



Backward-tracking simulations of sea ice in the Sea of Okhotsk toward understanding of material transport through sea ice

Mizuki Kuga¹ · Kay I. Ohshima¹ · Sachiko Kishi² · Noriaki Kimura³ · Takenobu Toyota¹ · Jun Nishioka¹

Received: 24 April 2023 / Revised: 25 July 2023 / Accepted: 29 September 2023 / Published online: 17 October 2023
© The Author(s), under exclusive licence to The Oceanographic Society of Japan 2023

Abstract

Material transport by sea ice plays an important role in the biological production of spring blooms. We conducted backward-tracking simulations to estimate the origins of the sea ice in the southern part of the Sea of Okhotsk and examine the relationship between the origin of sea ice and biological production, the concentration of iron, and the frazil ice fraction. The simulation of the sea ice melted in areas, where the net community production (NCP) was estimated shows that the sea ice that melted in areas with high NCP tended to originate in coastal areas, mostly the Terpenia Bay and Sakhalin polynyas, where ice production is high and sea ice can incorporate the seafloor sediments. This result supports the hypothesis that the incorporation of sedimentary particles into sea ice and their release during ice melt are key factors in high biological production. The simulation of the sea ice floes sampled by the icebreaker Soya off Hokkaido coast suggests that the samples collected over the shelf with depths of less than 500 m or so were formed over the shelf around the southern tip of Sakhalin Island, whereas the samples, including that with high iron concentration, collected over the shelf slope at greater depths were likely transported from the northern area up to Terpenia Bay but not further north. The simulation also suggests that the sea ice floes with a high fraction of frazil ice could be formed anywhere in the southern part of the Sea of Okhotsk.

Keywords Sea ice · Ice drift · Material transport · Coastal polynya · Sea of Okhotsk · Spring bloom

1 Introduction

The Sea of Okhotsk is the southernmost seasonal sea ice zone in the Northern Hemisphere. A remarkable phytoplankton bloom occurs in this sea just after the sea ice melts (Mustapha and Saitoh 2008; Kasai et al. 2010). Such a correlation between sea ice melt and large phytoplankton bloom has also been observed in other seasonal sea ice zones (e.g., Wilson et al. 1986; Niebauer et al. 1995). Several factors have been proposed to account for this enhancement of the spring phytoplankton bloom by sea ice melt, including (1)

increased primary production caused by the solar radiation (Niebauer et al. 1995), (2) enhancement of stratification caused by the freshening by sea ice melt, which enables phytoplankton to remain in the euphotic layer (Sorokin and Sorokin 1999), (3) the release of micro-nutrients, such as iron from the melting sea ice (Kanna et al. 2014), and (4) the seeding effect of ice algae (Yan et al. 2020). The latter two mechanisms imply that material transport by sea ice plays an important role in biological productivity. Kishi et al. (2021) showed that, in the southern part of the Sea of Okhotsk with sea ice melt, the enhancement of biological production in the spring phytoplankton bloom is not attributable solely to an intensification of the surface stratification. This finding suggests that the materials released from the melting sea ice could enhance the phytoplankton bloom.

Several studies have investigated the contribution of the materials released from sea ice to the growth of phytoplankton in the Sea of Okhotsk. One of these materials is iron, an essential micro-nutrient for phytoplankton. The subarctic North Pacific region adjacent to the Sea of Okhotsk is known as the high-nutrient low-chlorophyll region, indicating that the growth of phytoplankton there is limited by iron

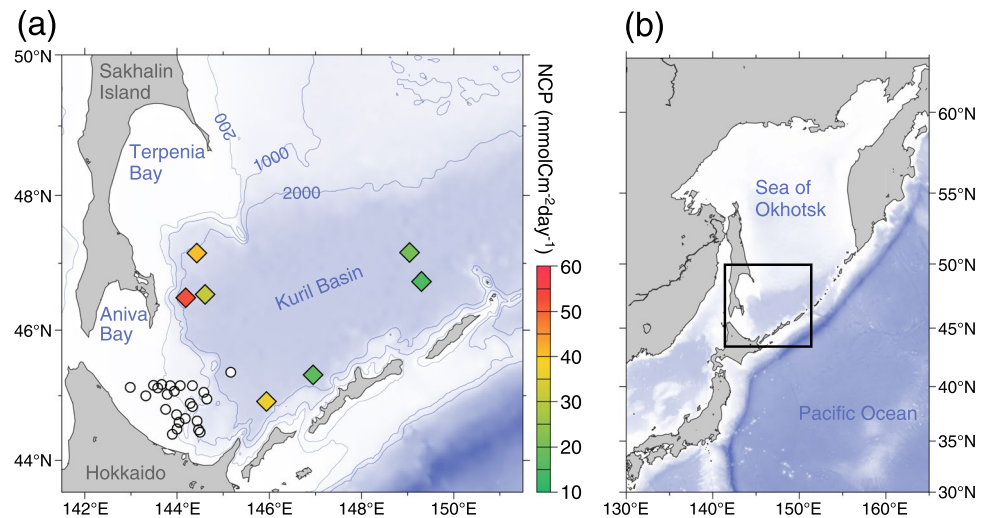
✉ Mizuki Kuga
mkuga@lowtem.hokudai.ac.jp

¹ Institute of Low Temperature Science, Hokkaido University, Sapporo, Hokkaido, Japan

² Japan Weather Association, Tokyo, Japan

³ Atmosphere and Ocean Research Institute, The University of Tokyo, Kashiwa, Chiba, Japan

Fig. 1 **a** Bathymetry of the southern part of the Sea of Okhotsk, which is indicated as the rectangular area in the larger area map (**b**). The blue contours indicate the 200, 1000, and 2000 m isobaths. The diamonds show the NCP-estimated locations, color-coded by the NCP value. The open circles show the locations at which the icebreaker Soya sampled the sea ice (color figure online)



availability (Tsuda et al. 2003). In the Kuril Basin of the Sea of Okhotsk, by contrast, the nitrate depletion in the surface layer observed during the summer implies that the iron supply is sufficient (Nishioka et al. 2014). Direct observations in the southern part of the Sea of Okhotsk (Kanna et al. 2014) have suggested that the supply of iron from melting sea ice increases the concentration of iron in the surface layer. Furthermore, it has been suggested that the iron contained in sea ice originates mainly in sedimentary particles on the continental shelf. Based on the results of a shipboard incubation experiment, Kanna et al. (2018) suggested that the iron release associated with ice melting contributes to growth of the phytoplankton. Another material released from the sea ice is ice algae. Yan et al. (2020, 2022) showed that the dominant species of ice algae in the sea ice sampled in the southern part of the Sea of Okhotsk can act as seeds for spring phytoplankton blooms and that the sampled sea ice contained a large number of pennate diatoms, this being the dominant species of benthic microalgae. These findings imply that algal incorporation occurs simultaneously with the process by which sediment is incorporated into sea ice.

Such material incorporation process can occur through interactions between sedimentary particles and frazil ice resulting from the simultaneous occurrence of upward sediment transport and frazil ice formation (suspension freezing). Ito et al. (2017) suggested that this process actually occurs in the coastal polynya over the Sakhalin shelf based on the analysis of the backscatter strength data from bottom-mounted acoustic Doppler current profilers (ADCPs). Furthermore, analyses of ADCP volume backscatter strength data showed that frazil ice can form to depths of nearly 100 m around the ice edge regions in the Sea of Okhotsk (Ito et al. 2021) and that deep-penetrating frazil ice up to 80 m or deeper frequently occurs in response to strong winds in an Antarctic coastal polynya (Ohshima et al. 2022). These results, then, indicate that frazil ice can reach the seafloor

at depths of about 100 m and that the direct incorporation of the bottom sediments into sea ice can be possible in the region shallower than 100 m.

