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2 Sea-ice dynamics in an Arctic coastal polynya during the past 3 6500 years

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8 **Abstract** The production of high-salinity brines during
9 sea-ice freezing in circum-arctic coastal polynyas is
10 thought to be part of northern deep water formation as it
11 supplies additional dense waters to the Atlantic meridional
12 overturning circulation system. To better predict the effect
13 of possible future summer ice-free conditions in the Arctic
14 Ocean on global climate, it is important to improve our
15 understanding of how climate change has affected sea-ice
16 and brine formation, and thus finally dense water formation
17 during the past. Here, we show temporal coherence
18 between sea-ice conditions in a key Arctic polynya (Stor-
19 fjorden, Svalbard) and patterns of deep water convection in
20 the neighbouring Nordic Seas over the last 6500 years. A
21 period of frequent sea-ice melting and freezing between 6.5
22 and 2.8 ka BP coincided with enhanced deep water
23 renewal, while near-permanent sea-ice cover and low brine
24 rejection after 2.8 ka BP likely reduced the overflow of
25 high-salinity shelf waters, concomitant with a gradual slow
26 down of deep water convection in the Nordic Seas, which
27 occurred along with a regional expansion in sea-ice and
28 surface water freshening. The Storfjorden polynya sea-ice
29 factory restarted at ~0.5 ka BP, coincident with renewed
30 deep water penetration to the Arctic and climate

amelioration over Svalbard. The identified synergy
between Arctic polynya sea-ice conditions and deep water
convection during the present interglacial is an indication
of the potential consequences for ocean ventilation during
states with permanent sea-ice cover or future Arctic ice-
free conditions.

Keywords Arctic · Storfjorden · Polynya · Holocene · Sea
ice

Introduction

The sinking of dense waters on Arctic and Antarctic
shelves through recurrent cooling and rejection of salt
during sea-ice growth is a key contributor to global ocean
circulation [24] with 10% of contemporary deep waters
formed in the Arctic Ocean and the Barents Sea derived
from these brine-enriched shelf waters [32]. High sea-ice
production in Arctic coastal polynyas facilitates dense
water production and ocean stratification, thus inhibiting
the upward mixing of warm Atlantic water and sea-ice melt
[1]. Coastal polynyas are persistent and recurrent areas of
open water that occur within locations of otherwise con-
solidated and thicker ice cover. Amongst these, the Stor-
fjorden coastal polynya in southern Spitsbergen (Fig. 1) is
known to be an important sea-ice factory [19] and a sig-
nificant source of brine rejection [32]. Dense brine-en-
riched waters from Storfjorden cascade downslope before
flowing north [41], where they descend to depths of more
than 2000 m [23] and account for up to 15% of the total
dense water generated in the entire Arctic [13, 43]. How-
ever, this has likely changed in the past either as a con-
tributor to, or because of climate change at high latitudes.
Indeed, millennial-scale reconstruction of past brine

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Fig. 1 Study area and investigated marine sediment surface, floodplain and core samples. Major oceanographic features and the maximum sea ice extent are indicated. *Inset* shows outline of

Storfjorden Polynya (grey shaded) superimposed on the geology of Svalbard. Arsenic concentrations (ppm) in both floodplain sediments onshore and marine surface sediments are shown

formation in the Storfjorden polynya based on the sedimentary distribution of calcareous and agglutinated benthic foraminifera has revealed a systematic pattern of high

(low) intensities during cold (warm) climate periods over the last 15,000 years [34, 35]. In contrast, large annual variability in brine formation has also been observed

during the most recent warm periods during the last century. Thus, reduced brine formation, and hence, strongly reduced export of dense water to the Arctic Ocean occurred during periods with exceptionally warm Atlantic water advection and reduced sea-ice coverage in the Barents Sea, while intense brine formation was re-established during periods of recurrent cooling [58]. Accordingly, since the process of brine rejection is largely dependent on the seasonal formation of sea-ice, past reconstruction of sea-ice coverage coupled with environmental inferences from benthic foraminifera assemblages in the Storfjorden polynya [34, 35] provides a more direct indication of past brine formation, and thus potentially, a new measure for evaluating the significance of Arctic coastal polynyas with respect to dense water formation on a glacial-interglacial timescale. This approach provides an alternative to the still disputed use of benthic foraminiferal stable isotope records as a measure of the influence of brine-enriched shelf waters on deep water production [15, 28, 33]. In this study, we combine down-core records of organic geochemical biomarkers of sea-ice variability (IP₂₅) [8] and open water phytoplankton (brassicasterol) with source-specific, sea-ice derived terrigenous sediments, supplemented by published agglutinated foraminifera (% of total benthic foraminifera) [34, 35]. We hereby present evidence that changes in sea-ice coverage and inferred brine formation in the Storfjorden polynya over the past 6500 years coincide with past variability in deep water renewal in the Nordic Seas. As such, we highlight the importance of Arctic coastal polynyas as one significant driver of deep water renewal processes during the present interglacial.

