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Key Points:

- Br_{enr} in Holtedahlfonna shallow cores is positively and significantly correlated with springtime regional first-year sea ice variability
- No significant link between Br_{enr} and multi-year sea ice, suggests that bromine emissions are largely modulated by younger ice
- Despite Na and Br reallocation, Br_{enr} is relatively stable over time and well-aligned with $\delta^{18}\text{O}$ values

Supporting Information:

Supporting Information may be found in the online version of this article.

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Bromine Enrichment Signal in Svalbard Shallow Cores Reflects Changes of Seasonal Sea Ice Variability

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Abstract Bromine enrichment (Br_{enr}) has been widely used as a proxy for past sea ice reconstructions. In this study, three firn cores drilled on Holtedahlfonna (Svalbard) were analyzed for trace elements. Excluding a single year data, a positive correlation was observed between Br_{enr} and springtime sea ice variability in the potential source region during 2005–2016. Accounting for different sea ice ages, Br_{enr} signal resulted significantly correlated only with first-year sea ice, reinforcing its role as a major contributor to springtime gas-phase bromine emissions. Comparisons between Na and Br concentrations in shallow cores and temporally corresponding values in annual snow pits collected at the same site reveal that elemental reallocation similarly affects both chemicals, resulting in a generally stable Br_{enr} signal over time. Finally, the negative correlation with the $\delta^{18}\text{O}$ temperature proxy further supports the capability of Br_{enr} to capture past climate-change-driven sea ice fluctuations.

Plain Language Summary Sea ice is a key component of Earth's climate system, and understanding its dynamics is essential in refining future models' accuracy. In this study, we analyzed three firn cores drilled on the Holtedahlfonna glacier (Svalbard), using bromine enrichment as a proxy to reconstruct past sea ice variability. Our main focus was to better understand the role of sea ice age in modulating the proxy signal and the impact of snow melting on the preservation of the tracer. The outcomes of our research confirm that this geochemical marker is mostly influenced by seasonal sea ice and past atmospheric temperature variability, remaining relatively well-preserved over time.

1. Introduction

Since the late 1970s, the Arctic has warmed nearly four times faster than the global average (Rantanen et al., 2022) resulting in declines in sea ice extent, thickness, and volume. Climate models struggle to fully capture these changes due to poor parametrization of key processes modulating sea ice dynamics (Spolaor, Opel, et al., 2016). Improved reconstructions of long-term variability are needed for better sea ice predictions (Vallalonga et al., 2021; Wolff et al., 2006). Over a decade ago, a new sea ice tracer in ice cores, known as bromine enrichment (Br_{enr}), was proposed (Spolaor, Vallenga, et al., 2013) and recently statistically validated against 30 years of satellite observations (Scoto et al., 2024):

$$\text{Br}_{\text{enr}} = \frac{\left(\frac{\text{Br}}{\text{Na}}\right)_{\text{icecore}}}{\left(\frac{\text{Br}}{\text{Na}}\right)_{\text{seawater}}} = \frac{\text{Br}_{\text{icecore}}}{\text{Na}_{\text{icecore}} \cdot 0.0062} \quad (1)$$

This proxy (Scoto et al., 2024; Vallenga et al., 2021) is based on the bromine-to-sodium mass ratio measured in the ice relative to that in bulk seawater (Millero et al., 2008). Although sea-salt aerosol is the major source of both sodium and bromine, in polar regions gas-phase bromine emissions are promoted by autocatalytic multiphase chain reactions over sea ice, salty blowing snow, and frost flowers (Chance, 1998; Platt & Wagner, 1998). Catalyzed by light, these reactions primary occur in spring, driving the transition from inert halide ions to reactive bromine monoxide (Bougoudis et al., 2020; Fan & Jacob, 1992; Simpson et al., 2007; Vogt et al., 1996). Due to the self-propagating nature of bromine explosion events, Br_{enr} is typically expressed on a base-2 logarithmic

