Rhizoplegma boreale (Radiolaria): A tracer for mesoscale eddies from coastal areas

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[1] The impact of mesoscale eddies on the production of radiolarian species *Rhizoplegma boreale* in the central subarctic Pacific was investigated through analysis of sinking particle fluxes collected using sediment-trap and altimetry data from satellite observations. Altimetry observations provided the locations of mesoscale eddies in time and space and indicated that mesoscale eddies propagating around sediment trap Station SA were closely related to the high *R. boreale* fluxes at the station. The mesoscale eddies likely provided the deep-sea region of the central subarctic Pacific with coastal nutrient-rich waters derived from the region around the Aleutian Islands, and influenced the productivity of microzooplankton groups at Station SA.

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1. Introduction

[2] Radiolarians represent one of the commonest pelagic microzooplankton groups, secrete siliceous skeletons, and their main dwelling habitats range from the pelagic to the neritic provinces, with a wide range in their vertical distribution [e.g., *Reshetnyak*, 1955; *Bjørklund et al.*, 1998; *Anderson et al.*, 2002; *Boltovskoy et al.*, 2010]. Their abundance reflects various environmental conditions. They can provide useful information as environmental tracers, especially for water mass changes [e.g., *Pisias et al.*, 1997; *Okazaki et al.*, 2004].

[3] Of the 110 taxa identified *Rhizoplegma boreale* is present with a maximum 7.3% showing that this species is one of the commonest species during the sampling period in the central subarctic Pacific Station SA (Figure 1), the target area of this study [*Ikenoue et al.*, 2012]. The geographic distribution of *R. boreale* has been reported from the high latitude regions: the Nordic Seas [e.g., *Cleve*, 1899; *Swanberg and Bjørklund*, 1987; *Bjørklund et al.*, 1998; *Dolven and Bjørklund*, 2001], the subarctic Pacific [*Tanaka and Takahashi*, 2008], the Okhotsk Sea [*Nimmergut and Abelmann*, 2002; *Okazaki et al.*, 2003], and the Southern Ocean [e.g., *Popofsky*, 1908; *Petrushevskaya*, 1967; *Abelmann*, 1992a, 1992b; *Nishimura et al.*, 1997]. *Nishimura et al.* [1997] investigated several surface sediment samples from the Antarctic Ocean. They proved *R. boreale* as a constituent of the coastal assemblage. *Dolven and Bjørklund* [2001] reported that high abundance of *R. boreale* in the Norwegian Sea was related to mixing of the warm North Atlantic Water and the cold Arctic Seawater masses with high primary production. *Abelmann and Nimmergut* [2005] also reported relatively high abundance of *R. boreale* in the northwestern part of the Okhotsk Sea affected by fresh water from the Amur River.

[4] Recently, *Ikenoue et al.* [2012] studied 15-year time series radiolarian fluxes at Station SA from August 1990 to July 2005. They suggested that inter-annual variation in most radiolarian species was related to the large-scale climate variation such as the Arctic Oscillation. However, the time series fluxes of *R. boreale* were different from those of the other radiolarian species and it was not possible to explain such a difference from the view point of large-scale climate variation. In this study, we investigate the seasonal and inter-annual variation of *R. boreale*, from the view point of a significant variability in the mesoscale eddies in the central subarctic Pacific.

[5] It is reported that mesoscale eddies have a significant impact on the physical, chemical and biological conditions in the subarctic Pacific [*Crawford*, 2002; *Mackas and Galbraith*, 2002; *Whitney and Robert*, 2002; *Crawford et al.*, 2005; *Johnson et al.*, 2005; *Ladd et al.*, 2005; *Ueno et al.*, 2009, 2010]. For example, *Ueno et al.* [2009] indicated that the an Alaskan Stream eddy formed south of the Alaskan Peninsula and Aleutian Islands transported the heat and freshwater which were comparable to the surface net heat and freshwater fluxes to the $5° \times 5°$ area in the central subarctic Pacific. *Ueno et al.* [2010] further indicated that chlorophyll *a* distribution in the central subarctic Pacific was closely related to the Alaskan Stream eddies probably because eddies transported macro- and micronutrients and biota from the Aleutian Islands region southwards. Therefore, mesoscale eddies including Alaskan Stream eddies may influence the productivity of micro zooplankton through changing physicochemical conditions, primary production,