100 **AQ7** Regional setting

101 Storfjorden, in southeastern Spitsbergen, is a ca. 200-km-long inlet, separated from the open ocean by a shallow sill (102 ~120 m). Surface waters are seasonally stratified, with 103 sea-ice and brine formation taking place each winter in the 104 inner fjord [41]. Strong northeasterly winds blow sea-ice 105 away from the eastern shelf, producing a large latent heat 106 polynya, where high sea-ice production and continuous 107 freezing generates cold (<−1.9 °C) and salty (34.8 to 108 >35.8 psu) water [19, 43], which sinks and fills the central 109 basin, finally overflowing the sill. Depending on its salinity 110 (34.3–35.3 psu) [43], the brine may continue downslope 111 reaching 2000 m into the deep-intermediate water of the 112 Greenland Sea [23, 32]. Surface currents in Storfjorden are 113 controlled by southwestward flowing, ice-covered polar 114 waters from the Arctic Ocean. The East Spitsbergen Cur- 115 rent (ESC) balances the bottom currents that transport the 116 dense water out of Storfjorden towards the deep ocean. 117 Sediments deposited in Storfjorden are enriched in organic 118

carbon (up to 2.4 wt%) and largely dominated by terrige- 119 nous derived organic matter [56]. Terrigenous sediments 120 are largely supplied by local (fast) ice entrainment pro- 121 cesses and episodic freezing/melting processes in the 122 polynya. Alternatively, terrigenous sediments transported 123 by polar surface waters (ESC) to Storfjorden are released 124 during frequent melting episodes and are deposited in 125 Storfjorden [56]. 126

Materials and methods 127

We studied inorganic elements and organic biomarkers in 128 sediment surface samples (0–1 cm) taken with multicorer 129 equipment from the western Barents Sea (Fig. 1; Table 1) 130 and a gravity core JM10-10GC (77.41°N, 20.10°E, 123 m 131 water depth, hereafter referred to as JM10), taken within 132 the Storfjorden polynya where brines form today (Fig. 1). 133 The surface samples were sliced onboard, frozen, and 134 subsequently freeze-dried prior to analysis. 135

Inorganic geochemistry 136

All surface samples were analysed for major and trace 137 elements using a Philips PW 1480 WD XRF instrument 138 equipped with an Rh X-ray tube. For XRF major elements 139 about 2 g of finely ground sample was preheated over a gas 140 burner to remove any organic material before pre-ignition 141 at 1000 ± 50 °C for at least 1 h. 4.200 ± 0.005 g Li₂B₄O₇ 142 (Claisse, Quebec, Canada) is mixed with 0.600 ± 0.005 g 143 pre-ignited sample and fused to glass beads in Pt—5% Au- 144 crucible. The method for determination of trace element 145 with XRF is based on pressed pellets. 1.2 ± 0.005 g 146 Hoechst wax was mixed with 5.4 ± 0.005 g dried and fine- 147 ground sample material in a Spex Mixer/Mill for at least 148 1 min. The mixture was pressed to a pellet in a Herzog 149 pelletizing press, with an applied force around 20 kN for 150 20 s. Methods accuracy for arsenic (As) and aluminium 151 (Al) was tested with several certified reference materials 152 (CRM), as shown in Tables 2 and 3. Relative percent dif- 153 ference between the duplicate samples was within ±10%. 154 Al-normalisation was applied for As data in core JM10 to 155 avoid dilution due to variable sedimentation rates 156 (19–104 cm/ka) in the record [34]. A correlation coeffi- 157 cient $R^2 = 0.88$ between As/Al ratio and As concentrations 158 (ppm) in core JM10 indicate no dilution effects on the As 159 concentrations in the sediments. 160

Concentration of leachable elements in the same sample 161 set was measured by ICP-AES with the instrument Perk- 162 inElmer 4300 DV. Nitric acid extraction was used to 163 estimate the amounts of As and Al present in the nonsili- 164 cate fraction of the sediment in all surface sediments and 165 core JM10. 1.000 ± 0.001 g of freeze-dried sediment was 166

