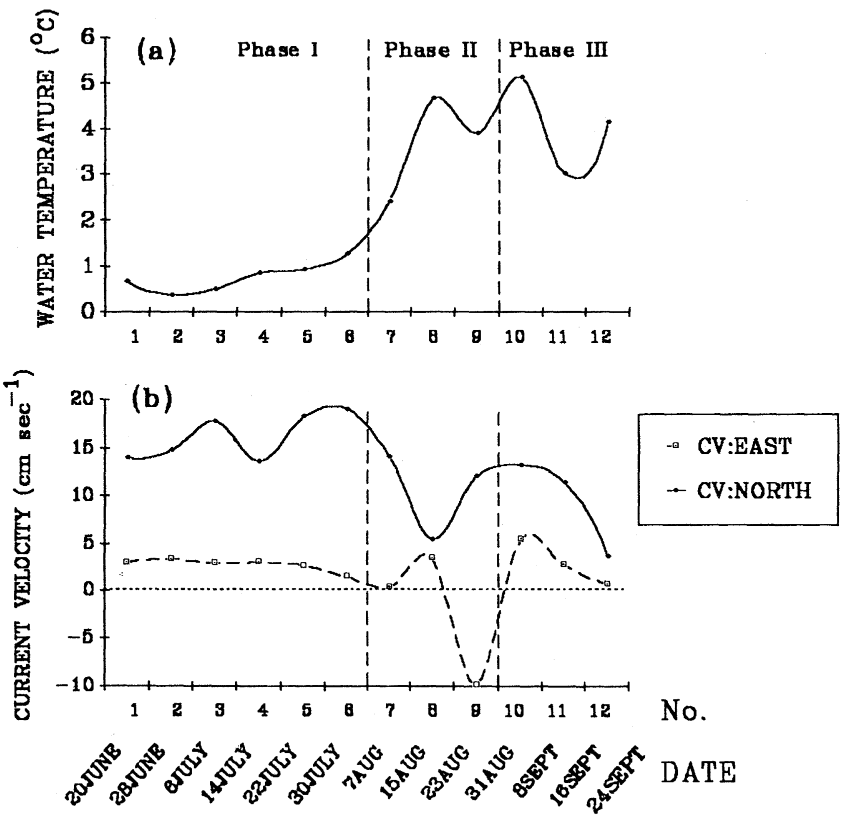

Fig. 5. Variabilities of 8-day mean water temperature (a) and current velocities both of northward (CV: NORTH) and eastward (CV: EAST) components at the Chirikov depocenter (TRIPP, personal communication). The period of 8-day corresponds to the collection interval of time-series sediment trap.

BSAW. From Nos. 7 through 9 (from 7 August to 31 August), water temperature increased to 4 to 5℃, and the current speeds and directions were relatively unstable. This may indicate an alternative occurrence of surrounding water masses including cold BSAW and slightly warm ACW in the transition zone. From Nos. 10 through 12 (from 31 August to 24 September), water temperature is high (about 4℃), and continuous and weak northward current were observed. This stream corresponds to ACW. According to these water conditions, the whole observation period can be separated into three short period; phase I (Nos. 1 through 6), phase II (Nos. 7 through 9) and phase III (Nos. 10 through 12).

Average parameters of sediment trap material in three phases at the Chirikov depocenter were summarized in Table 3. Average water temperatures and current speeds were recalculated from the data in Fig. 5.

In phase I, an average total POC flux (490 mgC $m^{-2}d^{-1}$) was higher than those in other phases. The flux of LG fraction was fairly high and the contribution of LG to total POC (42%) was slightly less than that of SM fraction (58%). Fecal pellets, a typical autochthonous source accounted for about 50% of LG POC. Fecal pellets obtained in this phase were mostly cylindrical forms.

Possible producers of these cylindrical pellets were relatively large oceanic copepods, such as *N. flemingeri* and/or *N. cristatus*, primarily because these pellets occurred in general accordance with the oceanic copepods mentioned above (Fig. 4, Table 3). This was supported by a previous study (SASAKI *et al.*, 1988), showing that the same-sized cylindrical pellets were

Table 3. Average parameters of sediment trap material at 36 m depth in three phases at the Chrikov depocenter in the northern Bering Sea. Average water temperature and current velocities at 24 m depth were recalculated from the current flow data (Tripp, personal communication).

Phase	I	II	III	Mean
Date	20 June~7 Aug	7 Aug~31 Aug	31 Aug~24 Sept	
Sample No.	1~6	7~9	10~12	1~12
Water temperature (℃)	0.76	3.65	4.08	
Current velocity (cm sec^{-1})				
Eastward component	2.68	−2.06	2.90	
Northward component	16.06	10.31	9.21	
Flux of LG fraction				
POC (mg m^{-2}d^{-1})	205	162	247	205
Fecal pellet POC (mg m^{-2}d^{-1})	103	37	158	100
CFP[*1] POC (mg m^{-2}d^{-1})	101	25	12	60
EFP[*2] POC (mg m^{-2}d^{-1})	2	12	146	40
Fecal pellet contribution to total LG POC (%)	50.2	22.8	64.0	48.8
Flux of SM fraction				
POC (mg m^{-2}d^{-1})	285	263	192	257
Total Flux (LG+SM)				
POC (mg m^{-2}d^{-1})	490	425	439	462
Contribution of LG (%)	41.8	38.1	56.3	44.4
Contribution of SM (%)	58.2	61.9	43.7	55.6
Trap-collected Zooplankton				
Number of oceanic copepods (No. trap^{-1})	34.7	16.7	7.3	
Contribution of oceanic copopods to total zooplankton[*3]	66.8	50.0	25.7	

[*1] CFP: Cylindrical Fecal Pellet
[*2] EFP: Elliptical Fecal Pellet
[*3] total zooplankton: zooplankton number except for small copepods (*Peudocalanus* spp.)

actually egested by oceanic calanoid copepods (e.g. *C. cristatus*, *C. plumchrus*).