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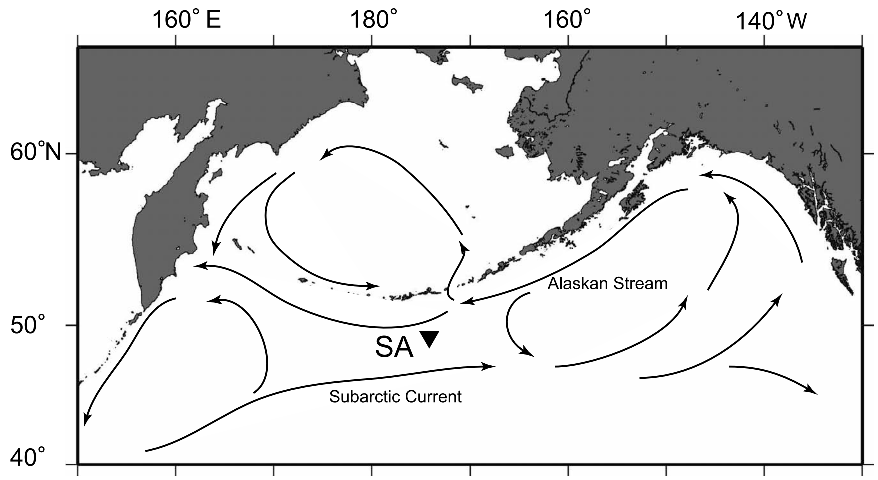

Figure 1. The location of the sediment trap station (inverted triangle): Station SA in the central subarctic Pacific. General surface water circulation patterns are also shown [*Nagata et al.*, 1992]. Map is drawn by Online Map Creation (M. Weinelt, http://www.unc.edu/awmc/web-onlinemapcreation.html, 1996).