Table 1 Inorganic geochemical data from Barents Sea surface sediments

Station ID	Latitude	Longitude	Water depth (m)	As (ppm)		Al (ppm)		Mn (ppm)		Fe (ppm)	
				ICP-AES	XRF	ICP-AES	XRF	ICP-AES	XRF	ICP-AES	XRF
623	71.05	21.65	166	13	6	20,200	62,768	933	929	31,300	33,573
627	72.32	24.06	264	4	6	13,100	54353	435	620	17,500	24,690
629	73.01	24.25	404	5	14	19,700	66949	704	1084	25,600	38050
631	73.67	24.47	451	9	10	22,400	68,907	483	620	32300	39,449
633	74.34	24.69	373	22	26	13700	57,264	471	465	29,000	36,931
635	75.00	24.94	182	12	16	17,200	60,016	204	232	25,100	29,866
639	75.57	27.90	263	19	23	22,700	71,236	277	310	33,800	40,148
643	76.49	29.91	291	7	9	22,600	72,294	190	232	29,400	36,581
645	75.86	29.46	296	25	23	18,200	67,372	163	232	33,900	39,309
647	75.20	29.01	343	14	28	19,600	72,241	277	465	29,000	44,345
649	74.54	28.58	394	22	27	20,700	64,885	543	697	32,700	39,239
651	74.64	26.08	317	18	29	20,100	64,461	745	929	32,500	38,959
653	73.97	25.81	441	9	11	22,700	73,512	251	310	32,000	40,008
655	73.31	25.54	412	10	15	19,800	67,319	539	697	30,300	38,190
657	72.64	25.27	268	6	10	11,000	54,035	261	387	16,500	24,341
659	71.98	25.06	256	2	5	9730	49,325	245	387	13,400	20,144
661	71.37	22.76	408	3	5	19,400	64,779	421	620	25,300	35,322
663	71.61	25.99	291	1	3	6560	42,392	187	387	9480	15,808
665	72.17	28.41	289	3	6	12,600	56,629	193	310	16,800	24,830
667	72.84	28.76	305	11	13	13,300	54,618	336	387	23,100	27,278
669	73.50	29.15	414	8	11	19,600	67,478	375	465	28,700	36,022
671	74.15	29.55	366	13	21	22,600	73,194	330	387	35,100	43,925
673	74.67	32.49	165	20	19	11,300	50,595	198	232	23,900	27,488
675	75.33	33.07	209	18	58	15,700	52,395	199	232	31,700	28,118
677	75.97	33.73	276	14	21	22,900	78,433	193	232	31,400	38,959
679	76.62	34.45	193	105	157	20,100	65,097	523	620	58,400	75,261
681	76.43	37.17	249	13	15	11,000	59,645	102	155	18,100	22,802
690	71.02	30.96	283	8	8	23,200	64,938	354	465	27,200	35,462
692	70.62	31.72	252	2	5	7280	45,885	190	232	10,900	17,556
St.1.	72.00	22.00	367	6	7	19,300	61,762	604	852	24,700	32,454
St.2.	72.02	20.92	371	7	8	21,900	63,932	1040	1317	28,300	35,532
St.3.	72.03	19.85	324	9	11	18800	50,966	725	929	23,000	29,377
St.4.	72.02	18.77	315	9	12	17,200	47,208	770	1084	20,700	27,348
St.5.	72.03	17.70	296	8	7	13,200	45,250	668	929	17,500	23,991
St.6.	72.02	16.62	362	8	3	9300	41,757	366	542	14,500	20,844
St.7.	72.02	15.52	767	10	12	8390	43,345	369	620	15,900	24,551
St.8.	72.01	14.73	1260	7	fi	18,000	65,573	336	465	25,700	33,084
St.9.	72.01	14.62	1317	7	6	13,500	51,707	873	1239	17000	25,740
St.11.	73.17	12.94	1499	8	6	14,600	46,467	854	1162	18,300	24,760
St.12.	73.17	14.09	1030	5	3	10,300	44,668	555	852	13,600	22,312
St.13.	73.17	15.23	485	8	11	8800	48,426	386	542	12,900	18,815
St.14.	73.17	16.38	475	8	11	12,500	54,088	434	542	18,000	24,411
St.15.	73.17	17.54	460	9	12	14,300	54,935	459	542	21,300	26,229
St.16.	73.17	18.82	423	16	18	12,700	52,977	421	542	21,900	26,929
St.17.	73.17	19.86	441	7	8	14,400	55,941	350	465	20,500	25,949
St.18.	73.17	20.95	463	12	15	17,900	62,768	642	774	27,000	33,713
St.19.	73.17	22.01	444	15	21	18,300	62,662	938	1084	27,900	34,832

Table 1 continued

Station ID	Latitude	Longitude	Water depth (m)	As (ppm)		Al (ppm)		Mn (ppm)		Fe (ppm)	
				ICP-AES	XRF	ICP-AES	XRF	ICP-AES	XRF	ICP-AES	XRF
St.20.	74.82	18.02	296	18	25	11,100	41,969	326	387	20,900	25,810
St. 21.	74.82	17.00	280	7	7	8120	35,353	212	310	14,700	18,465
St. 22.	74.82	16.03	356	8	7	10,100	42,763	275	387	16,900	20,354
St.23.	74.82	14.79	1507	9	10	19,200	52,448	1120	1471	23,600	30,636
St.24.	75.64	12.92	1500	10	14	18,900	51,971	1260	1626	24,000	31,055
St.25.	75.75	13.84	807	18	20	13,100	54,512	518	697	24,300	30,426
St.26.	75.83	14.77	370	18	25	19,200	66,949	800	929	31,600	36,511
St.27.	75.95	15.72	369	45	59	21,500	71,236	3650	4337	42,300	49,031
St.28.	76.05	16.67	328	21	25	17,200	63,509	942	1084	31,300	36,441
St.29.	76.16	17.62	309	45	57	20,500	67,108	1340	1549	40,200	44,625
St.30.	76.22	18.58	257	31	33	20,200	67,849	577	697	36,800	41,058
St.31.	76.31	19.57	258	53	66	19,400	70,019	2160	2556	42,100	49,801
St.32.	76.38	20.58	228	54	68	19,600	69,278	787	929	44,000	48,891
St.33.	76.47	21.60	262	91	117	20,200	71,447	1050	1239	46,900	53,927
St.34.	71.75	22.00	356	4	3	18,800	61,127	504	697	24,200	32,804
St.35.	71.62	21.07	319	5	6	13,900	51,813	490	697	17,800	24,970
St.36.	71.60	20.86	320	7	7	14,400	48,902	646	852	18,800	25,390
St.37.	71.60	21.19	335	5	6	14,300	53,347	464	620	18,600	25,460
St.38.	71.49	20.82	310	6	3	15,800	46,520	651	929	19,700	25,880
St.39.	71.34	20.19	234	5	5	13,800	39,958	695	1007	16,900	23,431
St.40.	71.18	19.56	225	6	3	12,700	39,111	718	1007	15,700	21,963
St.41.	71.03	18.95	199	1	3	6390	35,830	266	465	9060	15,598
St.42.	70.87	18.34	173	3	3	5860	23,657	219	387	8090	13,499
St.43.	70.72	17.75	273	7	5	11,300	41,651	606	929	14,700	22,382
St.44.	70.55	17.14	706	3	7	7290	39,746	274	620	9690	19,794
St.45.	70.44	16.75	1500	6	7	9350	53,136	517	929	14,000	26,859

