

**NOTES AND CORRESPONDENCE**

**Aragonitic Pteropod Flux to the Interior of the East Sea**

**(Sea of Japan)**

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**ABSTRACT**

Monthly aragonite fluxes of cosomatous pteropods in the deep Japan Basin in the East Sea (Japan Sea) were estimated using a bottom tethered time-series sediment trap for the 1-year period from July 1994 to August 1995. The trap with 13 time-series sediment collectors was placed at 2.8 km below the surface and 0.3 km above the bottom. It collected settling particles during twelve 30 or 31-day intervals over a total of 365 days. A single species of *Limacina helicina* dominated the settling pteropods. The annual pteropod flux at the depth of 2.8 km over 12-month period was 2328 individuals  $m^{-2}yr^{-1}$ . The fall-winter pteropod downward flux during the period of 19 November to 18 December 1994 may account 67% of the annual pteropod flux.

(Key words: Pteropod, Aragonite flux, East Sea (Sea of Japan))

**1. INTRODUCTION**

The East Sea (Japan Sea) is a typical example of marginal seas in the Western Pacific. The Tsushima Current, a branch of the Kuroshio, carries waters of high temperature and salinity into the sea through the Korea/Tsushima Strait (sill depth of 130m) from the East China Sea and flows northward along the east coast of Korea like a western boundary current. It flows out of the sea through the Tsugaru (sill depth of 130m) and Soya Straits (sill depth of 55m) to the Northwest Pacific and the Sea of Okhotsk, respectively. The subarctic front along 40° N separates the colder waters in the north from the warmer waters in the south. The East Sea Proper Water lies below 300-400 m and is homogeneous with potential temperatures be-

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tween 0°C and 1°C and high contents of oxygen; the oxygen contents, however, have decreased with time over the past 60 years (Chen et al. 1999). Recently, the carbonate chemistry of the sea has been studied comprehensively by Chen et al. (1995 and 1996). According to Chen et al. (1995), the concentrations of normalized alkalinity (NTA) and normalized total CO<sub>2</sub> (NTCO<sub>2</sub>) in the deep waters are low relative to those of the Northwest Pacific Ocean, indicating relatively little CaCO<sub>3</sub> dissolution and organic carbon decomposition in the subsurface waters. Carbonate saturation depths for aragonite and calcite are 300 and 1300 m in depth, respectively. Excess CO<sub>2</sub> is present from surface to bottom, confirming the rapid turnover of the deep water (100-year turnover time) based on the previously reported tritium, freons 11, 12 and <sup>226</sup>Ra data (Tsunogai et al. 1993).

The downward flux of particles from the surface to the bottom is a central process in the oceanic chemical cycle; however, long-term observations on aragonitic and calcitic particle fluxes are lacking in the open East Sea (Japan Sea). The existing carbonate particle flux data in the East Sea are restricted to a short period of time (two weeks in September 1984) by Masuzawa et al. (1989). In this paper, aragonite sinking flux in the near bottom waters of the interior of the East Sea observed over a one-year period are described for the first time in order to describe the seasonal variations of pteropod sedimentation.

## 2. MATERIALS AND METHODS

A PARFLUX Mark 7G-13 time series sediment trap with 13 rotary collectors was deployed at 2800 m depths in the southwestern part of the Japan Basin at Station T (39°40'N 132°24'E) where the water depth is 3100 m. A mooring array was deployed in July 1994 and retrieved in August 1995. The trap sampling cups were filled with a 5% sodium azide solution prior to deployment to prevent *in situ* microbial degradation and grazing by swimmers (Hong and Burrell 1988). The cups were mechanically sealed from the ambient water except during each month-long collection period. Microscopic observations indicated that the preservation of organisms in the sampling cups was excellent.

After recovery, the samples were then stored in darkness at 4°C until processed. In the laboratory, swimmers were isolated in the first sieving through a 1 mm Nitex™ mesh, and then the remainders were handpicked under a binocular microscope. Particles that passed through the 1 mm mesh were split into 10 aliquots using a rotating wet-sediment splitter (McLane WSD-10) with 10 splitting heads. The error during the splitting of the East Sea trap samples into 10 aliquots was about 5% for the <1 mm fraction. The remaining sample was freeze-dried and desalted for further analyses and estimations of the mass flux.

Pteropods were identified and counted using a binocular microscope, and the taxonomic keys of Bé and Gilmer (1977) were used. Some pteropod shells contained protoplasm, but some had been emptied.