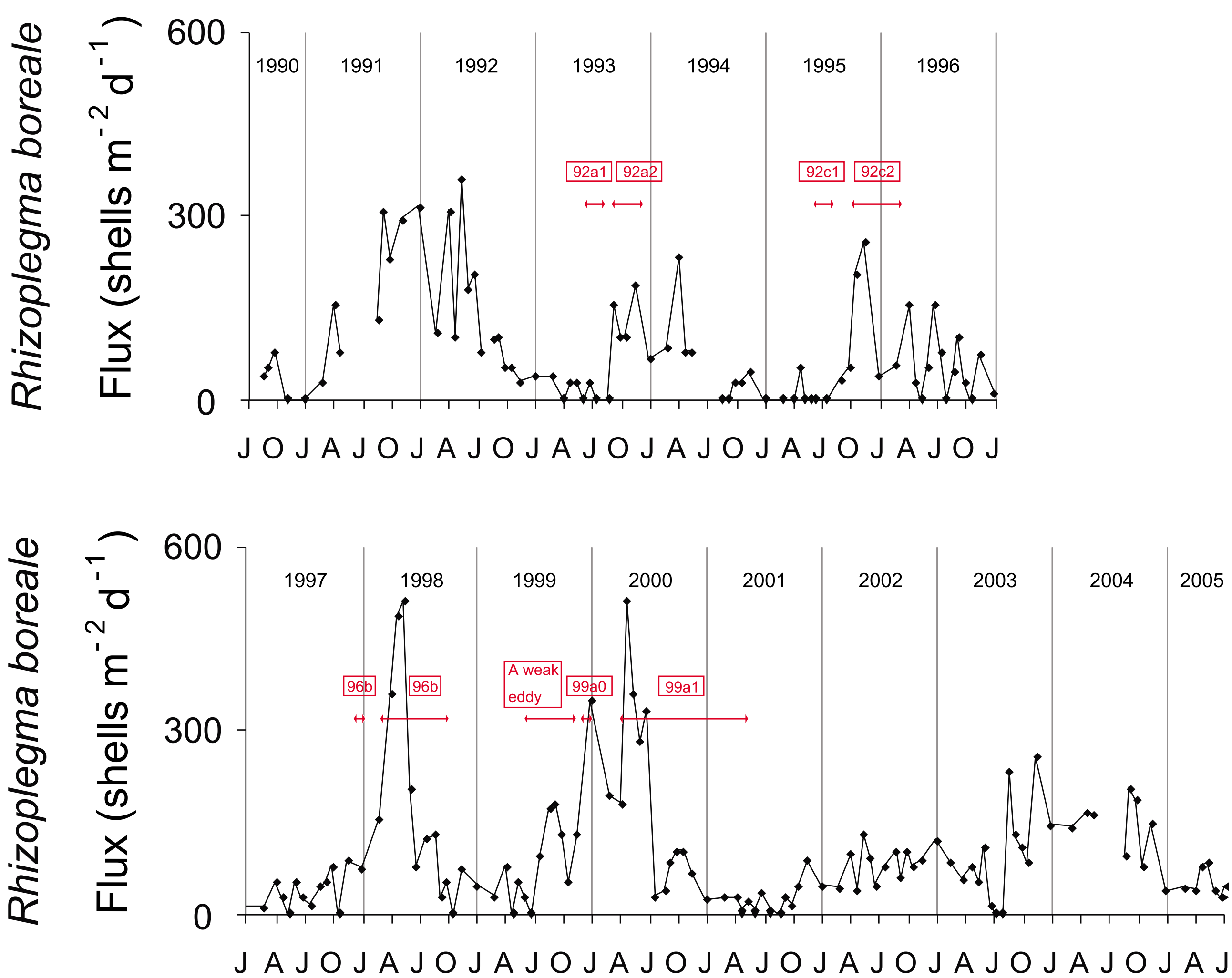

Figure 2. Time series fluxes of *R. boreale* in the coarse fraction (63 μm to 1 mm) at Station SA during 1990–2005 including the incidents of eddies (double-headed arrows). No altimetry data is available before October 1992.

Table 1. Features of Eight Eddies Propagating Around Station SA in the Central Subarctic Pacific

Eddy Name	Month of First Appearance	Formation	Period When the Eddy Stayed Around Station SA	Remarks
92a1	Jun 1993	Detached from Eddy92a between Station SA and the Aleutian Islands	Jun–Aug 1993	Eddy92a was mentioned by *Ueno et al.* [2009]
92a2	Aug 1993	Same as Eddy92a1	Sep–Dec 1993	Eddy92a was mentioned by *Ueno et al.* [2009]
92c1	May 1995	Detached from Eddy92c between Station SA and the Aleutian Islands	Jun–Aug 1995	Eddy92c was mentioned by *Ueno et al.* [2009]
92c2	Jun 1995	Same as Eddy92c1	Oct 1995 to Mar 1996	Eddy92c was mentioned by *Ueno et al.* [2009]
96b	13 Mar 1996	Formed at 157.75°W south of the Alaskan Peninsula	Dec 1997 to Jan 1998, Mar–Oct 1998	*Ueno et al.* [2009]
A weak eddy	Not identified	Not identified	Jun–Nov 1999	N/A
99a0	early 2000	Formed at 164.5W south of the Aleutian Islands	Dec 1999 to Jan 2000	*Ueno et al.* [2009]
99a1	Dec 1999	Detached from Eddy99a0 around 170°W	Apr 2000 to May 2001	*Ueno et al.* [2009]

and the distribution of phytoplankton standing stocks in the central subarctic Pacific. The impact of mesoscale eddies on the micro zooplankton production in the central subarctic Pacific has not been studied; therefore we focus on the relationships between the propagation of mesoscale eddies and the seasonal and inter-annual changes of the *R. boreale* flux, whose inter-annual variation could not be explained from the view point of large-scale climate variation. *Rhizoplegma boreale* is of particular interest to geologists because this species is preserved in the sedimentary record; therefore the present study may contribute toward an understanding of mesoscale eddies in the period where altimetry data were unavailable.

2. Data and Methods

[6] The samples employed in this study were obtained by the sediment trap (PARFLUX Mark 7G-13 with 13 rotary collectors) [*Honjo and Doherty*, 1988] moored in the central subarctic Pacific (Station SA: 49°N, 174°W, sea-floor depth: 5406 m, trap depth: 4812 m) during 1990–2005 (Figure 1) [*Takahashi et al.*, 2000, 2002; *Ikenoue et al.*, 2012]. Recoveries and redeployments of the traps were carried out on T/S *Oshoro-maru* of Hokkaido University, Japan. Most samples used in this study were collected in 10 to 56 day sampling intervals. Aliquot sizes ranged from 1/16 to 1/1,024. The split samples were sieved through a stainless steel screen with 63 μm mesh first and then filtered through Gelman® membrane filters with a nominal pore size of 0.45 μm for retaining all the particles for quantitative counts. The filtered samples were desalted with distilled water and dried in an oven at 50°C overnight. The dried filtered sample was divided into a half with a knife and mounted on microslides cleared with xylene with Canada balsam® and a cover slip was placed to complete the microslide preparation. Each sample was examined under an Olympus® compound light microscope at ×100–400 magnifications for species identification and counting.