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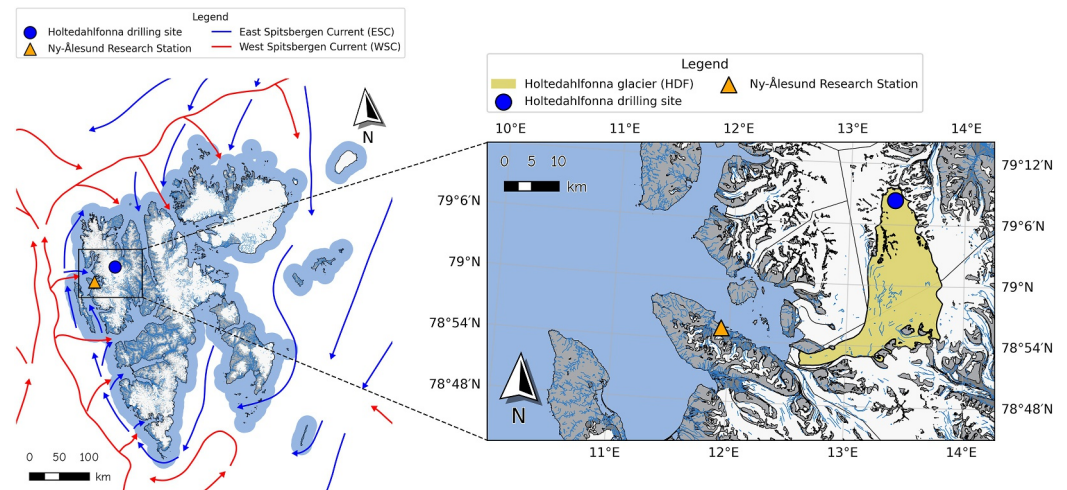


Figure 1. Overview of the Høltedahlfonna drilling site (blue dot; 79°09′N, 13°23′E; 1,150 m a.s.l.) with respect to the Ny-Ålesund Research Station (orange triangle). The spatial extent of the Høltedahlfonna glacier (yellow shading) is derived from Nuth et al. (2013), and the basemap is based on TopoSvalbard (Norwegian Polar Institute, <https://toposvalbard.npolar.no/>—accessed 24 February 2026). Red and blue arrows provided by Vihtakari (2020) display the West Spitsbergen Current (WSC) and the East Spitsbergen Current (ESC), respectively.

scale. While experimental studies (Scoto et al., 2024; Spolaor, Opel, et al., 2016) and satellite observations (Bougoudis et al., 2020) suggest that seasonal ice is a greater source of reactive bromine than multi-year ice, ice core records provide only partial support for this hypothesis (Scoto et al., 2024). In this study, we refine Br_{enr} as a sea ice proxy by comparing a stacked record from three Svalbard firn cores (2012, 2015, and 2017) covering the period 2005–2016, with sea ice variability in the identified bromine source area. Moreover, we employed satellite sea ice age data to distinguish the role of different sea ice types in modulating springtime bromine emissions. To evaluate the proxy stability over time we compared Br and Na concentrations in firn cores with those determined in the seasonal snow deposited in the corresponding years. Finally, the relationship between Br_{enr} and the $\delta^{18}O$ climate indicator in the shallow cores stacked record was explored to assess the capability of the investigated sea ice proxy to capture past climate variability.

2. Materials and Methods

2.1. Høltedahlfonna Drilling Site

Located 40 km north-east of Ny-Ålesund, the Høltedahlfonna glacier (Figure 1, HDF) spans for over 300 km² on Spitsbergen island with an elevation ranging from 0 to 1,241 m a.s.l. (Nuth et al., 2012). Since 2004 its summit area experiences a positive average annual snow mass balance of $+0.88 \pm 0.25 \text{ m we} \cdot \text{yr}^{-1}$ (Kohler, 2013; Spolaor et al., 2024; Van Pelt et al., 2019), making this location a valuable drilling site for ice-core based paleoclimate reconstructions. Radar data indicate ice thicknesses of ≈ 100 –250 m at the drilling site (Beaudon et al., 2013), while regarding its temperature profile, borehole single measurements carried in 2005 showed a firn temperature of approximately -0.4°C at 15 m depth (Sommer, 2005).