## 3. RESULTS AND DISCUSSION

### 3.1 Aragonite Flux to the Interior of the Sea

The settled pteropods were dominated by a single species, *Limacina helicina*. Total an-

nual pteropod flux was 2328 individuals  $\text{m}^{-2} \text{yr}^{-1}$ . The sedimentation pattern of pteropod shells in the Japan Basin showed a seasonal cycle, which was characterized by a unimodal distribution at 2800 m water depth (300 m above the bottom) in the East Sea (Japan Sea) (Table 1). The fifth sampling period from November through December 1994 recorded a high pteropod flux of 31 individuals  $\text{m}^{-2} \text{day}^{-1}$  (Fig. 1). Low pteropod fluxes were recorded during the remainder of the year. In the main sedimentation months of November and December, pteropod flux accounted for 67% of the annual total pteropod flux. Fluxes in the number of pteropod shells were followed closely by temporal phytoplankton peaks observed in the trap. In the study area, phytoplankton bloomed in autumn and to a much smaller extent in spring, due to the absence of sufficiently shallow surface mixed layer in spring (Hong et al. 1997).

The majority of pteropods were smaller than 1 mm, with a few individuals of larger than 1 mm in diameter in each sampling period. The average shell diameter of pteropods for less than 1 mm length was  $0.74 \pm 0.15$  mm, while the average shell weight was  $0.022 \pm 0.005$  mg ( $n=15$ ). These values agree well with those observed in the subarctic Pacific (Fabry 1989). Although the aragonite content in the shell varies over 2 orders of magnitude (Honjo 1977), preliminary estimates of the aragonite flux were made based on the annual shell flux and the average weight of the shell under the assumption that the shell is made of aragonite. In the main sedimentation months of November and December, the aragonite inorganic carbon fluxes were 0.05-0.08 mg C  $\text{m}^{-2} \text{d}^{-1}$ , assuming all pteropod shells were made of aragonite and the average weight of their shell was  $0.022 \pm 0.005$  mg. The annual total aragonitic C flux to the bottom was 6.10 mg C  $\text{m}^{-2} \text{yr}^{-1}$  in the 1994-1995 sampling period. This annual C flux represents approximately 0.3 % of the total annual carbonate flux measured during the same time interval (Table 1).

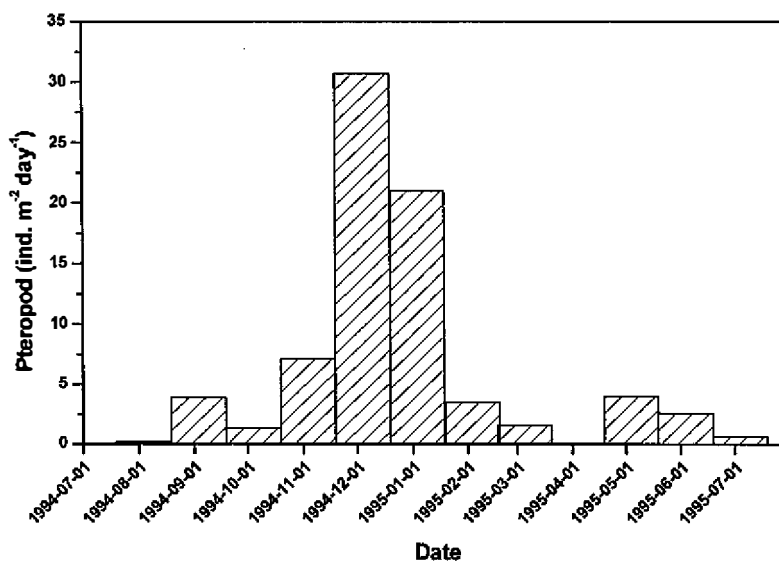


Fig. 1. Time-series of pteropod shell flux in the interior of the Japan Basin during the period of 17 July 1994 to 18 July 1995.

Table 1. Sediment trap open/close schedule and the time-series of pteropod shell flux in the interior of the Japan Basin during the period of 17 July 1994 to 18 July 1995. The inorganic C flux ( $\mu\text{g C m}^{-2}\text{d}^{-1}$ ) was calculated assuming all pteropod shells were made of aragonite and average weight of shell was  $0.022 \pm 0.005$  mg. Total inorganic C was determined by subtracting organic C content from total C content of bulk sample, using a Carlo Erba CNS elemental analyzer (Hong et al. 1997).