[7] For the enumeration of radiolarian taxa in this study, we counted all specimens of coarse-sized (63 μm–1 mm) radiolarian skeletons encountered on a microslide. The radiolarian flux (shells m^{-2} d^{-1}) was calculated from the count data using the formula, *Flux = (N*V)/(S*D)*, where N is the counted number of radiolarian shells, S the aperture area of the sediment trap (0.5 m^2), D the sampling interval, and V the aliquot size.

[8] In order to investigate propagation of mesoscale eddies in the central subarctic Pacific, we used delayed-time maps of sea level anomalies (SLA) of a merged altimeter satellite product distributed at 7-day intervals by *Archiving, Validation, and Interpretation of Satellite Oceanographic Data* [2011]. The spatial resolution of SLA is 1/4° × 1/4°, and we used the data from October 1992 to July 2005. The weekly spatial mean state in the area of 47°N–54°N and 170°W–180°W was removed from each weekly map of the SLA to compensate for seasonal steric effects. Using the SLA data, *Ueno et al.* [2009] identified 15 long-lived eddies propagating westward along the Alaskan Stream and named them based on the formation year (e.g., the first eddy formed in 1996 was named eddy 96a), and described their formation, propagation and termination in detail. Eddies, which already existed on 14 October 1992, the beginning of the altimetry data, were named eddies 92a, 92b, and 92c. In this article, we used the same eddy names as those used by *Ueno et al.* [2009] for readers to easily refer the trajectories of the eddy discussed in this article.

3. Results

[9] Time series fluxes of *Rhizoplegma boreale* at Station SA are shown in Figure 2. The fluxes of this species show a peak mostly every 2 years (1991–1992, 1993–1994, 1995–1996, 1998, 1999–2000, 2003–2004). No apparent peak was observed during 2001–2002 and the peaks during 1998 and 1999–2000 were significantly greater, almost double, than those in the other periods.

[10] During the period of 15 years for the present analysis, nine anticyclonic eddies passed around Station SA (Table 1 and Figure 3). Four of them (Eddies 96b, 99a0, 99a1, and 00a) were relatively strong Alaskan Stream eddies. Four of them (Eddies 92a1, 92a2, 92c1, and 92c2) were small eddies detached from strong eddies propagating westward along the Alaskan Stream (AS) (Eddies 92a and 92c), which already existed at the beginning of the altimetry data. The other eddy was a weak eddy, which formed as the result of merging and separation in the central subarctic Pacific and therefore whose formation area was hardly identified. The periods when these nine eddies pass around Station SA mostly corresponded to the periods when the flux of *R. boreale* at Station SA presented a peak except for the peak during 2003–2004. Therefore, next we discuss the relation between flux of *R. boreale* and eddy propagation.