Table 2 Methods accuracy for measuring As by XRF

Parameter	UB-N	MESS-1	JLK-1
Sample type	Serpentine	Marine sediment	Lake sediment
Average, three replicates, mg/kg	10.94	7.9	26.91
Standard deviation, three replicates, mg/kg	2.5	0.77	3.43
%RSD	23.20%	9.80%	12.80%
Certified value, mg/kg	10 ^a	10.6	27.7
Uncertainty, mg/kg	4.22	1.2	
References GeoReM	GeoReM 149	GeoReM 5021	
Bias, mg/kg	0.94	−2.7	−0.79
Relative bias	9.40%	−25.50%	−2.90%

^a Compiled value

167 digested with 20 ml 7 M HNO₃ for 30 min at 120 ± 4 °C
 168 in autoclave (CertoClav Sterilizer, CV-EL 18LGS), fol-
 169 lowing the procedure described in the Norwegian Standard
 170 NS 4770 from 1994. After cooling, the sample was filtered
 171 through Whatman grade 597 and further diluted. The
 172 analysed solution contains 10 ppm Rh as internal standard

and about 10% HNO₃ (v/v). Method quantification limits,
 respectively, 20 mg/kg Al and 2 mg/kg As, is based on ten
 times the standard deviation for ten replicates of method
 blanks. Relative percent difference between the duplicate
 samples was within ±10%. Certified reference material
 Mess-3 (marine sediment for trace elements and other

Table 3 Methods accuracy for measuring Al by XRF

Parameter	PACS-1	MESS-1	JLK-1
Sample type	Marine sediment	Marine sediment	Lake sediment
Measured, %	12.06	12.05	16.77
Certified value, %	12.23	11.03 ^a	16.73
Uncertainty, %	0.22	0.38	0.184
References GeoReM (Jochum et al. 2005)	GeoReM 5021	GeoReM 5021	GeoReM 659
Bias, mg/kg	−0.17	1.03	−0.04
Relative bias	−1.37%	9.26%	−0.23%

^a Compiled value

constituents, NRC-CNRC Canada) was routinely analysed to test methods analytical performance. The correlation coefficients between XRF and ICP-AES based arsenic and aluminium concentrations of 73 surface samples is $r^2 = 0.95$ and 0.75 , respectively. Arsenic concentrations in the remaining text are based on the ICP-AES extraction method to allow comparison with published As concentration in floodplain and overbank deposits from Spitsbergen [31] (Fig. 1).

Biomarkers

The biomarkers IP₂₅ [8] and brassicasterol were quantified following addition of internal standards (9-octylheptadec-8-ene, 10 μL ; 10 $\mu\text{g mL}^{-1}$; 5 α -androstan-3 β -ol, 10 μL ; 10 $\mu\text{g mL}^{-1}$, respectively), extraction (DCM/Methanol; 3 $\times$ 3 mL, 2:1 v/v) and purification of extracts using silica column chromatography (IP₂₅: hexane, 6 mL; brassicasterol: 20:80 methylacetate/hexane, 6 mL). Further purification of the IP₂₅ containing fraction was achieved by Ag-ion chromatography (Supelco discovery Ag-Ion; 0.1 g) with saturated hydrocarbons (hexane; 1 mL) and unsaturated hydrocarbons (including IP₂₅: acetone; 2 mL) eluted as two single fractions. All partially purified fractions were analysed using gas chromatography–mass spectrometry (GC–MS) according to established methods [5]. Brassicasterol was derivatized (BSTFA; 50 μL , 70 $^{\circ}\text{C}$, 1 h) prior to analysis by GC–MS.

Chronology

The chronology of the upper 325 cm of JM10 is based on 7 AMS ^{14}C radiocarbon dates obtained on bivalves and monospecific samples of the benthic foraminiferal species *N. labradorica* (Table 4) (see details in [35]). All AMS ^{14}C dates were calibrated to calendar ages by applying the Calib7.02 programs [45] and the Marine13 calibration curve [38]. The applied age model is consistent with the published model of Rasmussen and Thomsen [35]. The sedimentation rates vary between 19 and 104 cm/ka, with highest values (104 cm/ka) in the upper part of the

sediment cores (~ 1.0 – 0.5 ka BP), and lowest values (19 cm/ka) between ~ 2.8 and ~ 1.0 ka BP. Moreover, sedimentation rates in the lowermost part of the record (2.8 to ~ 6.5 ka BP) vary between 49 and 76 cm/ka. The quality of the dated material was checked by measuring bivalves and *N. labradorica* in two different samples within the same depth interval (324–326 cm). The dates are identical within error (Table 4), excluding the possibility of re-deposition of the bivalves in this environmental setting. However, we caution the reader that the observed changes in sedimentation rates between 2.8 and 1.0 ka BP are based on dating results from bivalves only, due to the lack of sufficient planktic or benthic foraminifera in this interval.

