Radiolarian faunal characteristics in surface-subsurface waters of the Japan Sea off Tassha, Sado Island, central Japan in June 2007: inflowing radiolarians on the Tsushima Warm Current

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Abstract

To assess the influence of the Tsushima Warm Current (TWC) on radiolarian inflow to the Japan Sea, we determined the faunal characteristics and water properties (temperature, salinity, density, and fluorescence intensity) of surface-subsurface waters shallower than 100 m depth in the Japan Sea off Tassha, Sado Island, central Japan on June 4, 2007. Compared with the water properties measured in June 2005, a thick temperature-stratified layer of 16.0-16.6 ℃ was recorded in water shallower than 32 m in June 2007, indicating that the flow force of the TWC had increased in June 2007 relative to that in 2005. This finding is independently supported by broad-based hydrographic data from the Japan Sea. Although the standing stock is very low, the radiolarian fauna consists of typical cold-water dwellers (*Larcopyle butschlii*, *Cyrtidosphaera reticulata*, *Spongotrochus glacialis*) throughout waters shallower than 100 m depth, along with a warm-water species (*Spongosphaera streptacantha*) that usually occurs in summer around Sado Island. Based on the compiled radiolarian faunal and temperature data, *S. streptacantha* can be considered a typical inflowing species transported by the TWC.

Key words: inflow, Japan Sea, Radiolaria, Sado Island, *Spongosphaera streptacantha*, Tsushima Warm Current, water properties.

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Introduction

Plankton communities in the Japan Sea and their fluctuations over time have previously been addressed in terms of various aspects of their ecosystem, e.g., trophic condition, food-web structure, and environmental change (e.g., Chiba and Saino, 2002). In the Japan Sea in particular, being a semi-closed marginal sea, the inflow and settlement of planktonic organisms via sea currents passing through adjoining straits have attracted much attention (e.g., Itaki et al., 2004; Kitamura and Kimoto, 2006), largely because the historical and dynamic states of these organisms provide information on the past oceanographic characteristics of the Japan Sea and the role of speciation within a geographically isolated marginal sea. The Japan Sea has also been likened to a miniature ocean, being of significant depth and influenced by subtropical and subarctic currents driven by aeolian and thermohaline circulations; consequently, knowledge of the ecosystem of this marginal sea is considered to provide a good analog of that in the large oceans of the world.

The Japan Sea is connected with adjacent seas via four straits: the Tsushima, Tsugaru, Soya, and Mamiya straits, with most of inflowing water originating from the Tsushima Warm Current (TWC) (Fig. 1A). The TWC is therefore of critical importance for the inflow and settlement of fauna and flora that originated from warm-water regions. Since the introductory study by Matsuoka et al. (2001), various studies of living radiolarians in the Japan Sea have targeted aspects of phenology and biosystematics (e.g., Matsuoka et al., 2002; Itaki et al., 2003; Kurihara and Matsuoka, 2004, 2005; Kurihara et al., 2006, 2007). Kurihara et al. (2006, 2007) reported the compositions of radiolarian faunas and water properties at the sampling site of the present study (Fig. 1B, C) during June and September 2005, respectively. In addition, Kurihara et al. (2007) provided a preliminarily discussion of the relationship between the composition of the radiolarian fauna and the TWC system, based on a compilation of the vertical species distribution and hydrographic data collected in September 2005. In the present paper, we describe the radiolarian faunal characteristics and water properties measured in June 2007, thereby providing supporting evidence for the identification of species inflowing to the Japan Sea upon the TWC.

Materials and methods

We collected samples of plankton and measured water properties (temperature, salinity, density, and fluorescence intensity) using a conductivity-temperature-depth (CTD) sensor (COMPACT-CTD; Alec Electronics Co. Ltd., Japan) on June 4, 2007 from aboard the research vessel *IBIS2000* of Sado Marine Biological Station, Japan. These operations were conducted at 38°05'N, 138°10'E, approximately 6 km west of Tassha, Sado City, Sado Island, Niigata Prefecture, central Japan (Fig. 1). Six plankton samples (604-8SD-1 to -6) were collected using a Marukawa-type 100 μm opening net with a mouth diameter of 0.3 m. To obtain