Based on these results; fairly high autochthonous production and advective inputs of allochthonous particles were strongly influenced by the northward flowing BSAW during the period of phase I. The northward current (BSAW) carried abundant nutrients to allow for high primary production and as a consequence it followed the high animal acitivities (autochthonous production) (Springer *et al.*, 1989). This strong current concurrently carried allochthonous organic matter from the south onto the shallow Chirikov basin during summer season.

The total POC flux in phase II slightly decreased to 425 mgC m^{-2}d^{-1}, and contributions of LG fraction and fecal pellets were apparently less than those in other phases. The decrease of LG fraction suggests the low autochthonous particle production primarily due to the decrease of influence of nutrient rich BSAW. On the other hand, no marked decrease of SM was found in this phase, possibly indicating that fairy high advective water movements still remained and they transported particles from surrounding waters including northward flowing BSAW.

In phase III, BSAW was replaced by ACW. Both of LG flux and fecal pellet flux were highest through the whole period, indicating the intensified autochthonous production. The increase of autochthonous sinking particles may be related to a fall bloom of phytoplankton which was observed using a time-series water sampler deployed with the same mooring system

(TANIGUCHI, personal communication). The fall bloom allowed to enhance fecel pellet production of herbivorous zooplankton.

Fecal pellets dominated by fresh, large (>1 mm) and elliptical pellets were the most important component of sinking particles, in contributing at least 36% of total POC flux. The producers of these fecal pellets, however, were not specified among the trap-collected zooplankton communities in this phase. No marked occurrence of the large fecal pellet producers were found in the net-collected zooplankton communities when the trap was recovered (HATTORI *et al.*, 1991; FUKUCHI *et al.*, 1993).

The compositions of zooplankton in a given location was a reliable indicator of the occurrence of the associated water mass in the northern Bering Sea as described by SPRINGER *et al.* (1989). For example, no marked increase of oceanic copepods collected in the trap was found in phase III, which supported the water mass replacement occurred between phase I and phase II in the physical processes of BSAW entering into the Chirikov basin area.

Average total carbon flux through the period in the present study (462 mgC $m^{-2}d^{-1}$) was slightly lower than that reported previously (501 mgC $m^{-2}d^{-1}$) which was obtained using another aliquot of the same trap sample (FUKUCHI *et al.*, 1993). The small difference between two aliquots is owing to the zooplankton carbon contribution, representing an average capture rate of zooplankton into the trap (39 mgC $m^{-2}d^{-1}$). The present data show exact particle flux, because most of large zooplankton swimmers were excluded from the LG samples.

Average fecal pellet contribution was 101 mgC $m^{-2}d^{-1}$, accounting for 22% of total flux and about 5 % of primary production (2 gC $m^{-2}d^{-1}$, ROBIE *et al.*, 1991). The relative contribution of pellets is not prominent, compared with those in the other shallow productive seas (DUNBAR and BERGER, 1981; KNAUER and MARTIN, 1981; SASAKI and NISHIZAWA, 1981; WEFER *et al.*, 1988). For example, BODUNGEN *et al.*, (1987) showed that >90% of sinking particles at 100 m was krill fecal pellets, which approximately corresponded to 20% of daily primary production during austral spring at a station (JV 85) in the Bransfield Strait, Antarctica. The last result suggests that the heavy grazing pressure of krill on the primary producers regulates the size of the downward particulate flux during austral productive season.

In the present study area, relatively low fecal pellet contribution may indicate that high primary production at the northern Bering Sea induced by advective nutrient supply is not controlled severely by herbivorous zooplankton (SPRINGER *et al.*, 1989) and provides rich foods for benthic animals (GREBMEIER *et al.*, 1988; GREBMEIER and MCROY, 1989; FUKUCHI *et al.*, 1993).

Large biogenic particle flux, LG contribution including fecal pellets and zooplankton in this case provide a primary information on the relative importance of autochthonous sources among the sedimenting material onto the bottom in the shallow waters in which an advective water movement is important in carrying many kinds of particles.

Acknowledgments

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1988年夏季の北部ベーリング海・キリコフ海盆域における急速沈降粒子フラックスの変動

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要旨：1988年の夏季に（6月20日から9月24日までの96日間），北部ベーリング海のキリコフ海盆域の定点（水深50m）において，時系列採集型のセディメントトラップを用いて沈降粒子の採集を行った。卓越する海流の違いから，観測期間は3期に分けられ（1期；6月20日～8月7日，2期；8月7日～8月31日，3期；8月31日～9月24日），それぞれの時期において異なった粒子沈降過程が観察された。特に大型の急速沈降粒子の挙動に注目した結果，1期においては，北上するアナディール海流の影響が強く，現地性生産および北方海域からの粒子の輸送のいずれも豊富であるのに対して，2期においては，北上海流の影響が弱く，現地性生産は低下する。3期において，アラスカ沿岸水が進入し，現地性生産が増加し，移流による粒子の輸送は最小となる。