Results and discussion

Proxies for sea-ice dynamics

To interpret our down-core record, we first provide the background to our combined proxy data by presenting measurements obtained from surface sediments that reflect the modern physico-geography of the region. Arsenic (As) concentration in near-shore unpolluted marine sediments is normally between 5 and 10 ppm [52]. Sedimentary arsenic is principally associated with sesquioxide material (mostly hydrous iron oxides) as shown by a positive correlation between As and Fe ($r^2 = 0.65$). Arsenic concentration in our Barents Sea surface sediments varies between 2 and 105 ppm, with a clear geographical boundary along the Marginal Ice Zone (MIZ) (Fig. 2). South of the MIZ, the mean As concentration (7 ppm) resembles values in uncontaminated soils from northern Scandinavia [37], while for sites north of the MIZ, a mean concentration of 27 ppm is significantly higher than the global average for coastal marine sediments (5–10 ppm; [52]). The enrichment in the northern sediments is, however, probably not related to diagenetic redox-cycling processes seen in other shelf environments [46] since As anomalies are not correlated with other redox-sensitive elements such as Mn ($r^2 < 0.2$). Instead, it is more likely that natural sources of

Table 4 AMS¹⁴C dates and calibrated dates for core JM10-10GC as published by Rasmussen and Thomsen [34, 35]

Core ID	Depth (cm)	14C Age	Calendar age	Lab. code	Species
JM10-10GC	44.5	832 ± 21	473 ± 20	UB-17204	<i>Nucula</i> sp.
JM10-10GC	102.5	1491 ± 22	1029 ± 43	UB-17205	<i>Nuculana</i> sp.
JM10-10GC	136.5	3008 ± 27	2770 ± 32	UB-17206	<i>Astarte</i> sp.
JM10-10GC	210.5	4182 ± 41	4278 ± 73	UB-18845	<i>N. labradorica</i>
JM10-10GC	250.5	4573 ± 28	4805 ± 34	UB-18946	<i>N. labradorica</i>
JM10-10GC	324–326	6065 ± 31	6482 ± 49	UB-17207	<i>Bivalve</i>
JM10-10GC	325	5990 ± 43	6398 ± 57	UB-21198	<i>N. labradorica</i>

Fig. 2 Proxy data for modern sea-ice variability in the Barents Sea. *Left* Arsenic concentration (As in ppm) in Barents Sea surface samples. *Right* Sea-ice biomarker IP₂₅ concentration in Barents Sea surface samples [30]. Storfjorden Polynya (stippled polygon), studied core position JM10 (green square), maximum of marginal ice zone (MIZ) (black line) and the Barents Sea polar front (stippled line) are indicated

As-rich deposits and dissolved As in the water column are the causes of the sedimentary enhancements. As-rich sediments are most likely transported by sea-ice and released along the MIZ [21], while dissolved As can be taken up by phytoplankton blooms in the MIZ, and thus incorporated into the sedimentary cycle [10]. Indeed, local As anomalies are reported from Paleogene sequences, SW Spitsbergen (Fig. 1) [31] and As concentrations as high as 225 ppm have been recorded in coal seams interbedded with marine and lacustrine siltstones and shales [22]. Arsenic anomalies (>50 ppm) also occur in nearby floodplain sediments sourced from Carboniferous-Cretaceous organic-rich deposits along the coastline adjacent to Storfjorden (Fig. 1) [31]. Coastal freezing processes along the shoreline or within coastal polynyas [16] allow entrainment of As-enriched sediments in sea-ice with subsequent release during melt within the MIZ. Other As anomalies in sediments are reported from the Laptev Sea and Kara Sea shelves [21, 26, 27], where incorporation of As-enriched particles in newly formed sea-ice and transportation within the

Transpolar Drift and East Spitsbergen Current may have caused the As anomalies identified below the MIZ in the northwestern Barents Sea (Fig. 2). Hence, we use the As anomalies in the sedimentary record as evidence for newly formed sea-ice that allowed incorporation of terrigenous (As-rich) particles in coastal areas, and subsequent sea-ice melting and release of As-rich ice-rafted sediments within the MIZ. To complement the As data, we also measured the distribution of the organic geochemical sea-ice proxy IP₂₅ in the same surface sediments. IP₂₅ is a highly specific lipid biosynthesized by certain diatoms residing in the underside of seasonal Arctic sea-ice [11] and whose presence and abundance in sediments is strongly associated with overlying sea-ice cover [6, 8], including the Barents Sea [7, 30]. In general, higher or increasing sedimentary abundances of IP₂₅ are positively associated with seasonal sea-ice occurrence (or change) as shown through various surface and down-core records from across the Arctic [6]. However, lower IP₂₅ abundances have been found in sediments from regions of much higher or near-permanent sea-ice cover

including East Greenland [3] and the High Arctic ($>80^{\circ}\text{N}$) [50, 57]. In such settings, the abundances of phytoplankton biomarkers, including brassicasterol, are also low; both observations being consistent with light-inhibited and therefore low biological productivity.

Sea-ice dynamics in an Arctic coastal polynya

The accumulation of IP_{25} in the MIZ sediments [30] closely resembles the spatial distribution of As (Fig. 2) consistent with recurrent freezing and melting of sea-ice in the region. Furthermore, the release of sea-ice debris is known to stimulate phytoplankton blooms during spring, resulting in high export production rates during peak-bloom stages within the MIZ [36]. Through particle scavenging, this provides an additional mechanism that leads to enhanced sedimentary As. Down-core analyses of these sea-ice (IP_{25} , As) and phytoplankton (brassicasterol) proxies (Fig. 3), therefore, provide a temporal measure of variable sea-ice coverage in the Storfjorden polynya, and by inference, changes in high-salinity brine rejection due to variable polynyal activity resulting from freezing/melting processes. The results are discussed for three different time intervals (6.5–2.8, 2.8–0.5, <0.5 ka BP), with the boundary at 2.8 ka based on the gradual decline of the IP_{25} concentration between 3.0 and 2.5 ka and the abrupt increase in percentages of agglutinated forams at this time (Fig. 4). Notched box-whisker plots for the distributions of As/Al, IP_{25} , and brassicasterol in these time intervals (Fig. 3) confirm that, for all parameters, the median in the interval 2.8–0.5 ka is largely different from the median in the time

intervals 6.5–2.8 and 0.5–0 ka on 5% level. However, on a 5% level, notched regions of As/Al distribution in intervals 2.8–0.5 and 0.5–0 ka do overlap (Fig. 3), implying that paleoenvironmental conditions for sedimentary As deposition during these time intervals were not significantly different compared to the interval 6.5–2.8 ka (see discussion below).