2.2. Shallow Cores and Snow Pits: Collection and Analysis

Three shallow firn cores were drilled from the bottom of the annual snowpack at the HDF summit (79°09′N, 13°23′E; 1,150 m a.s.l.) in 2012, 2015, and 2017 attaining length of 954, 1,185, and 736 cm, respectively. All three cores were previously analyzed for their $\delta^{18}O$ composition by Spolaor et al. (2024), and dated based on $\delta^{18}O$ -seasonal cycles combined with surface mass balance data (Kohler, 2013). According to Spolaor et al. (2024) the general trend in atmospheric temperature is consistently reflected in the HDF cores until 2016 with a notable seasonality for both the 2012 and 2015 cores, thereby confirming the reliability of the chronology. Additionally, the 2015 core was examined for elemental carbon by Ruppel et al. (2017), whereas the 2017 one was analyzed for iron by Burgay et al. (2021). These analyses complement paleoclimate reconstructions spanning the past 300 years reported by Goto-Azuma et al. (1995), Divine et al. (2011), and Beaudon et al. (2013).

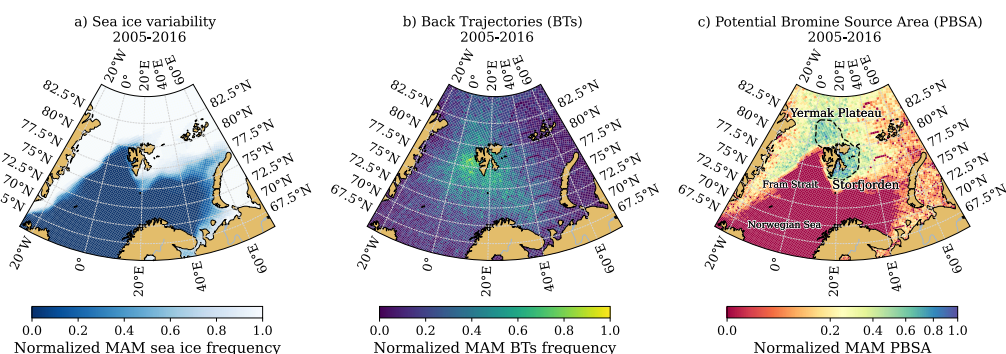


Figure 2. Quantification of the Potential Bromine Source Area of the Holtedahlfonna drilling site. (a) Normalized springtime sea ice area variability around Svalbard (2005–2016). Values range from 0 (no sea ice) to 1 (sea ice all three spring months). (b) Normalized springtime 3-day back trajectories analysis of air masses arriving at the Holtedahlfonna summit for the period 2005–2016. (c) Identified normalized Potential Bromine Source Area for the Holtedahlfonna drilling site for 2005–2016 with the two main sectors, Storfjorden and Yermak Plateau, highlighted with a dashed boundary.

Firn core sections were partially cut into ≈ 5 cm pieces using a ceramic knife under a Class 100 laminar flow hood, with the outer 2 cm scraped off to minimize contamination. Inner sections were melted, aliquoted, and stored in pre-cleaned polypropylene vials at -20°C in the dark to prevent photolysis. To preserve water-soluble bromine, one aliquot was kept unacidified while others were acidified with 2% (v/v) Ultra-Pure nitric acid (68% w/w) for major ion (including sodium) and trace element analysis. Four seasonal snow pits were dug at the same location in 2012, 2013, 2015, and 2016 following the procedure described in Gallet et al. (2018). Each snow pit was dug in April to mostly capture the annual bromine depositions while minimizing the potential effects of summer melting. The investigated seasonal snow pits ranged in depth from 137 to 263 cm, down to the visible snow-firn interface. Snow samples were collected at ≈ 5 cm resolution after removing ≈ 10 cm from the inner-facing wall, and melted at ambient temperature in a Class 100 laminar flow bench. Na, Br, and trace element concentrations were measured following the procedure described in Spolaor, Gabrieli, et al. (2013) and Spolaor, Vallengona, et al. (2013). The instrumental Limit of Detection (LoD), calculated as three times the standard deviation of the blanks, was $0.8 \text{ ng} \cdot \text{g}^{-1}$ for Na and $0.05 \text{ ng} \cdot \text{g}^{-1}$ for Br, while the residual standard deviation ranged between 4% and 6%, respectively.