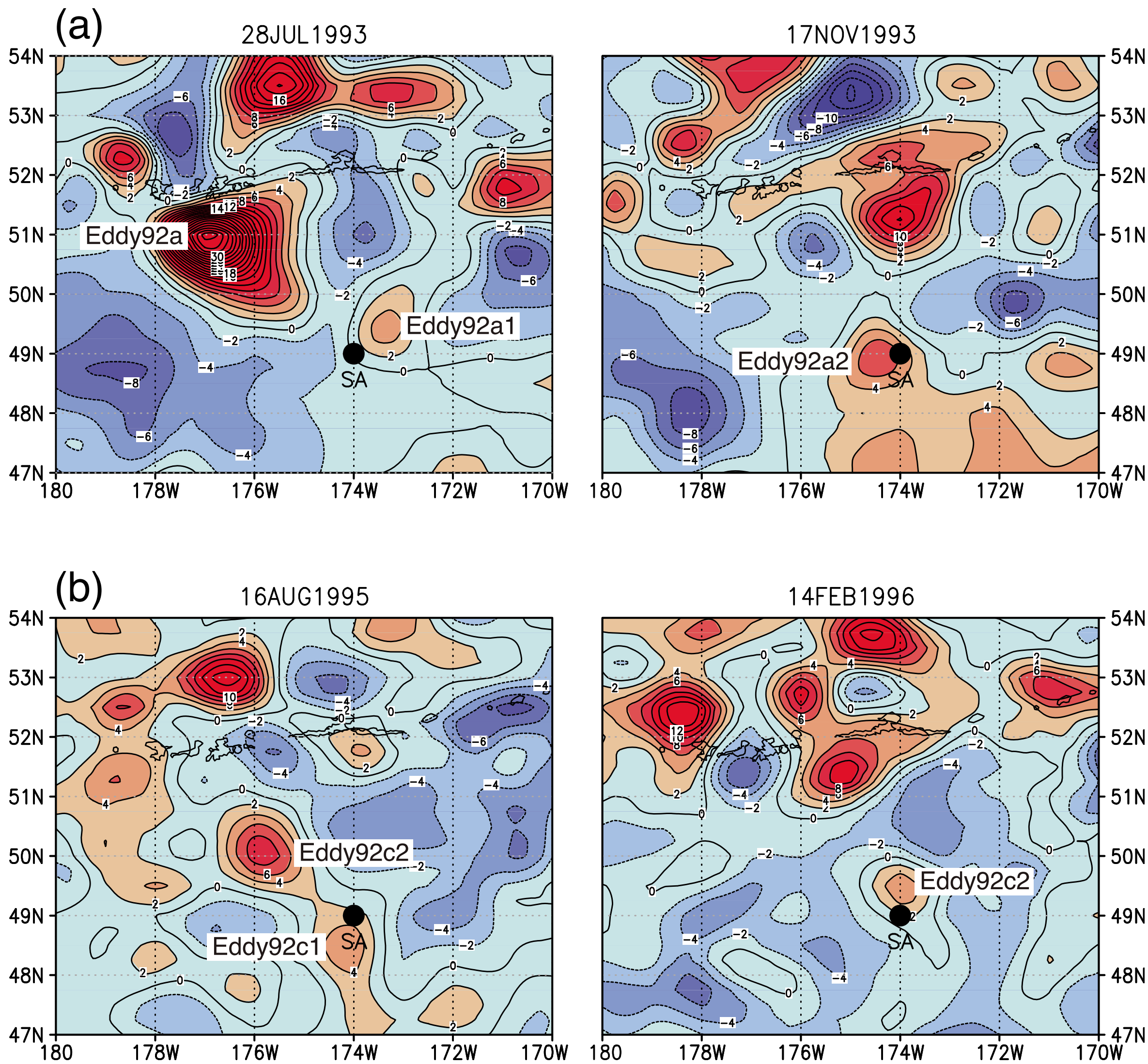

Figure 3. Eddy locations during high *R. boreale* flux period of (a) 1993–1994, (b) 1995–1996, (c) 1998, and (d) 1999–2000. Contours and colors represent sea level anomalies from Archiving, Validation, and Interpretation of Satellite Oceanographic data. Closed circles at 49°N, 174°W indicate the location of Stations SA.

3.1. In 1993–1994

[11] Relatively high *R. boreale* flux was observed from September 1993 to March 1994. Just before and in the early part of the high-flux period, i.e., June–December 1993 two small eddies (Eddies 92a1 and 92a2) passed around Station SA. In June 1993, Eddy 92a [see *Ueno et al.*, 2009], which was located between Station SA and the Aleutian Islands, became elongated southeastward and detached a small eddy, Eddy 92a1. Eddy 92a1 stayed around Station SA in June–August 1993 (Figure 3a) and decayed in September 1993. Eddy 92a detached another eddy in August 1993, forming Eddy 92a2 in the area northwest of Station SA. After its formation, Eddy 92a2 propagated southeastward, stayed around Station SA in September–December 1993, and decayed in early 1994.

3.2. In 1995–1996

[12] The situation occurred during 1995–1996 was similar to that during 1993–1994. From October 1995 to June 1996, *R. boreale* flux was relatively high with some fluctuations. Just before and in the early part of this period, i.e., from June 1995 to March 1996, two small eddies (Eddies 92c1 and 92c2) passed around Station SA. In May 1995, Eddy 92c [see *Ueno et al.*, 2009] was located between Station SA and the Aleutian Islands, elongated southeastward and detached a small eddy, Eddy 92c1, in a similar way to Eddy 92a. Eddy 92c1 stayed around Station SA in June–August 1995 (Figure 3b) and decayed in August 1995. In June 1995, Eddy 92c detached another eddy (Eddy 92c2) in the area northwest of Station SA. Eddy 92c2 stayed around Station SA from October 1995 to March 1996, and decayed in March 1996.