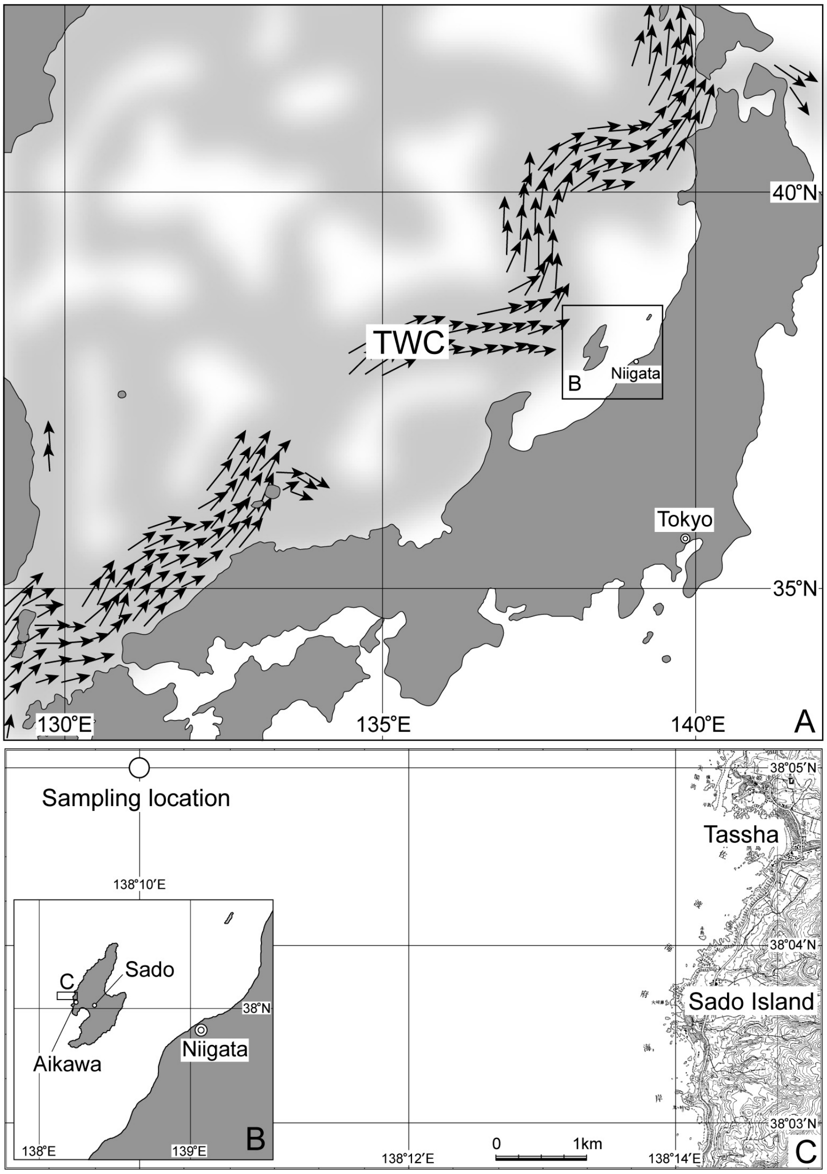

Fig. 1. (A): Main surface currents within the Japan Sea. Arrows indicate the current direction at flow rates of ca. 0.2-0.3 m/sec. Gray areas without arrows indicate waters flowing at less than ca. 0.15 m/sec. The base map was compiled from 10 days of mean sea surface current for the period June 1-10, 2007 (Japan Meteorological Agency, available online a). TWC: Tsushima Warm Current. (B), (C): Index map showing the sampling location. Topographic data are from the 1:25,000 "Aikawa" map sheet published by the Geographical Survey Institute of Japan.