A large amount of sea ice melts in the southern part of the Sea of Okhotsk after March. The prevailing northwesterly winds and the East Sakhalin Current transport most of this ice from the northern part of the sea, where a large amount of sea ice is produced (Simizu et al. 2014). Kuga et al. (2023) conducted the particle-tracking experiments for sea ice originating from all the coastal polynyas in the Sea of Okhotsk and suggested that most of the coastal-origin sea ice melting in the southwestern part of the Sea of Okhotsk comes from the Terpenia Bay and Sakhalin polynyas. Analysis of satellite microwave data indicates that active frazil occurs at a high rate in Terpenia Bay (Nakata and Ohshima 2022). Kuga et al. (2023) also conducted particle-tracking experiments on the frazil ice produced in the coastal polynyas and attributed the large contribution of the sea ice originating from Terpenia Bay to the high biological production area in the Kuril Basin.

Kishi et al. (2021) quantified the relationship between the melting of sea ice and biological production by estimating Net Community Production (NCP) as an index of biological productivity, based on the oxygen increase from the profiling floats deployed in the Sea of Okhotsk. They found the NCP for the case in which the sea ice existed just before the phytoplankton bloom (the prior-ice case) (31.2 ± 12.3 mmolC/m²/day) to be significantly greater than that for the non-ice case (11.6 ± 5.5 mmolC/m²/day). Even for the prior-ice cases (see Fig. 1 for locations of the NCP estimated), the estimated NCP shows a large range of values, with the maximum value (52 mmolC/m²/day) being more than three times the minimum (15 mmolC/m²/day) (Table 1). This difference of NCP is presumably related to the cause of the spring phytoplankton bloom, but this relationship has not been well-understood. One possible factor is the difference

Table 1 Start dates and positions of the simulations with the NCP values for sea ice in the NCP-estimated areas

	Date	Latitude	Longitude	NCP ^a [mmolC m ⁻² day ⁻¹]
a	2018/03/29	46.49	144.19	52
b	2017/04/05	47.09	144.4	41
c	2008/04/04	44.91	145.94	37
d	2009/03/27	46.55	144.6	31
e	2013/04/03	47.16	149.04	20
f	2019/03/23	45.31	146.96	17
g	2013/03/31	46.73	149.3	15

^aKishi et al. (2021)

in the materials released from the sea ice, which is related to the origin of sea ice. However, the origins of the sea ice floes melting in the NCP-estimated areas have not been identified. On the other hand, intensive sea ice observation has been conducted in the southwestern part of the Sea of Okhotsk on board the icebreaker Soya since 1996 (Toyota et al. 2022). According to their ice sampling studies, sea ice floes have relatively high concentrations of iron and a relatively high fraction of frazil ice (Kanna et al. 2014; Nomura et al. 2010; Toyota et al. 2007, 2022). However, the origins of sampled sea ice were not identified. For both cases of NCP estimation and ice sampling studies, identifying the origin of sea ice will provide important information for elucidating the relationship between biological production and sea ice. In this study, we estimate the origins of these sea ice floes by backward-tracking simulations and investigate relationship among the origin of sea ice and the biological production, iron concentration, and the frazil ice fraction in the southern part of the Sea of Okhotsk. The results of the study thus provide the basic information for clarifying the roles of sea ice on stimulating biological production.

2 Data and methods

2.1 Basic concept

We conducted the backward-tracking simulations of sea ice for the two cases in the southern part of the Sea of Okhotsk; one is the simulation of the sea ice melting in the areas, where NCP estimated in Kishi et al. (2021) and the other is the simulation of the sea ice floes sampled by the icebreaker Soya in the southern part of the Sea of Okhotsk. We used the method of Kuga et al. (2023) for the particle tracking simulations except that we replaced forward tracking with backward tracking. We calculated the particle tracking at a time step of 6 h, ending when the sea ice concentration fell below 10% for 5 days in a row. The ETOPO2 bathymetry data were

used to determine the land and ocean areas. When a particle position calculated from the ice drift velocity intrudes into the land or comes within 3 km of the land, it was taken back to the position 3 km from the land along the trajectory. The ETOPO2 was also used to correct the ice drift by ocean current along the isobaths.

Since we traced back a large number of particles placed at slightly varying times and locations for each case, the estimated ice origin area is obtained as the spatial distribution of particles. In this study, we take the following two viewpoints to interpret such spatial distribution as sea ice origin area; (A) the spatial probability distribution of formation origin for a sea ice floe that existed at a specific location, and (B) the spatial distribution of the origins location for a bunch of sea ice floes in a certain area. We follow the viewpoint of (A) for the origin of a sea ice sample collected at a specific point by the icebreaker Soya. Regarding the formation origin of the sea ice floes melting around the NCP-estimated area, we follow the viewpoint of (B), because the sea ice melt in a relatively wide area likely determines NCP. Even for this case, the viewpoint of (A) is also applicable.

2.2 Setting for the case of the NCP-estimated area

For the study, we first conducted the backward-tracking simulations of the sea ice melting in the NCP-estimated areas to investigate the relationship between magnitude of biological production and the locations in which the sea ice originated. We used the NCP values estimated by Kishi et al. (2021) (Table 1), who converted the rate of oxygen increase during the oxygen-increase period (40–50 days) into the organic carbon increase rate using the Redfield ratio and integrated it from the surface to 50 m in depth. This NCP estimation is only investigation that quantifies the biological production in the large area of the Sea of Okhotsk, although NCP is not pure primary production. Before the tracking simulation, we have checked the relation of the areas of high NCP estimation with the distribution of Chl-a concentration which represents the amount of phytoplankton directly but only at the surface. As shown in the Supplementary Fig. S1, areas of high NCP correspond well with high Chl-a concentration areas except for the case of (f).

We conducted a backward-tracking experiment for seven cases of NCP estimation in which sea ice was present just before the spring phytoplankton bloom; sea ice concentration exceeded 30% on two consecutive days within 10 days before the first day of the NCP-estimated period. The simulation start date and position were set to the final day on which the sea ice concentration exceeded 30%. The simulation start date and position (indicated by the diamonds in Fig. 1) are listed in Table 1. We placed 200 particles at every 6-h time step for the 7 days preceding the start date within a 25 km radius from the start position. The 25 km corresponds to the

Table 2 Sampling dates and locations, sea ice thickness, fraction of frazil ice, and iron concentrations (total dissolvable Fe: TDFe) for the sea ice collected by the icebreaker Soya