3.3. In 1997–1998

[13] *Rhizoplegma boreale* represented the highest flux peak in April–May 1998, with relatively high values from February to August 1998. During the period from December 1997 to October 1998, which included the period of

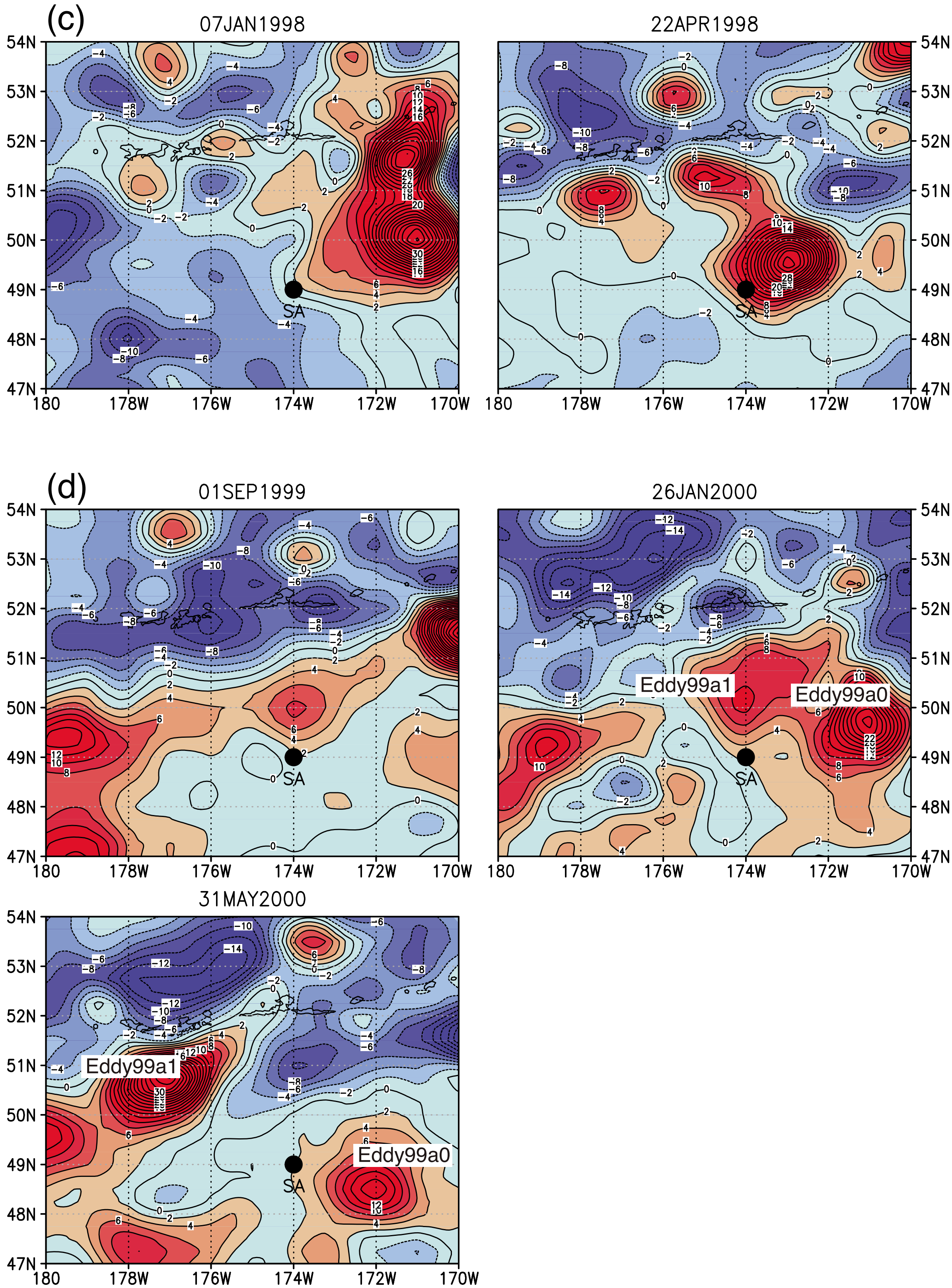

Figure 3. (continued)