2.3. Back-Trajectories Calculations and Sea Ice Satellite Data Extraction

Air mass frequency plots covering the three stacked cores period (2005–2016) were retrieved from back trajectories (BTs) computed using the HYSPLIT model by Stein et al. (2015), following the methodology of Vallengona et al. (2021) and Scoto et al. (2024). The 72-hr-long backward trajectories were initiated from the HDF coring site, and to emphasize bromine explosion events, only springtime (March–April–May; MAM) BTs crossing the marine boundary layer for at least 10 hr were retained (Maffezzoli et al., 2019). Similarly, average springtime SIE frequency maps were derived for 2005–2016 from the *Sea Ice Index, Version 3* by Fetterer et al. (2017) in which only cells with a sea ice concentration greater than 15% are flagged as ice-covered. Springtime air mass back trajectory frequencies and corresponding sea ice variability were combined to identify the HDF firn cores' Potential Bromine Source Area (PBSA) as defined by Scoto et al. (2024). Finally, Pearson correlation was calculated between the interannual SIE variability in the PBSA and stacked annual Br_{enr} values from the three investigated cores. To evaluate the influence of sea ice age in modulating gas-phase bromine emissions, the same statistical analysis was conducted using frequency maps of sea ice extent for individual age classes derived from *EASE-Grid Sea Ice Age, Version 4* (Tschudi et al., 2020).

3. Results and Discussion

3.1. Holtedahlfonna Potential Bromine Source Area

Based on the outcomes of the computed BTs (Figure 2b) combined with the extracted sea ice variability (Figure 2a), the PBSA of the HDF drilling site mainly aligns with two distinct oceanic sectors: the Storfjorden basin, located on the east side of Svalbard, and with a region of the Arctic Ocean near the Yermak Plateau to the

north-west (Figure 2c). Although both the identified bromine source regions are sea ice-covered during springtime, sea ice age observations (Tschudi et al., 2020) reveal a clear distinction between the types of sea ice in each region. The sea ice in the Storfjorden sector is indeed primarily seasonal, while the Yermak Plateau is characterized by a mixture of first-year sea ice (FYSI) and multi-year sea ice (MYSI) exported from the Fram Strait (Figures S2–S4 in Supporting Information S1).

3.2. Sodium, Bromine, and Bromine Enrichment Profiles

The three HDF shallow core records (2012, 2015, and 2017) were stacked together to obtain monthly mean Br_{enr} values spanning the period 2005–2016. Although a limited temporal overlap, the Br_{enr} profiles were overall consistent among the investigated cores (Figure S1 in Supporting Information S1). The stacked record showed a mean value of 1.89 ± 0.87 , in line with the slightly enriched conditions typically found at HDF, with only few Br-depleted samples, primarily after 2012 (Figure 3a). Over the entire record, a significant correlation ($r = 0.84$, p -value < 0.001) was found between Na and Br concentrations, suggesting a common sea spray emission source and similar deposition pattern due to the coastal proximity of the drilling site (Segato et al., 2024; Vallelonga et al., 2021). Relatively high concentrations of Na and Br (up to 1,014 and $5.77 \text{ ng} \cdot \text{g}^{-1}$, respectively) were observed in 2006 resulting in lower Br_{enr} levels (Figure 3a). Between mid-2006 and 2008 Br_{enr} increased significantly, reaching a value of 5.15, consistent with an increase in bromine levels. After 2008, Br_{enr} generally decreases, except for two major peaks in 2010 and 2016, with values ≈ 1 , which may indicate deposition of bulk seawater aerosol due to reduced sea-ice area, or rather reflect that the climate proxy is approaching its detection limit.