	Date	Latitude	Longitude	Thickness (cm)	Frazil ice (%)	TDFe[nM]
T1	2003/02/07	45.16	143.49	35	47	–
T2	2003/02/08	45.17	143.67	35	30	–
T3	2003/02/09	45.36	145.17	37	57	–
T4	2003/02/11	44.83	144.33	101	6	–
T5	2003/02/12	44.95	144.65	84	75	–
T6	2003/02/12	44.61	144.44	36	5	–
T7	2003/02/12	44.44	144.5	72	36	–
T8	2004/02/07	45.0	143.32	197	65	–
T9	2004/02/08	44.79	143.75	222	43	–
T10	2004/02/09	44.65	144.18	213	75	–
T11	2004/02/09	44.49	144.0	104	74	–
T12	2004/02/11	44.48	144.47	117	48	–
T13	2004/02/12	44.71	143.99	141	30	–
T14	2005/02/14	44.41	143.9	30	4	–
T15	2005/02/15	44.88	144.29	119	12	–
N1	2007/02/12	45.05	144.58	41	44	–
N2	2007/02/12	45.05	144.58	55	78	–
N3	2007/02/13	45.02	143.79	75	52	–
N4	2008/02/11	44.59	144.04	35	29	–
N5	2008/02/12	45.16	144.33	49	55	–
N6	2008/02/13	45.12	143.58	26	47	–
K1	2010/02/08	45.07	143.94	98	–	163 ± 42
K2	2010/02/08	45.16	143.85	109	–	1218 ± 15
K3	2011/02/14	45.13	142.98	33	–	1414 ± 1159
K4	2011/02/16	45.16	144.07	80	–	883 ± 699

The prefixes “T”, “N”, and “K” of the IDs indicate the samples from Toyota et al. (2007), Nomura et al. (2010), and Kanna et al. (2014), respectively

resolution of sea ice concentration. The initial deployment of the particles was made using a uniform random number for distance and the angle from the start position as the center. Thus, the density of the deployed particles increases closer to the center position. In areas of 0% sea ice concentration within a radius of 25 km, no particles were deployed.

2.3 Setting for the case of the sampled sea ice

Next, we performed backward tracking of sea ice sampled in the Sea of Okhotsk to investigate the relationship between its structure and/or iron concentration and its origin location. The sea ice was sampled by the icebreaker Soya in February from 2003 to 2011 and analyzed for its structure and/or concentrations of nutrient (Toyota et al. 2007; Nomura et al. 2010; Kanna et al. 2014). For the area of ice sampling by the Soya, Toyota et al. (2022) reported thickness to be 0.64 ± 0.38 m on average for the period from 1996 to 2020. Some of the thin sea ice samples are considered to have formed near the sampling sites. To focus on the sea ice that could transport the materials, we chose 30 samples with a thickness exceeding 30 cm, which we regarded as

representative of sea ice transported from a distant location. Sea ice sampled within 25 km from the Hokkaido coast, which drift is considerably affected by the Soya Warm Current, was excluded, because the drift velocity used in this study cannot correctly represent the drift component by the current. Table 2 lists the dates and locations of the sampling, and the thickness, frazil ice fraction, and iron concentration of the sea ice for which we performed the backward tracking. Since this experiment simulates the transport of specific sampled ice, we deployed the particles only on the sampling day and interpreted the estimated distribution of the origins of the sea ice in terms of (A). Considering the drift on a timescale shorter than 1 day and existing errors in the drift velocity data, we initially placed a large number of particles with a spatial distribution centered on the sampling location and then obtained the spatial probability distribution of the origins of the sea ice. Specifically, 400 particles were randomly placed at every 6-h time step on a given sampling day (for 1600 particles in total) within a 15-km radius of the sampling location (represented by the open circles in Fig. 1), using the uniform random numbers for the distances and angles from the sampling locations. We deployed the

particles in more confined areas, compared with the case of the NCP-estimated area, because the sampling locations were determined exactly.

2.4 Method of the backward tracking

For each particle, the sea ice drift velocity was given for every 6-h step and the transport path was backward-tracked. We estimated the drift velocities from satellite and wind data, using the method of Kuga et al. (2023) except that forward tracking was replaced by backward tracking using the reversed drift velocities. The primary satellite drift velocities are the daily gridded data with a 50 km spatial resolution derived from the Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E) and AMSR2 brightness temperatures using the maximum cross-correlation method (Kimura et al. 2013). Although these data are relatively reliable in areas far from the coast, the drift speed is underestimated in the coastal area when land is included in a grid cell (Kuga et al. 2023). This less-accurate estimation can be diffused to the offshore grid cells in the range of 50–100 km from the coast when their missing values are interpolated from the values of the cells that contained land.

To compensate for the inaccurate satellite-estimated drift velocity near the coast, we also used drift velocity data U_w (U_w, V_w) (m/s), derived from the 10-m wind (u, v) (m/s) of ERA-5 at every 6-h step with the wind factor F and turning angle θ as

$$\begin{pmatrix} U_w \\ V_w \end{pmatrix} = F \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} u \\ v \end{pmatrix}. \quad (1)$$

We used values of $F=0.027$ and $\theta=-12^\circ$,¹ which were estimated based on simultaneous observations of the ocean currents and ice drift velocities from the moored ADCPs on the shelf off Sakhalin (Kuga et al. 2023). The negative value of θ indicates that the drift velocity directs to the right of the wind vector. This wind-estimated drift velocity does not include the drift component by the ocean current. Over the continental shelf, sea ice drift is enhanced by the dynamical coupling between sea ice and a coastal ocean resulting from a coastal-trapped current caused by alongshore wind stress (Nakayama et al. 2012). The enhancement of the ice drift by this effect becomes larger with shallower bottom depths. To represent the ice drift that include the ocean drift component, we used the enhancement ratio γ , which represents the enhancement of the alongshore ocean drift component, proposed by Nakayama et al (2012). Based on the estimation by Kuga et al. (2023) from the mooring observations on the

shelf off Sakhalin, we used values of the enhancement ratio γ as a function of bottom depth h (m), represented by

$$\gamma = \begin{cases} 1 + a(h - 1000), & a = -1.250 \times 10^{-3} \quad h < 1000 \\ 1 & h \geq 1000 \end{cases}. \quad (2)$$

We used the combined drift velocity U (m/s) from the satellite U_s (cm/s) and wind U_w (cm/s) within 200 km of the coast with a larger weighting of the wind estimation closer to the coast, using the following equation:

$$U = f(x) \times U_w + (1 - f(x)) \times U_s, \quad f(x) = \exp \left\{ -x^2 / (2 \times 50^2) \right\}, \quad (3)$$

where x (km) is the distance from the coast. The daily ice drift velocities from the satellite (AMSR) were linearly interpolated into the 6-h data, and the ice drift velocities from the satellite and/or wind were linearly interpolated into the space from the four surrounding grid points.

2.5 Determination of ice formation area

It is the most difficult part to determine, where backward-tracked sea ice was formed, because the sea ice formation could occur at any location along the tracking path. In this study, the location with the largest daily sea ice production on the tracking path of each particle is regarded as the origin (site of formation) of the sea ice. For the daily sea ice production, we used the 12.5 km resolution gridded data by Nakata and Ohshima (2022). The sea ice production was derived from the thin ice thickness by the AMSR thin ice algorithm (Nakata et al. 2019) and heat budget calculation assuming that all heat loss is used for sea ice formation. If an AMSR pixel is not detected as a thin ice area or the net heat budget of the pixel is positive (i.e., the ice/ocean gains heat from the atmosphere), it is regarded as a no-ice production pixel. The predominant ice production regions are the coastal polynyas, and the ice edge areas are often identified as sea ice production areas.

3 Results

3.1 Sensitivity of transport path to the drift velocity data

First, we checked the effectiveness of combined use of the satellite- and wind-derived drift data. Figure 2 shows the transport paths of the backward-tracking simulations from the two ways; one is the use of the drift velocity estimated only from the satellite data (indicated by black), and the other is the use of the combined drift velocity from the satellite and wind by Eq. (3) with the enhancement ratio γ by Eq. (2) (indicated by red). In the experiment using the

¹ $\theta=-12^\circ$ was misprinted as $\theta=12^\circ$ in Kuga et al. (2023).