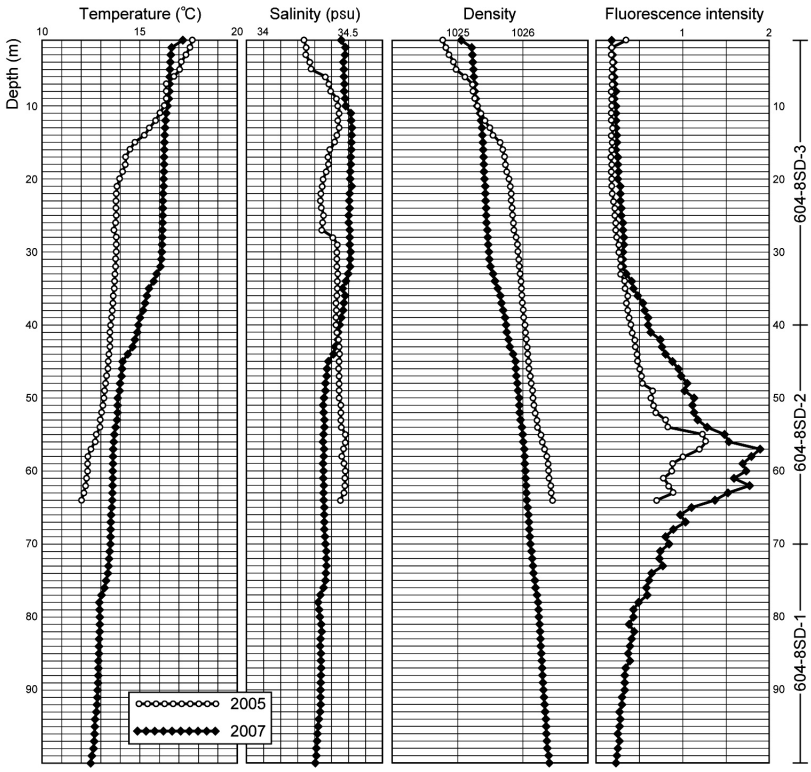

Fig. 2. Plankton sampling intervals and vertical profiles of temperature, salinity, density, and fluorescence intensity for June 6, 2005 and June 4, 2007 at the sampling location off Tassha, Sado Island.

radiolarian faunal data at various depth intervals (< 100 m depth), samples 604-8SD-1 and -2 were collected from water depths of 70-100 m and 40-70 m, respectively, by closing the net using a messenger. Sample 604-8SD-3 was taken from 0-40 m depth without closing the net (Fig. 2). We obtained other samples from 0-100 m depth without closing the net: sample 604-8SD-4 was used for total faunal-composition analysis, and samples 604-8SD-5 and -6 for observations of living radiolarians and other planktons (see Kurihara et al., 2006 for details of observation equipment and procedures). For samples 604-8SD-1 to -4, the siliceous residues were mounted in Canada balsam after acid-dissolution treatment of organic matter by ca. 50% sulfuric acid and washing in a sieve (46 μm opening). Microscopic images of radiolarian skeletons (Fig. 3) were taken using a digital camera mounted upon a transmitted light microscope (Nikon Coolscope).