3.3. Bromine and Sodium Remobilization in the Snowpack, and Evaluation of the Magnitude of Non-Sea-Salt Sodium

Surface melting and occasional rain-on-snow events may present significant challenges for the interpretation of ice-climate proxies (Moser et al., 2024). To assess the stability of Na and Br within the snowpack over time, we compared annual average Br_{enr} values (i.e., winter-to-winter averages) measured in shallow cores with those obtained from four temporally corresponding annual snow pits. While firn cores have undergone summer melting, samples from undisturbed snow pits were potentially not affected by thawing during winter as the snowpack showed no evident refrozen layers at the time of samples collection. Annual mean Na, Br, and Br_{enr} values were calculated for each snow pit from 2012 to 2016, excluding 2014 due to lack of chemical data. Br_{enr} values were generally close to one, indicating low enrichment at HDF, likely reflecting its proximity to ice-free western Spitsbergen (Barbaro et al., 2021; Jacobi et al., 2019). Both Br and Na in the stacked firn core record resulted similarly depleted compared to the original snow pit values ($-74 \pm 10\%$ and $-74 \pm 14\%$, respectively; Table 1). Although both chemicals are leached during the seasonal snow to firn transition, similar Br and Na concentrations in shallow cores suggest that washout mostly occurs within the seasonal snowpack rather than in firn layers, as continuous washing would reduce concentrations in deeper layers. Given the numerous ice lenses observed in the firn cores and the glacial site's morphology, horizontal run-off is likely to be favored over vertical percolation. This is consistent with ice-penetrating radar and GPS observations from the Holtedahlfonna ice field, which reveal the development of a firn aquifer recharged by downward percolation of near-surface meltwater and drained by flow subparallel to both ice flow and glacier surface (Christianson et al., 2015). Despite Na and Br pronounced reduction in the firn cores, the overall magnitude of loss for both elements remains relatively consistent, resulting in comparable Br_{enr} values between the shallow cores stacked record and the annual snow pits (Table 1). The highest discrepancies between snow pit and shallow core Br_{enr} values occurred in 2013, followed by similarly moderate differences in 2012 and 2015 and low changes in 2016. The difference observed in 2013 may be explained by the negative net mass balance recorded that year on the glacier ($-20.4 \text{ Gt} \cdot \text{yr}^{-1}$) (Lang et al., 2015), which resulted in an ablation zone covering 77% of the land ice area (Noël et al., 2020) and to a potential degradation of the chemical signal preserved in the firn cores. Moreover, the mass-balance measurements, along with the modeled precipitation and snow-melt at the drilling site, indicate that 2013 experienced a low winter mass balance and a relatively high modeled melt-to-precipitation ratio (Spolaor et al., 2024). Overall, Br_{enr} appears to be relatively stable over time, whereas Na and Br are most affected by snowpack remobilization with snow pit values up to six-times higher than in the shallow cores stacked record. Our findings are in line with a previous study by Spolaor et al. (2021), which explored the impact of melting on the annual snowpack and