Consistent with the surface sediment data, As/Al and IP_{25} co-vary in the 6500-year record (core JM10), with highest values between 2.8 and 6.5 ka, a decreasing trend towards 0.5 ka, and an increase towards the core-top (Fig. 4). The occurrence of IP_{25} at the core-top is consistent with modern observations of annual sea-ice formation in the polynya [19], while its presence throughout the record demonstrates persistent (but variable) seasonal sea-ice occurrence. Highest IP_{25} concentrations and As/Al ratios between 6.5 and 2.8 ka are accompanied by enhanced brassicasterol concentrations and lower relative abundances of agglutinated foraminifera (Fig. 4), implying a variable sea-ice margin and recurrent melting/freezing periods with associated phytoplankton blooms. These modern-like conditions, with seasonal sea-ice formation and increased polynyal activity, are in accordance with environmental inferences from calcareous and agglutinated foraminiferal assemblages in the fjord during this time interval [35]. Our proxy data are also consistent with simulations of increased sea-ice production (+15%) and extent (+14%) in the circum-Arctic [9], likely as a consequence of the flooding of the Arctic Siberian shelf [4] and potentially positive ocean-sea ice-atmosphere feedbacks in the Barents Sea [42], and further evidenced by

Fig. 3 Notched box-whisker plots for all down-core measurements of JM10-10GC for the parameters As/Al, IP_{25} , and brassicasterol in the time intervals 0–500 a BP, 500–2800 a BP, and 2800–6500 a BP.

White lines mark the estimated positions, and notched intervals the 95%-confidence limits for the medians of the distributions

Fig. 4 Proxy data for sea-ice variability in Storfjorden polynya (core JM10-10GC) over the past 6500 years BP. Bottom to top: IP₂₅ concentration (μg/gSed and μg/gTOC), As/Al ratio (×1000), agglutinated foraminifera (% of total benthic assemblages), and brassicasterol concentration (μg/gSed). Stippled lines indicate the mean values for each proxy in the three intervals discussed in the main text. Note that IP₂₅ concentrations normalized to μg/g Sediment and μg/g TOC indicate no dilution effect on biomarker records due to variable sedimentation rates

353 reduced sea surface temperatures off western Svalbard
354 around 5 ka [54] (Fig. 5). Elsewhere, a gradual southward
355 expansion of the MIZ has been reconstructed for the
356 Canadian Archipelago [50] and the Fram Strait [29].
357 Werner et al. [54] hypothesized that the occurrence of
358 heavy winter sea-ice off the western Svalbard coast after
359 5.2 ka BP is due to established modern sea-ice production
360 in the Arctic Ocean after the Holocene transgression. The
361 distinct cooling trend in the Nordic Sea connected to the
362 sea-ice expansion as a consequence of the flooding [9] and
363 declining insolation [25] (Fig. 5) provides the prerequisite
364 for the advection and persistent presence of seasonal sea-
365 ice in the Storfjorden polynya.

366 A distinct change in sea-ice coverage in the Storfjorden
367 polynya occurred after 2.8 ka BP. While a seasonally

368 fluctuating MIZ similar to its present (winter) location
369 prevailed along western Spitsbergen [29], the reduced sea-
370 ice and phytoplankton biomarkers together with higher
371 mean proportions of agglutinated foraminifera (Fig. 4)
372 demonstrated a clear change in sea-ice conditions in the
373 Storfjorden polynya between 2.8 and 0.5 ka, with low
374 entrainment/freezing of terrestrial sediments, diminished
375 surface water productivity and dense/packed sea-ice cov-
376 erage. At the same time, on the western Svalbard/Barents
377 Sea margin, decreasing values in planktic $\delta^{13}\text{C}$ records and
378 a downward migration of the planktic foraminifera
379 *Neoglobobulimina pachyderma* sin., also point to surface
380 water freshening and saltier, warmer sub-surface waters
381 (Fig. 5) [40, 55], thus preconditioning the setting for
382 extensive sea-ice formation. The dominance of the

Fig. 5 Sea-ice reconstruction, brine formation and deep water penetration to the Arctic over the past 6500 years. *Bottom to top*, IP₂₅ concentration (μg/gSed) in Storfjorden, seawater-derived Nd isotope variations expressed as εNd in the eastern Fram Strait [53], planktic foraminifera δ¹³C from western Svalbard/Barents Sea [40, 54], benthic foraminiferal δ¹³C from Greenland Sea [49], June/July/August (JJA) air temperatures over Svalbard [14], sea surface temperatures (SST) off western Svalbard [44, 54, 55], Greenland ice core data from DYE-3, GRIP and NGRIP on the GICC05 timescale [51] and solar irradiance [25]