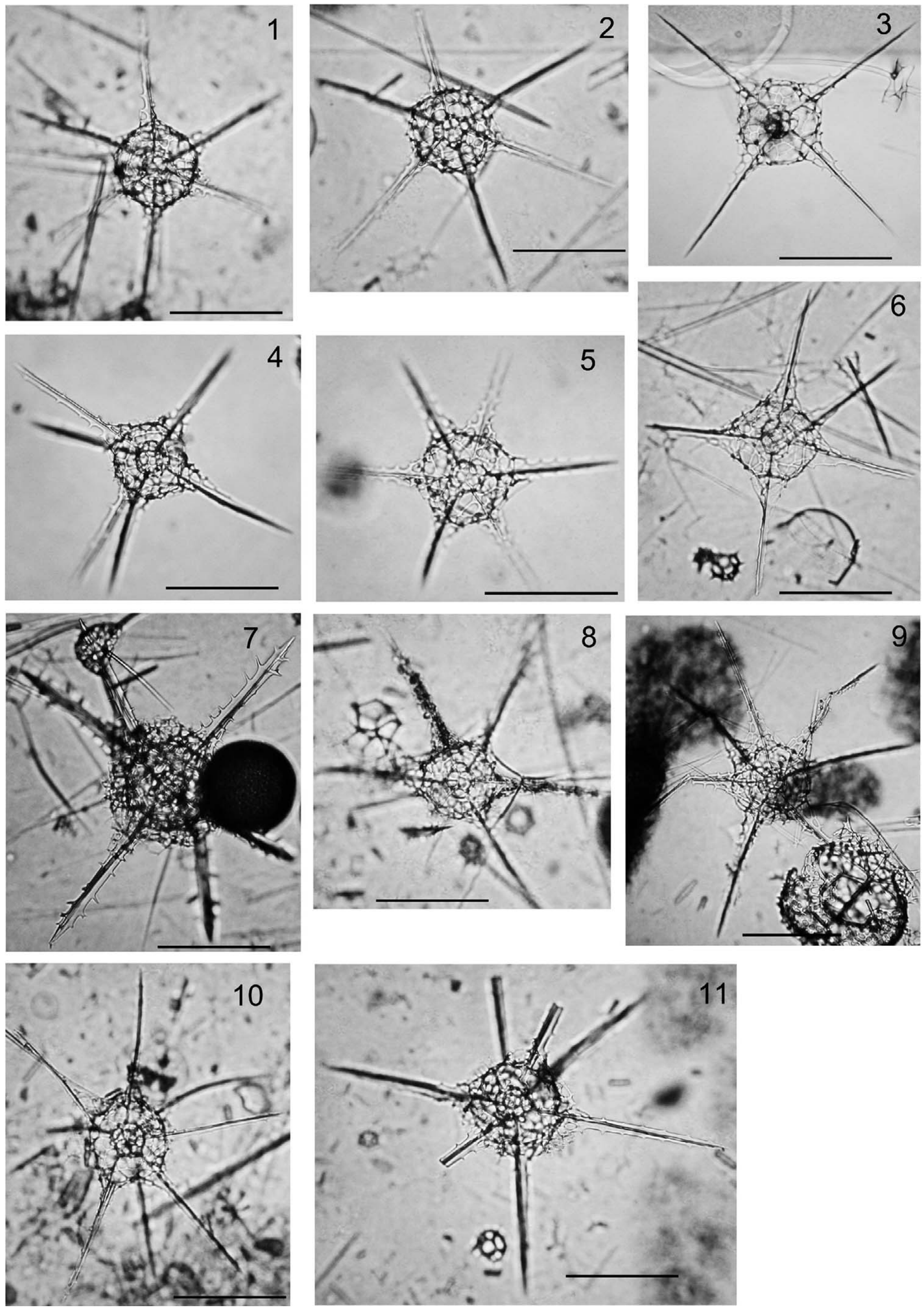

Figure 4. *Rhizoplegma boreale* (Cleve), specimens from the central subarctic Pacific (Station SA). All scale bars are 50 μm. The sample numbers correspond to those published by *Ikenoue et al.* [2012]: 1, from SA7#4; 2, from SA11#9; 3, from SA11#2; 4, from SA11#9; 5, from SA11#6; 6, from SA11#9; 7, from SA11#9; 8, from SA7#4; 9, from SA11#6; 10, from SA7#3; 11, from SA7#2.

relatively high flux, Station SA was located within or around Eddy 96b. Eddy 96b first appeared at 158°W south of the Alaska Peninsula in March 1996, propagated southwestward along the Alaskan Stream [*Ueno et al.*, 2009]. Eddy 96b was located just east of Station SA from December 1997 to January 1998, was slightly away from Station SA in February 1998, included Station SA inside of it during March–September 1998, and was located just west of Station SA in October 1998 (Figure 3c). After passing Station SA, Eddy 96b propagated southwestward and decayed at 178.5°E in July 2000.

3.4. In 1999–2000

[14] From August 1999 to June 2000, *R. boreale* flux showed high values with a significant maximum in April 2000, which was nearly as high as that of 1998. During this period,

three eddies, a weak eddy, Eddy 99a1 and Eddy 99a0 (see *Ueno et al.* [2009] for Eddies 99a1 and 99a0) passed around Station SA. From June to November 1999, a weak eddy, whose formation area and time could not be identified, was located just north of Station SA (Figure 3d). In December 1999, Eddy 99a0, which was located northeast of Station SA, detached Eddy 99a1, and Eddy 99a1 passed just north of Station SA from December 1999 to January 2000. After the crossing of Eddy 99a1, Eddy 99a0 crossed Station SA from April 2000 to May 2001.