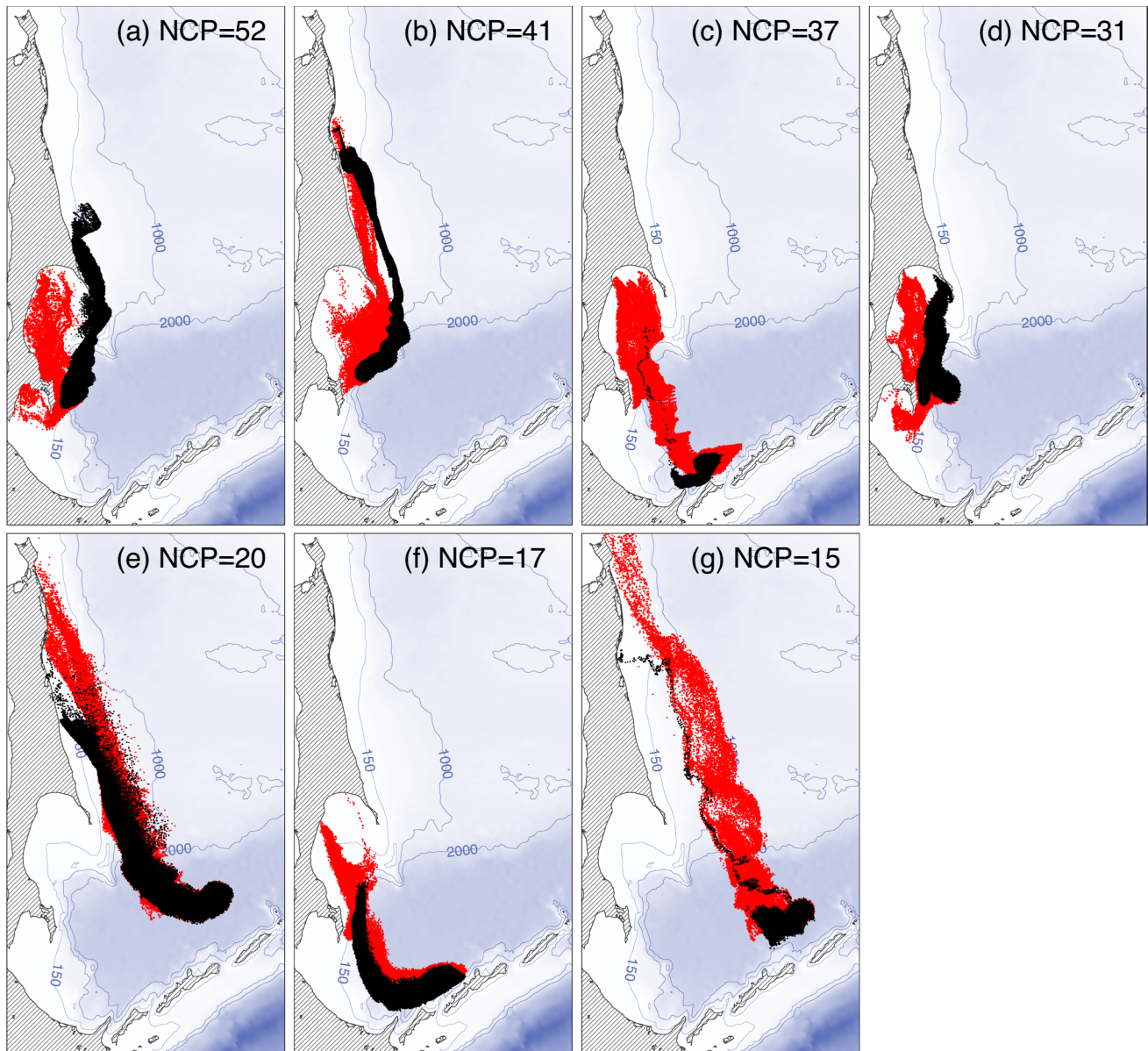


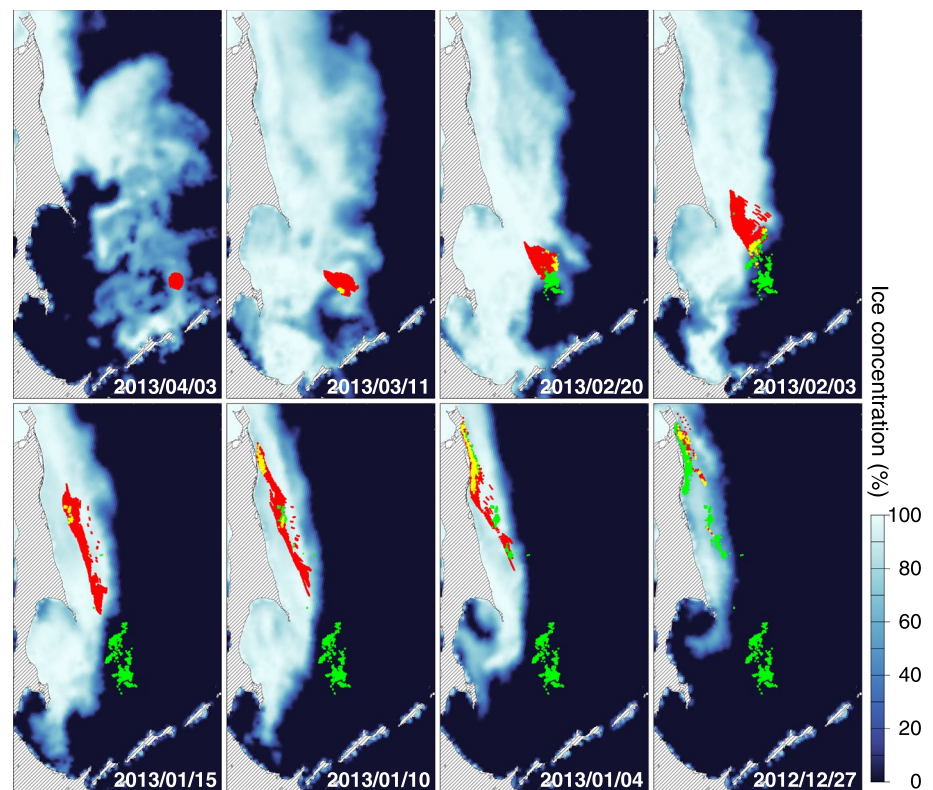
Fig. 2 Transport paths of backward-tracking particles for the simulation of the sea ice melting in the NCP-estimated areas for seven cases (a–g) listed in Table 1. The simulation was made by two ways. One is the use of the drift velocity estimated only from the satellite data

(shown in black). The other is the use of the combined drift velocity estimated from the satellite and wind data, with the enhancement ratio representing the ice drift by coastal currents (shown in red). The unit of NCP in each panel is $\text{mmolCm}^{-2} \text{ day}^{-1}$ (color figure online)

combined drift velocity, the transport path is aligned more along the continental shelf and the transport distance is longer. Since the experiment using only the satellite data significantly underestimates the drift within 100 km of the coast, the drift from the coast to the offshore direction was not correctly represented. Thus, the backward drift toward the coast was significantly underestimated (Fig. 2a–d). Furthermore, the satellite-only data do not represent the drift enhancement by the alongshore currents. As a result,

the drift distance in the alongshore direction was also significantly underestimated (Fig. 2e, f). These shortcomings of the satellite-only data are critical in regard to the identification of the origin of sea ice, particularly for the sea ice originating near the coast. As such, correction of the satellite-derived drift data, by combination with the wind-derived data and inclusion of the alongshore enhancement factor, is indispensable to identify the sea ice origin from the backward tracking.