Sampling sequence	Sampling Date		Pteropod (individuals $\text{m}^{-2}\text{month}^{-1}$ )	Aragonitic inorganic C $\mu\text{g C m}^{-2}\text{d}^{-1}$	Total inorganic C* $\text{mg C m}^{-2}\text{d}^{-1}$
	Trap Open (mm/dd/yy)	Trap Close (mm/dd/yy)			
1	07/19/94	08/18/94	6	0.5	1.99
2	08/19/94	09/18/94	120	10.1	2.52
3	09/19/94	10/18/94	40	3.5	5.13
4	10/19/94	11/18/94	220	18.6	12.94
5	11/19/94	12/18/94	920	80.3	10.99
6	12/19/94	01/18/94	650	54.9	7.30
7	01/19/95	02/18/94	108	9.1	5.20
8	02/19/95	03/18/94	44	4.1	3.06
9	03/19/95	04/18/94	0	0.0	2.51
10	04/19/95	05/18/94	120	10.5	2.13
11	05/19/95	06/18/94	80	6.8	4.22
12	06/19/95	07/18/94	20	1.7	3.95

\* Hong et al. (1997)

Gelatinous pteropods tend to produce aggregated mucous which can be several centimeters in diameter, and they tend to collect small particles while slowly descending in the water column, therefore enhancing the sinking flux of small particles (Bathmann et al. 1991). Since pteropods live in the upper 300 m water depths (Fabry 1989), over trapping them, as observed in the shallow depths by Harbison and Gilmer (1986), was not likely at the 2800 m water depth in our measurements.

### 3.2 Dissolution of Pteropod Shells in the Interior of the Sea

Dissolution of pteropod shells was expected due to the corrosive nature of deep water. Chen et al. (1995) have determined the degrees of saturation for aragonite and calcite. The saturation horizons for aragonite and calcite are at 300 m and 1300 m, respectively. The aragonite saturation depth in the Northwest Pacific ranges from 120 m in the north ( $50^{\circ}\text{N}$   $175^{\circ}\text{E}$ ) to 700 m in the mid-latitude region ( $32^{\circ}\text{N}$ ,  $165^{\circ}\text{E}$ ) (Feely et al. 1984). According to Chen et al. (1995), below the 2000 m water depth of the East Sea Proper Water, the degree of saturation is about 50-60 and 70-80% for aragonite and calcite, respectively. The lysocline depth in the East Sea has been reported at between 1218 and 1410 m, and the calcium carbonate compensation depth lies at between 1437 and 1596 m (Ujiie and Ichkijura 1973, as referred

in Chen et al. 1995). Hence, pteropods sinking in the interior of the East Sea must be subjected to dissolution due to the undersaturation of aragonite, which depends upon the nature of the tissue (Honjo 1977). Owing to a lack of information on the pteropod flux just below the euphotic zone, it is difficult to establish the extent to which these flux variations are affected by the dissolution of aragonite shells. Therefore, in this work, the measurements on sinking flux can be viewed as the lower limit of aragonite flux on the basin floor. The particles in the trap had also undergone dissolution during their deployment up to a year.

*In situ* dissolution for a year at the 1000 and 2000 m depth in the central East Sea was estimated from the sediment trap moored in the southern station M of Ulleung Basin (37°02.15'N 131°04.36'E, water depth, 2130 m) deployed for about 1 year in the period of 1997-1998 (Hong et al. a manuscript under preparation). Excess dissolved calcium content over the *in situ* dissolved calcium concentration in the sampling cups was determined for 3 ten-day sampling sequences at 1000 and 2000 m depths from 1 October to 31 October 1997. Pteropods were present in 2 sampling cups for the first two sampling sequences. Pteropod shells weighed from 1.4 to 8.4 mg. If we assume that all the excess Ca present in the sampling cup originated from the carbonate shells, then the total dissolution of carbonate shell is  $173 \pm 55$  and  $153 \pm 13$  mg  $\text{CaCO}_3 \text{ m}^{-2} \text{ yr}^{-1}$  at 1000 and 2000 m depths, respectively. The surface water is more productive in the southern area (St. M) than in the northern area (St. T) of the subarctic front. However, the deep water carbonate chemistry is almost uniform in the East Sea (Chen et al. 1995).

Masuzawa et al. (1989) observed that carbonate particles of  $1.2 \text{ mg CaCO}_3 \text{ m}^{-2} \text{ d}^{-1}$  dissolved between 1870 and 3240 m depths (25% of the carbonate flux at the 1870 m depth) in the eastern part of the Japan Basin (40°49.4'N, 138°40.7'E) during September 1984. This value corresponds to  $3.1 \times 10^{-6} \text{ mmol CaCO}_3 \text{ kg}^{-1} \text{ yr}^{-1}$  and is very small compared to that of the Northwest Pacific Ocean as reported by Chen et al. (1986).

#### 4. CONCLUSIONS

The settling pteropods are dominated by a single subarctic species of *Limacina helicina*. Generally, except for a few individuals, the size of pteropods is smaller than 1 mm in diameter. The settling flux of individuals near the bottom shows a uni-modal distribution peak during the period of 19 November to 18 December 1994, with only a very minor spring peak. Since pteropods sinking in the deep interior of the East Sea (Japan Sea) are subjected to dissolution due to the undersaturation of aragonite, the measurements here on sinking flux to the basin floor provide a constraint on the total aragonite flux.

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