3.5. In 2003–2004

[15] Relatively high fluxes of *R. boreale* were also observed from August 2003 to November 2004, but no eddy was detected around Station SA during the period.

[16] Eddy 00a also passed around Station SA in May–July 2005, although high *R. boreale* flux was not observed during the period. However, the period of May–July 2005 was just the end of the analysis period; therefore it is difficult to evaluate the relation between Eddy 00a and *R. boreale* flux. In addition to 9 eddies described above, Eddies 96a and 02a passed the longitude of Station SA along the Aleutian Islands in February 1997 and May–July 2002, when high *R. boreale* flux was not observed. This is probably because Eddies 96a and 02a took relatively northern route and the flow field due to Eddies 96a and 02a hardly influenced Station SA.

4. Discussion

[17] We investigated inter-annual variation of *R. boreale* flux at Station SA and its relation to passages of mesoscale anticyclonic eddy in the central subarctic Pacific from October 1992 to July 2005. The flux of this species presented five peaks during the analysis period and four of them corresponded to the passages of mesoscale eddy around Station SA, suggesting that mesoscale eddies influenced the flux of *R. boreale* (Figure 2). In this section, we briefly discuss the mechanisms for mesoscale eddies to affect production and subsequent flux of *R. boreale.*

[18] In the subarctic Pacific, eddies were indicated to have a significant impact on the exchange of heat, freshwater, macro- and micronutrients and biota between the shelf region and the offshore region by trapping coastal water at the eddy center and propagating offshore and also by advection in the outer ring of the eddy [*Crawford*, 2002; *Mackas and Galbraith*, 2002; *Whitney and Robert*, 2002; *Crawford et al.*, 2005; *Johnson et al.*, 2005; *Ladd et al.*, 2005; *Ueno et al.*, 2009, 2010]. This suggests that mesoscale eddies passing Station SA provide the Station SA area with coastal waters. Since anticyclonic eddies (eddies with sea level anomaly maximum at the center) induce clockwise circulation, Figures 3c and 3d (top), for example, suggest that a combination of eddies locating north of Station SA transport coastal waters to the area of Station SA.

[19] Previous studies indicated that *R. boreale* preferred coastal water [*Nishimura et al.*, 1997; *Dolven and Bjørklund*, 2001]. Therefore coastal water transport due to eddies described in the previous paragraph might enhance high productivity of *R. boreale* at Station SA. In addition to coastal water transport, mesoscale eddies affect biota field via upwelling due to eddy/wind interactions and submesoscale processes in and around the eddy [e.g., *McGillicuddy et al.*, 2007; *Mahadevan et al.*, 2008]. Such vertical processes also might influence the productivity of *R. boreale* at Station SA. However, it is important to note that the fifth peak from August 2003 to November 2004 cannot be explained by mesoscale eddies. The mechanism for this peak still remains to be seen and further studies are necessary.

[20] From observations in the Norwegian Sea and fjords, *Dolven and Bjørklund* [2001] showed that there were two morphotypes of *R. boreale* (oceanic form with six radial spines and coastal form with eight spines). They further indicated that the differences in the morphotypes between the Norwegian Sea and fjords might be due to a phenotypic response to the different ecological conditions. Therefore, we studied the morphological variability of *R. boreale* in the central subarctic Pacific (Station SA), by examining the difference in radial spines just before, during and just after *R. boreale* flux peaks due to mesoscale eddies. The specimens are characterized by bearing six radial spines (Figure 4, samples 1–8). The following numbers of specimens were examined: 256, 512 and 512 specimens for the peaks in November 1995, May 1998, and April 2000, respectively. However, clear change in the form of *R. boreale* skeletons was not observed: the forms of *R. boreale* skeletons were mainly classified into (1) the form with six radial spines; and (2) the form with greater than six radial spines (Figure 4, samples 9–11) which was very rare (<<1%).

[21] In this study we showed that *R. boreale* flux mostly corresponded with the propagation of mesoscale eddies and suggested the significance of *R. boreale* as a tracer for mesoscale eddies from coastal areas. However, further investigations including physicochemical and biological data analyses are necessary for better understanding of its values as a tracer for mesoscale eddies, which may contribute to clarify the environmental conditions of the present and the past.

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