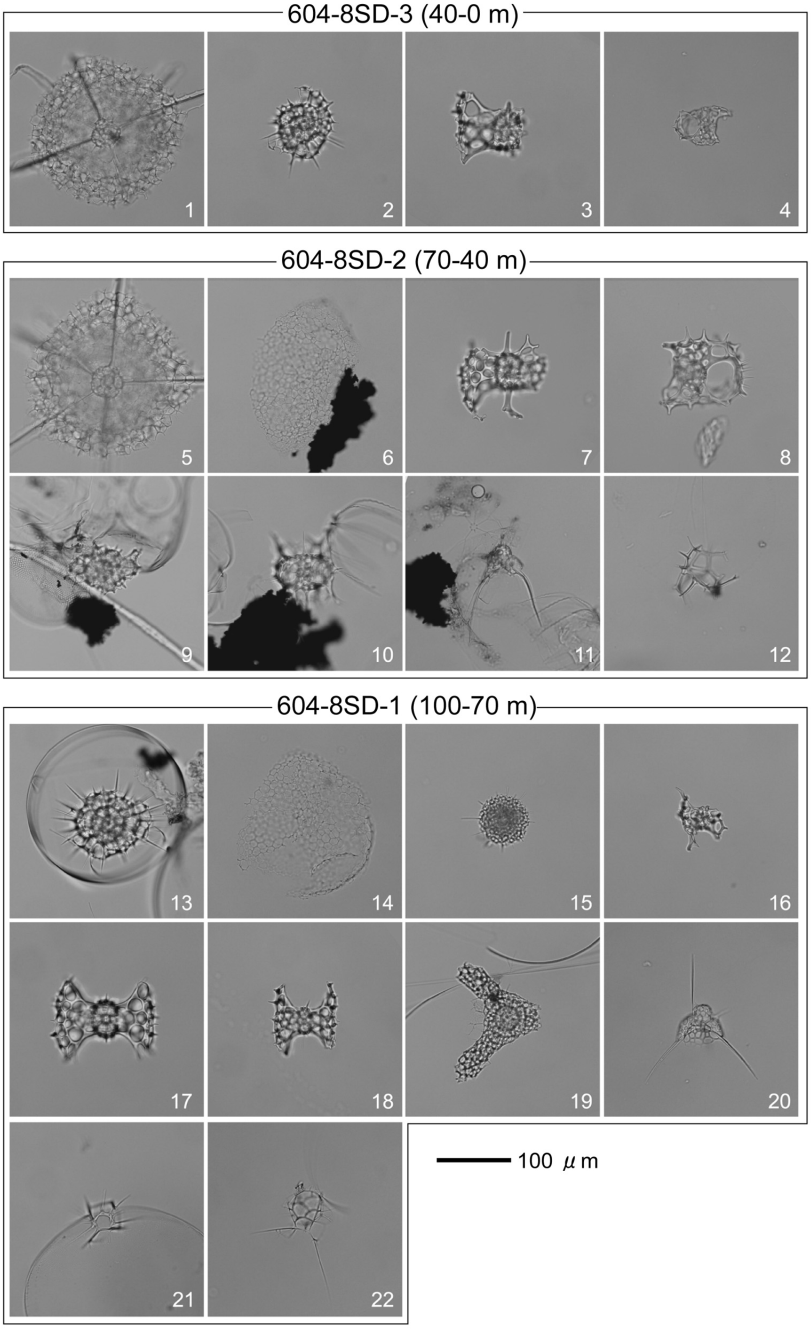

Fig. 3. Transmitted light microscopic images of radiolarian skeletons from surface-subsurface waters off Tassha, Sado Island. 1-4 were collected from sample 604-8SD-3 (40-0 m), 5-12 from sample 604-8SD-2 (70-40 m), and 13-22 from sample 604-8SD-1 (100-70 m). 1, 5: *Spongosphaera streptacantha* Haeckel; 2, 13: *Larcopyle butschlii* Dreyer; 3, 4, 7-10, 16-18: *Tetrapyle octacantha* Müller; 6, 14: *Cyrtidosphaera reticulata* Haeckel; 11, 20: *Pseudodictyophimus gracilipes* (Bailey); 12: *Lophospyris* sp.; 15: *Spongotrochus glacialis* Popofsky; 19: *Euchitonia elegans* (Ehrenberg); 21: *Pseudocubus obeliscus* Haeckel; 22: *Plectacantha oikiskos* (Jørgensen).

Water properties

We constructed vertical profiles at the sampling site from 198 m depth to the surface using a CTD sensor attached to a 200 m rope, taking measurements at 1 m intervals. Temperature, salinity, density, and fluorescence intensity of water (< 100 m depth) data are presented in Fig. 2, along with the data (< 64 m depth) collected on June 6, 2005 (Kurihara et al., 2006) for comparison. For depths between 100 m and the surface, temperature was measured using a conventional digital thermometer.

Temperature: The temperature of the water mass from 100 m depth to the surface ranges from 12.5 to 17.2 ℃. Although there exist slight changes in the temperature gradient at water depths of 78, 45, and 32 m, the water temperature over the interval of 100-32 m depth shows a gentle increase from ca. 12.5 to 16. 0 ℃ with decreasing depth (Fig. 2). Temperature stratification is developed from 32 to 2 m depth, with values of around 16.0-16.6 ℃.

Salinity: The salinity of the water mass between 100 m depth and the surface ranges from 34.30 to 34.52 psu (Fig. 2). At 100-45 m depth, the salinity is almost constant at around 34.35 psu, with values increasing with shallowing depth, reaching 34.51 psu at around 32 m depth. A constant salinity of around 34.5 psu is recorded from 32 m depth to the surface, although marginally lower values (ca. 34.47) are recorded at depths of less than 10 m.

Density: The density of the water mass from 100 m depth to the surface decreases gently from 1026.4 to 1025.1 with decreasing depth (Fig. 2).

Fluorescence intensity: The fluorescence intensity from 100 m depth to the surface shows a single peak at around 60 m depth (Fig. 2). The intensity is consistently low in water shallower than 32 m.