Fig. 3 Simulated backward time-series of the ice particle distribution for the case of Table 1 (e) superimposed on the sea ice concentration. The particles newly determined to be formed are shown in yellow, the locations previously determined to be the origin of the sea ice are shown in green, and the remaining particles that should be formed earlier shown in red (color figure online)



3.2 Origin of sea ice in the NCP-estimated area

Figure 3 shows an example of a simulated backward time-series of ice particle distribution traced back to the end of the simulation for Table 1 (e), superimposed on the sea ice concentration. Of the sea ice particles that had existed in the center of the Kuril Basin at the beginning of April, 43% of them are judged to have been formed at the ice edge in the basin area from the beginning of March to February. Other sea ice particles are traced back northward along the continental slope off Sakhalin Island and up to around the Sakhalin polynya and judged to have been formed at the beginning of January.

Figure 4 shows the results of the backward-tracking simulations for the seven cases of sea ice in the NCP estimated. The black circle, blue/red dots, and gray line indicate the initial positions, the locations, where the sea ice formed, and the transport path, respectively. The locations of sea ice formation (origin) distributed in Terpenia Bay, the Sakhalin polynya, the shelf slope areas off Sakhalin and the Kuril Basin. The sea ice initially located in the northwestern Kuril Basin has been traced back via two paths, one along the coast of Sakhalin Island (Fig. 4a, d) and the other from off-shore to Terpenia Bay (Fig. 4b). The sea ice initially located near the Kuril Islands in the southwestern Kuril Basin traced back along the continental slope to Terpenia Bay after approaching the coast of Hokkaido (Fig. 4c, f). Most of the

sea ice initially located around the central part of the Kuril Basin is judged to have originated in the Kuril Basin, while the rest has been traced back along the continental slope to the Sakhalin polynya (Fig. 4e, g).

3.3 Relationship between NCP and the origin of sea ice

In a coastal polynya, the simultaneous occurrence of frazil ice formation and upward sediment transport over the shallow shelf can incorporate sedimentary particles into the sea ice (Ito et al. 2017). The winter mixed layer off Sakhalin Island reaches nearly 150 m in depth (Ohshima et al. 2005) and frazil ice can be generated at depths of up to 100 m (Ito et al. 2021). These findings suggest that frazil ice can directly incorporate sediments from the seafloor. In Fig. 4, the ice particles judged to have originated in the continental shelf with a depth of < 150 m are shown in red and are regarded as continental shelf origin that can contain sediments. The percentages of the particles judged to be of continental shelf origin are (a) 89%, (b) 97%, (c) 97%, (d) 86%, (e) 40%, (f) 57%, and (g) 4% in descending order of NCP (Fig. 5). In the cases with high NCP, most of the ice particles originate in the continental shelf, especially in the Terpenia Bay polynya [cases (a)–(d)]. In case (b), the sea ice origin is also distributed in the Sakhalin polynya. By contrast, in the low-NCP cases [(e)–(g)], many ice particles originate

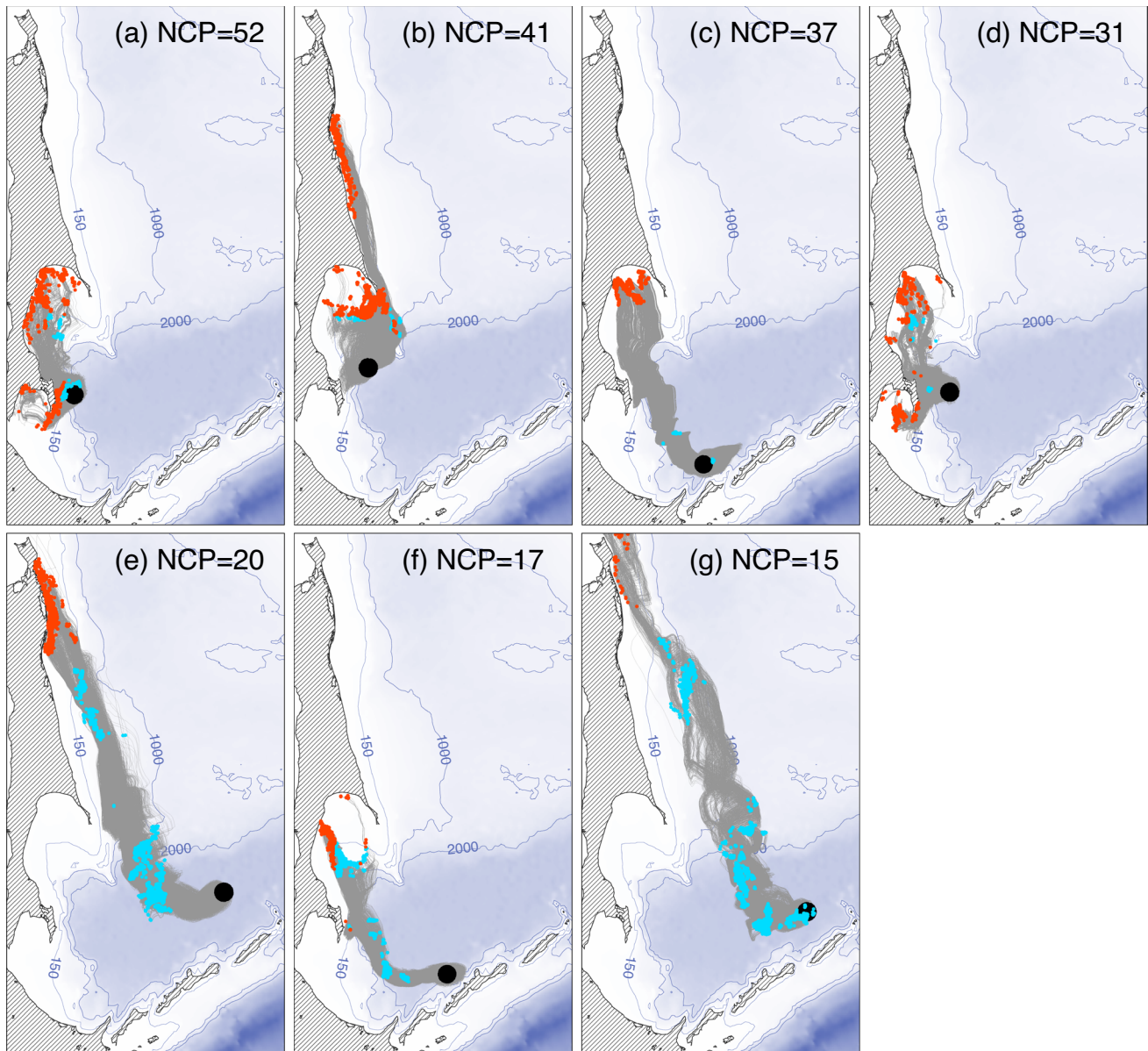


Fig. 4 Distribution of the simulated origin of the sea ice that existed in the NCP-estimated areas for seven cases (a–g) listed in Table 1. The black circles, blue/red dots, and gray lines indicate the initial position, the location where the sea ice formed, and the transport

path, respectively. The blue and red dots indicate location depths of >150 m and of <150 m, respectively. The unit of NCP in each panel is $\text{mmolCm}^{-2} \text{day}^{-1}$ (color figure online)

in the ice edge. This relationship between NCP and sea ice origin well demonstrates that sea ice whose melting leads to high biological production originates in the Terpeniya Bay and Sakhalin polynyas, also as Kuga et al. (2023) suggested.