calcareous benthic foraminifera species *Elphidium excavatum* in the Storfjorden sediments provides further evidence for more extensive seasonal ice cover [35]. A permanent sea-ice cover in Storfjorden is also in agreement with observations from western coastal Svalbard, where enhanced formation of shore-fast sea-ice and/or dense sea-ice coverage has been suggested [17]. On the other hand, pulses of advected Atlantic water along the Barents and Svalbard margin during this period [40, 53] did not influence the persistent sea-ice coverage in Storfjorden. However, confirmation of the latter requires a higher resolution IP₂₅ record, as intervals with more variable sea-ice conditions inferred from highly fluctuating proportions of agglutinated foraminifera, which are not covered with the current IP₂₅ dataset (Fig. 4). In the meantime, the high-resolution As/AI record of constantly low values (<0.5) throughout this interval implies dense sea-ice coverage, suggesting that increased proportions of agglutinated foraminifera in some intervals may reflect variable preservational conditions under the dominant influence of Arctic waters rather than strong polynyal activity, and thus brine formation. However, the latter needs to be explored further with additional records from the Storfjorden area and adjacent trough.

Fig. 6 Down-core variability of sea ice (IP₂₅), phytoplankton (brassicasterol), and agglutinated foraminifera indicators in Storfjorden polynya over the past ca. 500 years. Orange bars indicate the correspondence of high sea ice variability, phytoplankton production and strong polynyal activity as inferred from higher proportions of agglutinated foraminifera [34]. Blue bar shows no response

Rapidly increasing phytoplankton production, and enhanced IP₂₅ concentrations demonstrate that the sea-ice factory restarted abruptly ~0.5 ka BP, at which time, sediment entrainment/release processes also recovered, with higher As/AI ratios towards the core-top (Fig. 4). The establishment of a highly fluctuating sea-ice boundary would have finally led to formation of a coastal polynya with seasonally variable sea-ice conditions. Enhanced IP₂₅ and brassicasterol concentrations are largely consistent (except one interval centered on 0.3 ka) with increased proportions of agglutinated foraminifera (Fig. 6), supporting inferences by Rasmussen and Thomsen [34] of an intensified but variable polynyal activity. Thus, constantly high sea-ice production throughout the last ~500 years is likely the result of inferred mild summer temperatures on Spitsbergen including the Little Ice Age (Fig. 5) [14]. These modern-like conditions in Storfjorden, with variable sea-ice coverage over the last 500 years, contrast the more dense/packed sea-ice conditions in the preceding interval (~2.8–0.5 ka BP), but corroborate a recent biomarker-based sea-ice reconstruction for western Svalbard, which showed a gradual decline in spring sea-ice concentration over the past 400 years [12].

Relationship between sea-ice, brines and deep water production

In modern times, it is well known that dynamic sea-ice production and brine rejection within the wind-driven polynyas in the circum-Arctic are important contributors for deep water convection in the Nordic Seas and Arctic Ocean [2, 41, 43]. Further, Bauch et al. [4] suggested that for the Last Glacial Maximum, enhanced sea-ice production and dense bottom water formation could be attributed to the formation of katabatic wind-driven polynyas in front of the western Svalbard-Barents Sea ice sheet. Similarly, based on calcareous and agglutinated foraminifera, Rasmussen and Thomsen [34, 35] showed that the strength of brine formation in the Storfjorden polynya over the last 15 ka BP was largely related to climatic conditions, with enhancements during cold periods (and vice versa). However, such studies were based on rather unselective proxies for sea-ice reconstruction (i.e. stable isotopes and assemblages of benthic and planktic foraminifera), which potentially limits their value in terms of confirming the significance of brine rejection on deep water formation in palaeo records (Table 5).

In this study, we demonstrate temporal coherence between our more direct proxy-based sea-ice reconstruction (and inferred brine intensity changes) and changes to deep water convection obtained from local and other regional records from the Nordic Seas (Fig. 5). Thus, the recurrent freezing/melting of sea-ice in the Storfjorden

Table 5 Down-core variability of IP₂₅ concentrations in JM10-10GC

Depth_cm	Age_a_BP1950	IP25com µg/gSed	IP25com µg/gTOC
2.5	26.57	0.00799	0.467
4.5	47.83	0.00759	0.440
6.5	69.09	0.00862	0.499
8.5	90.35	0.00826	0.492
10.5	111.61	0.00804	0.496
12.5	132.87	0.00789	0.507
14.5	154.12	0.00777	0.509
16.5	175.38	0.00527	0.362
18.5	196.64	0.00706	0.409
20.5	217.90	0.00612	0.375
24.5	260.42	0.00781	0.460
26.5	281.67	0.00961	0.553
28.5	302.93	0.00782	0.442
30.5	324.19	0.00794	0.454
32.5	345.45	0.00518	0.298
34.5	366.71	0.00822	0.473
36.5	387.97	0.00660	0.377
38.5	409.22	0.00655	0.389
40.5	430.48	0.00617	0.349
42.5	451.74	0.00589	0.332
44.5	473.00	0.00709	0.402
46.5	492.17	0.00782	0.449
48.5	511.34	0.00585	0.337
68.5	703.07	0.00558	0.371
80.5	818.10	0.00560	0.367
104.5	1131.41	0.00553	0.379
110.5	1438.65	0.00566	0.329
118.5	1848.29	0.00576	0.353
126.5	2257.94	0.00642	0.370
130.5	2462.76	0.00636	0.359
132.5	2565.18	0.00782	0.446
142.5	2892.27	0.00747	0.429
152.5	3096.05	0.01052	0.605
156.5	3177.57	0.00801	0.457
170.5	3462.86	0.00719	0.427
176.5	3585.14	0.01502	0.849
178.5	3625.89	0.00837	0.472
190.5	3870.43	0.00867	0.492
192.5	3911.19	0.00690	0.396
208.5	4237.24	0.00683	0.394
210.5	4278.00	0.00686	0.401
224.5	4462.45	0.00890	0.487
246.5	4752.30	0.00874	0.466
250.5	4805.00	0.00790	0.424
266.5	5165.16	0.00777	0.414
280.5	5480.30	0.00932	0.502
284.5	5570.34	0.00811	0.436
298.5	5885.48	0.00760	0.421
324.5	6470.74	0.00622	0.383