Interrelationships among different water properties: The water mass shallower than 32 m depth constitutes a distinctive stratified layer in terms of temperature, although the salinity over this interval is almost constant. Decreasing density over this interval is attributed to increasing temperature. Fluorescence intensity shows a clear increase below the stratified layer, at depths greater than 32 m (Fig. 2), implying that the stratified layer is oligotrophic.

Comparison with water properties in June 2005: The temperature of shallower water (< ca. 40 m depth) shows a remarkable difference between June 2005 and June 2007 (Fig. 2). According to Kurihara et al. (2006), the water mass shallower than 21 m depth is characterized by a high temperature gradient (ca. 2.0 ℃/10 m), with values ranging from 13.8 to 17.7 ℃; in contrast, the water mass at depths of 21-64 m shows almost constant temperature values and a low gradient (ca. 13.8 ℃ , 0.4-0.5 ℃/10 m, respectively). Water shallower than 32 m depth, as measured in June 2007, constitutes a well-developed temperature-stratified layer (as described above), with temperatures ranging from 16.0 to 16.6 ℃. As a result, the difference in temperature between 30 and 20 m depth, in both 2005 and 2007, exceeds 2 ℃ (Fig. 2).

Other properties (salinity, density, and fluorescence intensity) show little change between 2005 and 2007 (Fig. 2).

Radiolarian faunal characteristics and their implications

Ten radiolarian species were identified from samples 604-8SD-1 to -3 (Table 1). All of the obtained radiolarians (22 shells) are shown in Fig. 3, including *Larcopyle butschlii* Dreyer, *Cyrtidosphaera reticulata* Haeckel, *Spongotrochus glacialis* Popofsky, *Tetrapyle octacantha* Müller, *Spongosphaera streptacantha* Haeckel, *Euchitonia elegans* (Ehrenberg), *Pseudodictyophimus gracilipes* (Bailey), *Pseudocubus obeliscus* Haeckel, *Plectacantha oikiskos* (Jørgensen), and *Lophospyris* sp. The concentrations of radiolarian shells per 1 m^3 of sea water in samples 604-8SD-1, 604-8SD-2, and 604-8SD-3 were 1.18, 0.94, and 0.35 shells/m^3, respectively.

From sample 604-8SD-1, collected from water depths of 100-70 m, we obtained the following radiolarian species: *L. butschlii*, *C. reticulata*, *S. glacialis*, *T. octacantha*, *E. elegans*, *P. gracilipes*, *P. obeliscus*, and *P. oikiskos* (Fig. 3). *Larcopyle butschlii* is abundant in the Japan Sea at depths of 1000-200 m (Itaki, 2003). This species has been commonly observed in the plankton samples (< 100 m depth) collected previously by our research group at the same sampling location, especially in the spring to early summer fauna (Matsuoka et al., 2002; Kurihara et al., 2006). *Cyrtidosphaera reticulata* has a similar seasonal occurrence to *L. butschlii*, being most abundant in the June fauna around Sado Island (Matsuoka et al., 2002; Kurihara et al., 2006). The abundant occurrence of *S. glacialis* has also been reported by Matsuoka et al. (2002) from a plankton sample (< ca. 70 m depth) collected on June 25, 2001. According to Itaki (2003), there occurs a peak abundance of *S. glacialis* in the water mass at 80-160 m depth within the northeastern Japan Sea (west of Hokkaido, 42° 52'N, 145° 55'E). The common occurrence of this species has also been reported from the Sea of Okhotsk and the Arctic Ocean (e.g., Itaki et al., 2003; Okazaki et al., 2004; Ablemann and Nimmergut, 2005). Other species in the present sample are well known as faunal constituents of early summer to autumn around Sado Island (Matsuoka et al., 2001, 2002; Itaki et al., 2003; Kurihara and Matsuoka, 2005; Kurihara et al., 2006, 2007). Among them, *T. octacantha* is generally considered a warm surface-water dweller, particularly preferring coastal seawater (e.g., Kling, 1979; Kling and Boltovskoy, 1995; Chen and Tan, 1997; Yamashita et al., 2002).

We obtained radiolarian species from sample 604-8SD-2 (collected from water depths of 70-40 m), including *C. reticulata*, *S. streptacantha*, *T. octacantha*, *P. gracilipes*, and *Lophospyris* sp. *Spongosphaera streptacantha* is a representative faunal constituent of the period July-September around Sado Island; for example, this species made up 18.8 % of the fauna collected on September 28, 2005 (Kurihara et al., 2007). Sample 604-8SD-3, collected from between 40 m depth and the surface, contains only four radiolarian shells, identified as *L. butschlii*, *S. streptacantha*, and *T. octacantha*.