Next, we examine the condition of polynyas from which ice particles are judged to be originate. Figure 6 shows the time series of sea ice production in the polynya areas (black lines) for the 5 cases of high percentage of polynya origin (a–e), superimposed by the number of ice particles that are judged to be formed in each polynya (colored bar). The map in the right shows locations of the three polynya areas,

Terpeniya Bay polynya (red), Southern Sakhalin polynya (blue), and Northern Sakhalin polynya (purple). In most cases, ice particles originate from high ice production periods when higher and deeper frazil ice formation is expected, which provides favorable condition that sea ice incorporates the bottom sediments.

3.4 Origin of the sea ice sampled off Hokkaido

Sea ice sampled in the region off the shore of Hokkaido over the continental shelf and slope has a relatively high

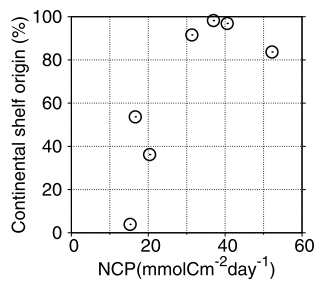


Fig. 5 Relationship between NCP and sea ice origin. The percentage of sea ice particles determined to have originated in the continental shelf (< 150 m) is shown as a function of NCP

percentage of granular ice formed by the aggregation of frazil ice. The percentage of granular ice in the ice samples was reported as 64% by Toyota et al. (2004), 48% by Toyota et al. (2007), and 53% by Nomura et al. (2010). We conducted the backward-tracking simulations for 21 samples with a thickness of > 30 cm (T1–15, N1–6 in Table 2). In this sea, thick ice is formed by the piling up process (rafting) of ice floes (Toyota et al. 2004). Therefore, multiple granular ice layers containing sediment exist throughout the sea ice column (Nomura et al. 2010).

Figure 7a shows the estimated locations of sea ice origin (formation) colored with the frazil ice fraction of the sampled ice. The origins of the sea ice are distributed over the continental shelf off Aniva Bay, the southern Sakhalin shelf, and Terpenia Bay. There is no clear relationship between the frazil ice fraction and the location of sea ice

origin. Although the satellite observations suggested a relatively high occurrence of frazil ice in the Terpenia Bay polynya (Nakata and Ohshima 2022), our simulations suggest that the sea ice floes with a high fraction of frazil (granular) ice could form anywhere in the southern part of the Sea of Okhotsk. Therefore, the origin of the sea ice cannot be identified solely by the fraction of frazil (granular) ice.

Kanna et al. (2014) measured the iron concentration of the sea ice and surface water sampled by the Soya observations in the southwestern part of the Sea of Okhotsk and showed that the iron concentration of the sea ice was significantly higher than that of the surface water. The iron concentration was particularly high in thick sea ice with layered structure and relatively low in thin sea ice, which is considered to have formed near the sampled location. Figure 7b shows the simulated distribution of origin location of sea ice for which the iron measurement (K1–4 in Table 2) was made. The origin locations are distributed off Aniva Bay, around the southern tip of Sakhalin Island, and in Terpenia Bay. Of the simulated origin location, 74% located on the continental shelf with depths of < 200 m. In the case of K4 (shown in red in Fig. 7b), there is a possibility that the sea ice originated from Terpenia Bay, where active frazil ice formation occurs (Nakata and Ohshima 2022). Our backward-tracking simulations for the iron-sampled sea ice suggest that the sea ice with a relatively high concentration of iron formed in the shelf area off southern Sakhalin Island and Terpenia Bay and

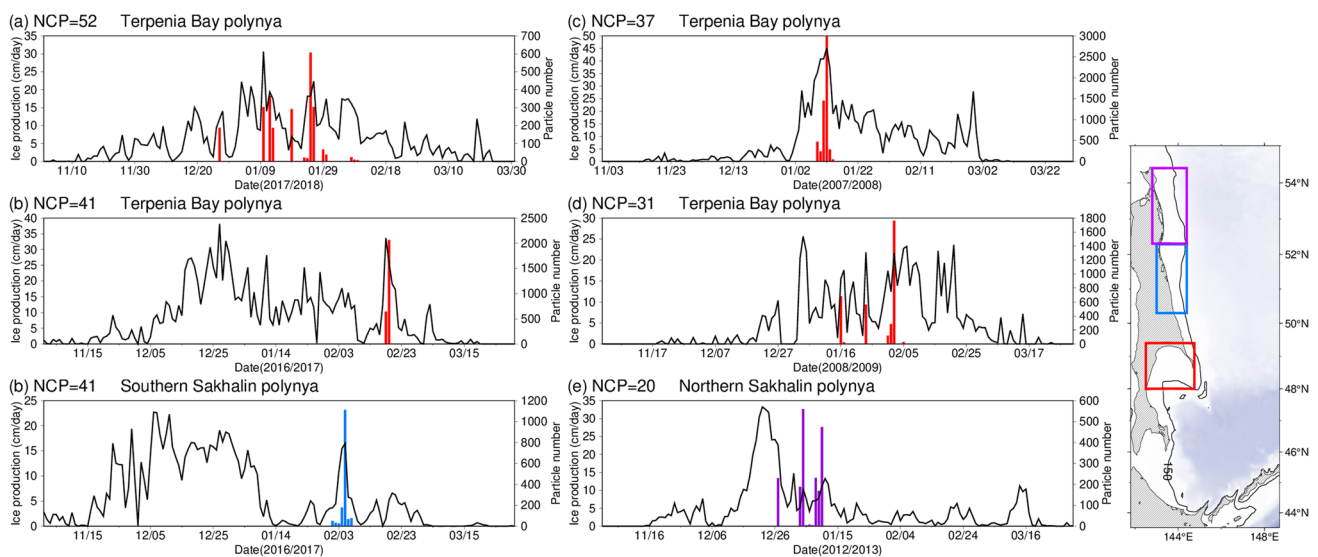
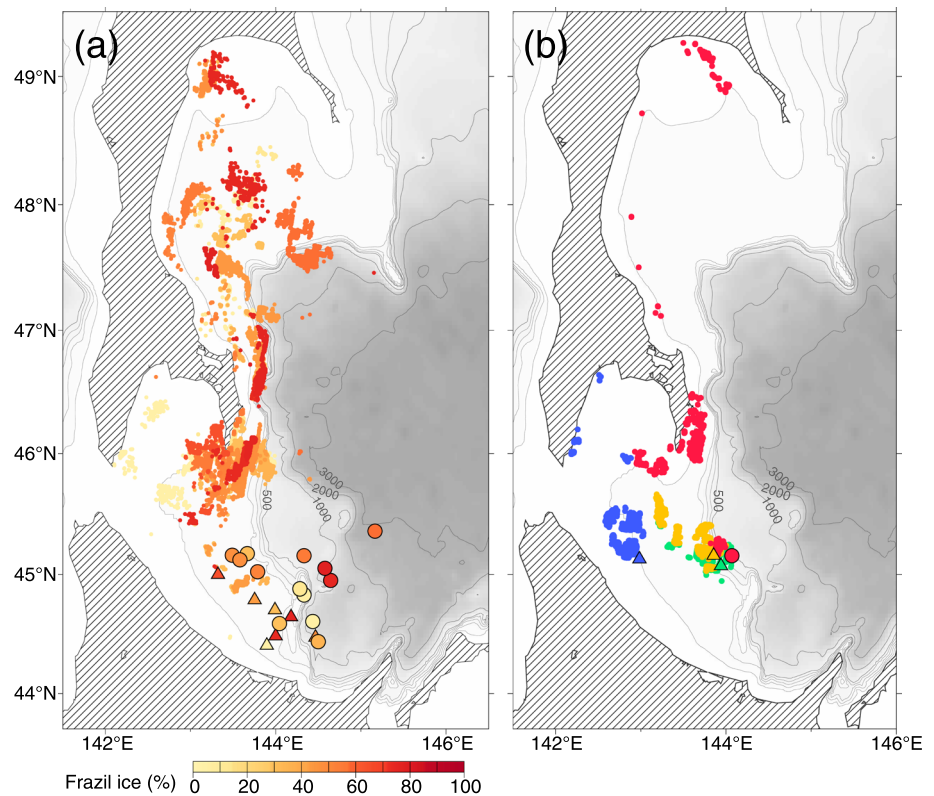