Fig. 7 Location of coastal polynyas in the Arctic with variable sea-ice dynamics. **a** Modern sea-ice distribution and strong deep convections (crosses) with vigorous sea-ice factories (orange polygons) for brine-enriched shelf water formation. Blue arrows cold, ice-covered surface currents. Red arrows: warm, saline Atlantic-derived water masses. **b** Less sea-ice in the Arctic with shut down of sea-ice factories (open polygons) and slow down of deep convection (minus). NWP North Water polynya, NEWP Northeast Water polynya, NB Nordbukta, WBP Whaler's Bay polynya, SP Storfjorden Polynya, KSP Kara Sea polynya, LSP Laptev Sea polynya

polynya and associated strong brine formation between 6.5 and 2.8 ka BP coincides with less radiogenic ϵ_{Nd} values (−9.4 to −10.6) from western Spitsbergen, as seen for present-day deep water penetration to the Arctic Ocean [53] (Fig. 5). During the same interval, high convection rates in most areas of the Nordic Seas is evident from high carbon isotope values in both planktic and benthic foraminifera [4, 40], together with a period of maximum ventilation in the Greenland Sea (Fig. 5) [48, 49] and AMOC strengthening [20]. In contrast, more permanent sea-ice cover and probably subdued brine formation in Storfjorden polynya after 2.8 ka, is accompanied by a prominent shift to more radiogenic ϵ_{Nd} along the western Spitsbergen continental margin (Fig. 5) [53]. At the same time, freshening of surface waters and intensification (thickening) of sea-ice in the Fram Strait has been deduced from carbon isotope data of planktic foraminifera [54] (Fig. 5) and elevated IP₂₅ abundances [29], while increased sea-ice production in the Arctic and export through Fram Strait also coincides with a proposed reduction of deep convection in the Greenland Sea [49] (Fig. 5). Modelling results also suggest that negative anomalies in total solar irradiance ~2.7 ka may have been responsible for local shutdown of deep water formation in the Nordic Seas at this time [39], which when superimposed on decreasing

insolation (Fig. 5) may have stimulated positive oceanic feedbacks, such as enhanced stratification, expansion of sea-ice and less deep water formation leading to additional cooling and more sea-ice (e.g. [48, 49]. Regardless of the ultimate trigger for the abrupt changes in sea-ice coverage in Storfjorden polynya at ~2.8 ka, the timing of such solar-forced cooling events demonstrates that the most severe climatic conditions in the Nordic Seas and circum-Arctic reduced the contribution of Arctic sea-ice factories (i.e. polynyas) to deep water production.

The enhancement of the sea-ice factory and phytoplankton production in Storfjorden at ~0.5 ka BP, when recurrent freezing/melting of sea-ice in the polynya coincides largely with the increased admixture of deep waters from the Nordic Sea (less radiogenic ϵ_{Nd}) (Fig. 5) and increased proportions of agglutinated foraminifera (Fig. 6), supports the notion of enhanced brine formation during stronger polynyal activity. The transition to more intense polynyal activity ~0.5 ka BP, coupled to higher sea-ice variability thereafter, also aligns with observations from western Svalbard, where spring sea-ice concentration has steadily declined over the past 400 years [12] and heat transport into the Arctic via the West Spitsbergen Current has increased [14, 44].

Implications and conclusions

The Arctic Ocean halocline is maintained by the contribution of cold and brine-enriched deep waters [1, 13], which are formed because of high sea-ice production in coastal polynyas over the continental shelves (Fig. 7) [47]. Tamura and Ohshima [47] showed that the current polar amplification of global warming will lead to negative trends in sea-ice production in most of the Arctic polynyas and with future projections of a summer ice-free Arctic Ocean (IPCC 2013), sea-ice factories in Arctic coastal polynyas may lose their significance entirely (Fig. 7). A likely cause for this trend could be delayed sea-ice freezing and increased Arctic air temperatures [47]. The last time a similar scenario occurred was during the Holocene Thermal Maximum when Arctic Ocean sea-ice cover was believed to be less than half of the minimum summer extent in 2007 [18]. Indeed, Árrthun et al. [58] showed that during periods of maximum warming in the central Barents Sea, formation of brine-enriched shelf waters, and thus export of deep waters to the Nordic Seas and Arctic Ocean, was strongly reduced. Whether this reduced export contributed to the slow down in AMOC in the twentieth century (Rahmstorf et al. 2015) remains speculative. However, from this study we conclude that sea-ice production in Arctic coastal polynyas is highly sensitive to variable, externally forced climate or ocean feedback mechanisms.

The correspondence between high (low) polynal activity and variable sea-ice conditions in one important Arctic sea-ice factory, and observations of stronger (weaker) deep water renewal processes in the Nordic Seas during the present interglacial highlight the potential consequences for ocean ventilation during states with permanent sea-ice cover or future Arctic ice-free conditions.

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