Based on the above radiolarian occurrences, the faunal characteristics of June 2007 are summarized as follows: (1) well-known cold water dwellers (*L. butschlii*, *C. reticulata*, and *S. glacialis*) comprise the fauna throughout depths shallower than 100 m, and (2) a typical

Table 1. List of all radiolarian species identified in the present study.

Sample number	604-8SD-1	604-8SD-2	604-8SD-3
Sampling depth	100-70 m	70-40 m	40-0 m
	Number of skeletons		
SPUMELLARIA			
Tetrapyle octacantha Müller	3	4	2
Cyrtidosphaera reticulata Haeckel	1	1	0
Larcopyle butschlii Dreyer	1	0	1
Spongotrochus glacialis Popofsky	1	0	0
Spongosphaera streptacantha Haeckel	0	1	1
Euchitonia elegans (Ehrenberg)	1	0	0
NASSELLARIA			
Plectacantha oikiskos (Jørgensen)	1	0	0
Pseudocubus obeliscus Haeckel	1	0	0
Pseudodictyophimus gracilipes (Bailey)	1	1	0
Lophospyris sp.	0	1	0
Total	10	8	4

summer species (*S. streptacantha*) around Sado Island occurs in samples collected from water shallower than 70 m (604-8SD-2 and -3).

With regard to (1), the faunal constituents are similar in June 2001 and 2005 (Matsuoka et al., 2002; Kurihara et al., 2006); however, in terms of the standing stock, the fauna of 2007 is depleted relative to those of 2001 and 2005. According to Kurihara et al. (2006), the dominant constituents in 2005 are two species of *Plectacantha*: *Plectacantha trichoides* Jørgensen and *P. oikiskos*. Only one shell of *P. oikiskos* was collected in 2007, indicating that the low standing stock in 2007 was partly due to the lack of proliferation of *Plectacantha* species in June.

As for (2), Kurihara et al. (2007) noted that *S. streptacantha* is present from July to October and absent from March to June. Based on the surface water temperatures measured in 2005, the authors also suggested that *S. streptacantha* prefers water warmer than approximately 20 ℃. In this regard, the reason for the appearance of *S. streptacantha* in June of 2007 should be considered, because the water temperature at that time was relatively cool, ranging from ca. 13.5 to 17.2 ℃ (< 70 m depth). A relevant factor may be that the flow force of the Tsushima Warm Current (TWC) gained strength from February to June of 2007 (Japan Meteorological Agency, available online b). In comparing the 2007 and 2005 data, the occurrence of an increase in flow force is supported by the development of a thick stratified layer of moderate temperature (16.0-16.6 ℃.) in the water mass from 32 m depth to near the surface (Fig. 2). In typical years, the peak occurrence of *S. streptacantha* (as documented by Kurihara et al., 2007) largely corresponds to the seasonal increase in the flow force of the TWC. In addition, *S. streptacantha* is expected to be unable to overwinter in the Japan Sea around Sado Island (Matsuoka, unpublished data from 2000-2006). Therefore, the occurrence of *S. streptacantha* in June is possibly attributed to the increased flow force of the TWC; that is, *S. streptacantha* is an inflowing species carried by the TWC.

In terms of the characteristics of the biofacies of the Japan Sea, Nishimura (1974) noted that secondary deep-water dwellers in a wide variety of marine species, differentiated recently from shallow-water species, comprise representative faunas that lack typical primary deep-water dwellers that live in the truly deep part of the ocean. Studies of radiolarians in the Japan Sea reveal that deep-dwelling radiolarians are no exception to this trend (e.g., Itaki, 2007), indicating that present-day secondary deep-water planktons flowed into the Japan Sea upon sea currents originating from surrounding seas via restricted straits, subsequently becoming established in vacant ecological niches. Bearing this process in mind, it is possible that *S. streptacantha* is now following the spreading and settlement processes of species that previously inflowed upon sea currents. Ongoing monitoring of this progressive phenomenon will reveal the geographic dispersion and speciation of radiolarians, focusing on its dynamic state in the upper (Tsushima Straits), middle (around Sado Island), and lower reaches (Tsugaru Strait) of the TWC.

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