Fig. 6 Time series of sea ice production and the number of ice particles that are judged to be formed in the three polynya areas with depths of < 150 m for five cases of the NCP estimation (a–e). Sea ice production is indicated by black lines and the particle numbers are

plotted as colored bars. The map in the right shows locations of the three polynya areas, Terpenia Bay polynya (red), Southern Sakhalin polynya (blue), and Northern Sakhalin polynya (purple) (color figure online)

Fig. 7 **a** Distribution of origin location of the sampled sea ice for which the frazil ice fraction was analyzed. The sampling locations at which at least one of the sea ice particles originated in Terpenia Bay are indicated by large circles, and the other sampling locations are indicated by triangles. The color indicates the frazil ice fraction of the sampled ice. **b** Distribution of the origin location of sampled sea ice for which the iron concentration was measured. The four cases [Table 2, (K1–4)] are distinguished by color. The symbols of the sampling locations are the same as those of (a) (color figure online)



is transported to the Soya observation area (southwestern part of the Sea of Okhotsk).

In Fig. 7, the samples that have possibility of originating from Terpenia Bay are indicated by large circles, and other samples are indicated by triangles. Regarding the sea ice samples collected over the shelf with depths shallower than about 500 m are likely formed over the shelf around the southern tip of Sakhalin Island, whereas the samples taken over the shelf slope with depth deeper than about 500 m are likely transported from the northern area up to Terpenia Bay but not further north.

4 Discussion

Based on the NCP estimation by the oxygen increase from the profiling floats, Kishi et al. (2021) showed that the sea-ice melt enhances the NCP and, thus, can be a key factor for the prominent spring phytoplankton bloom in the southern part of the Sea of Okhotsk. From the backward-tracking simulations for the sea ice in the NCP-estimated areas, we further surmised that the melting of coastal-origin sea ice, which can incorporate sedimentary particles, induces higher NCP. This surmise strongly supports the hypothesis that material transport by sea ice plays an important role in the

biological production of spring phytoplankton blooms in the Sea of Okhotsk.

Many sea ice samples have been collected by the ice-breaker Soya and analyzed for their structure and the contained materials (Toyota et al. 2004, 2007; Nomura et al. 2010; Kanna et al. 2014, 2018). However, origins of the sea ice have not been clarified, which hampers understanding of formation and material incorporation of sea ice in the Sea of Okhotsk. This study is the first attempt to infer the origin of the sea ice samples collected by the Soya observation. The backward-tracking simulations suggested that the ice samples collected over the shelf forms around the southern tip of Sakhalin Island, whereas samples taken over the shelf slope are transported from the northern area up to Terpenia Bay. These findings provide insights useful for clarifying the origin of the materials contained in previously sampled sea ice. To examine the sea ice that could incorporate the sediment/iron in the high ice production area, the ice sampling in the shelf slope region is recommended in the future Soya observation.

It is demonstrated that the ice drift velocity derived from the satellite data cannot be used directly for the backward tracking of the sea ice that originates in coastal areas (Fig. 2). The approach described in this study makes it possible to trace the sea ice back and infer its origin in

coastal areas with some accuracy through the combined use of the wind-estimated drift velocity and inclusion of the enhancement ratio representing the ice drift by coastal currents.

However, some uncertainties remain regarding the estimation of sea ice origin in this study. One uncertainty arises from the uncertainty of drift velocity data. For the areas within 200 km of the coast, we used the enhanced ratio to represent the ocean current component. This method is not sufficiently accurate especially for regions of strong current and complex bottom topography. Near the coast with a shallower depth, the ocean current tends to be stronger and, thus, influences the ice drift strongly (Simizu et al. 2014). In addition, the complex bottom topography of the shelf off the Hokkaido coast and the southern part of Sakhalin Island complicates the current. Therefore, the origin of the sea ice sampled in the coastal areas might not be correctly estimated due to the higher uncertainty of the ocean current component of the drift velocity. Furthermore, the deformation of sea ice due to internal stress becomes larger near the coast. For more accurate tracking of coastal sea ice drift, improvements are needed such as using high-resolution satellite data (i.e., Moderate Resolution Imaging Spectroradiometer) and incorporation of the ocean drift component from a high-resolution ocean model.

The other uncertainty arises from the determination of the ice origin on the tracked paths, because there is arbitrary to some extent. In this study, the location with the largest sea ice production along the tracked path is judged to be the origin of formation. However, sea ice could form at all of the locations with a certain value of sea ice production along the tracked path. To test the sensitivity of the estimated locations of sea ice origin to the determination, we also estimated the distribution of the origins of the sea ice to be the location with a certain ice production (judged as a thin ice pixel with negative heat budget) closest to the end of the tracking. The results (not shown) did not substantially change the conclusions described above. We, therefore, consider that our method can, to some extent, simulate the origin of sea ice. According to our backward-tracking simulations sea ice that induces high biological production in the southern Sea of Okhotsk mostly originates from coastal high ice production areas, where sediment can be incorporated into sea ice.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10872-023-00706-4>.

Acknowledgements This work was supported by Grants-in-Aids for Scientific Research (17H01157 and 20H05707) and Arctic Challenge for Sustainability II (ArCS II) from the Ministry of Education, Culture, Sports, Science and Technology in Japan. This work was also supported by a research fund for Global Change Observation Mission Water 1 (GCOM-W1) of the Japan Aerospace Exploration Agency

(JAXA) (PI No. ER2GWF404 and ER3AMF424). The figures were produced with the Generic Mapping Tools (GMT) and gnuplot.

Data availability The authors declare that all data supporting the findings of this study are available within the article and its supplementary information files.

References

- Ito M, Ohshima KI, Fukamachi Y, Mizuta G, Kusumoto Y, Nishioka J (2017) Observations of frazil ice formation and upward sediment transport in the Sea of Okhotsk: a possible mechanism of iron supply to sea ice. *J Geophys Res Oceans* 122:788–802. <https://doi.org/10.1002/2016JC012198>
- Ito M, Ohshima KI, Fukamachi Y, Mizuta G, Kusumoto Y, Kikuchi T (2021) Underwater frazil ice and its suspension depth detected from ADCP backscatter data around sea ice edge in the Sea of Okhotsk. *Cold Reg Sci Technol* 192:103382. <https://doi.org/10.1016/j.coldregions.2021.103382>
- Kanna N, Toyota T, Nishioka J (2014) Iron and macro-nutrient concentrations in sea ice and their impact on the nutritional status of surface waters in the southern Okhotsk Sea. *Prog Oceanogr* 126:44–57. <https://doi.org/10.1016/j.pocean.2014.04.012>
- Kanna N, Sibano Y, Toyota T, Nishioka J (2018) Winter iron supply processes fueling spring phytoplankton growth in a sub-polar marginal sea, the Sea of Okhotsk: importance of sea ice and the East Sakhalin Current. *Mar Chem* 206:109–120. <https://doi.org/10.1016/j.marchem.2018.08.006>
- Kasai H, Nakano Y, Ono T, Tsuda A (2010) Seasonal change of oceanographic conditions and chlorophyll a vertical distribution in the southwestern Okhotsk Sea during the non-iced season. *J Oceanogr* 66:13–26. <https://doi.org/10.1007/s10872-010-0002-3>
- Kimura N, Nishimura A, Tanaka Y, Yamaguchi H (2013) Influence of winter sea-ice motion on summer ice cover in the Arctic. *Polar Res* 32:20193. <https://doi.org/10.3402/polar.v32i0.20193>
- Kishi S, Ohshima KI, Nishioka J, Isshiki N, Nishashi S, Riser SC (2021) The prominent spring bloom and its relation to sea-ice melt in the Sea of Okhotsk, revealed by profiling floats. *Geophys Res Lett* 48:e2020GL091394. <https://doi.org/10.1029/2020GL091394>
- Kuga M, Ohshima KI, Kimura N, Nakata K, Fukamachi Y (2023) Particle-tracking experiments of coastal-origin sea ice that could induce high biological productivity in the Sea of Okhotsk. *J Oceanogr* 79:145–159. <https://doi.org/10.1007/s10872-022-00670-5>
- Mustapha MA, Saitoh S (2008) Observations of sea ice interannual variations and spring bloom occurrences at the Japanese scallop farming area in the Okhotsk Sea using satellite imagery. *Est Coast Shelf Sci* 77:577–588. <https://doi.org/10.1016/j.ecss.2007.10.021>
- Nakata K, Ohshima KI (2022) Mapping of active frazil and sea ice production in the Northern Hemisphere, with comparison to the Southern Hemisphere. *J Geophys Res Oceans* 127:e2022JC018553. <https://doi.org/10.1029/2022JC018553>
- Nakata K, Ohshima KI, Nishashi S (2019) Estimation of thin-ice thickness and discrimination of ice type from AMSR-E passive microwave data. *IEEE Trans Geosci Remote Sens* 57:263–276. <https://doi.org/10.1109/TGRS.2018.2853590>
- Nakayama Y, Ohshima KI, Fukamachi Y (2012) Enhancement of sea ice drift due to the dynamical interaction between sea ice and a coastal ocean. *J Phys Oceanogr* 42:179–192. <https://doi.org/10.1175/JPO-D-11-018.1>

- Niebauer HJ, Alexander V, Henrichs SM (1995) A time-series study of the spring bloom at the Bering Sea ice edge I. Physical processes, chlorophyll and nutrient chemistry. *Cont Shelf Res* 15:1859–1877. [https://doi.org/10.1016/0278-4343\(94\)00097-7](https://doi.org/10.1016/0278-4343(94)00097-7)
- Nishioka J, Nakatsuka T, Ono K, Volkov YN, Scherbinin A, Shiraiwa T (2014) Quantitative evaluation of iron transport processes in the Sea of Okhotsk. *Prog Oceanogr* 126:180–193. <https://doi.org/10.1016/j.pocean.2014.04.011>
- Nomura D, Nishioka J, Granskog MA, Krell A, Matoba S, Toyota T, Hattori H, Shirasawa K (2010) Nutrient distributions associated with snow and sediment-laden layers in sea ice of the southern Sea of Okhotsk. *Mar Chem* 119:1–8. <https://doi.org/10.1016/j.marchem.2009.11.005>
- Ohshima KI, Riser SC, Wakatsuchi M (2005) Mixed layer evolution in the Sea of Okhotsk observed with profiling floats and its relation to sea ice formation. *Geophys Res Lett* 32:L06607. <https://doi.org/10.1029/2004GL021823>
- Ohshima KI, Fukamachi Y, Ito M, Nakata K, Simizu D, Ono K, Nomura D, Hashida G, Tamura T (2022) Dominant frazil ice production in the Cape Darnley polynya leading to Antarctic Bottom Water formation. *Sci Adv* 8:eadc9174. <https://doi.org/10.1126/sciadv.adc9174>
- Simizu D, Ohshima KI, Ono J, Fukamachi Y, Mizuta G (2014) What drives the southward drift of sea ice in the Sea of Okhotsk? *Prog Oceanogr* 126:33–43. <https://doi.org/10.1016/j.pocean.2014.05.013>
- Sorokin YI, Sorokin PY (1999) Production in the Sea of Okhotsk. *J Plankton Res* 21:201–230
- Toyota T, Kawamura T, Ohshima KI, Shimoda H, Wakatsuchi M (2004) Thickness distribution, texture and stratigraphy, and a simple probabilistic model for dynamical thickening of sea ice in the southern Sea of Okhotsk. *J Geophys Res* 109:C06001. <https://doi.org/10.1029/2003JC002090>
- Toyota T, Takatsuji S, Tateyama K, Naoki K, Ohshima KI (2007) Properties of sea ice and overlying snow in the Southern Sea of Okhotsk. *J Oceanogr* 63:393–411. <https://doi.org/10.1007/s10872-007-0037-2>
- Toyota T, Kimura N, Nishioka J, Ito M, Nomura D, Mitsudera H (2022) The Interannual variability of sea ice area, thickness, and volume in the southern Sea of Okhotsk and its likely factors. *J Geophys Res Oceans* 127:e2022JC019069. <https://doi.org/10.1029/2022JC019069>
- Tsuda A, Takeda S, Saito H, Nishioka J, Nojiri Y, Kudo I, Kiyosawa H, Shiimoto A, Imai K, Ono T, Shimamoto A, Tsumune D, Yoshimura T, Aono T, Hinuma A, Kinugasa M, Suzuki K, Sohrin Y, Noiri Y, Tani H, Deguchi Y, Tsurushima N, Ogawa H, Fukami K, Kuma K, Saino T (2003) A mesoscale iron enrichment in the western subarctic Pacific induces a large centric diatom bloom. *Science* 300:958–961. <https://doi.org/10.1126/science.1082000>
- Wilson DL, Smith WO, Nelson DM (1986) Phytoplankton bloom dynamics of the western Ross Sea ice edge-I. Primary productivity and species-specific production. *Deep Sea Res Part A* 33:1375–1387. [https://doi.org/10.1016/0198-0149\(86\)90041-5](https://doi.org/10.1016/0198-0149(86)90041-5)
- Yan D, Yoshida K, Nishioka J, Ito M, Toyota T, Suzuki K (2020) Response to sea ice melt indicates high seeding potential of the ice diatom *Thalassiosira* to spring phytoplankton blooms: a laboratory study on an ice algal community from the Sea of Okhotsk. *Front Mar Sci* 7:613. <https://doi.org/10.3389/fmars.2020.00613>
- Yan D, Nishioka J, Toyota T, Suzuki K (2022) Winter microalgal communities of the southern Sea of Okhotsk: a comparison of sea ice, coastal, and basinal seawater. *Prog Oceanogr* 204:102806. <https://doi.org/10.1016/j.pocean.2022.102806>

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.