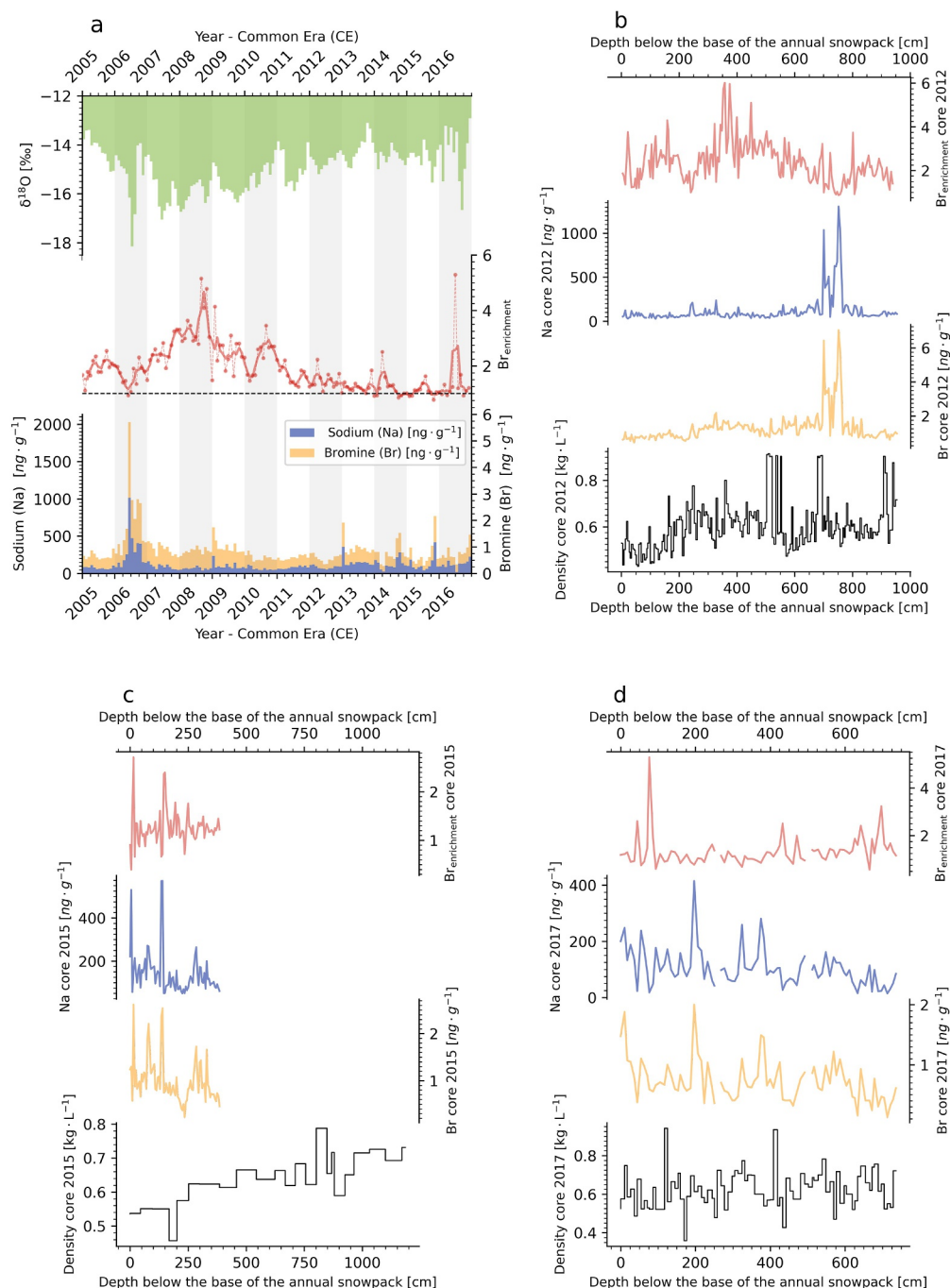


Figure 3. (a) Time series of bromine (Br; orange), sodium (Na; blue), bromine enrichment (Br_{enr} ; red), and $\delta^{18}\text{O}$ (green) from the stacked Høltedahlfonna shallow firn core record (2005–2016). (b–d) Density (black), Br (orange), Na (blue) and Br_{enr} (red) profiles of the three shallow firn cores. Density data for the 2012, 2015, and 2017 cores are taken from Spolaor, Gabrieli, et al. (2013), Ruppel et al. (2017), and Spolaor et al. (2024), respectively.

identified a preferential washout sequence ($\text{Cl}^- < \text{Ca}^{2+} < \text{Mg}^{2+} < \text{K}^+ < \text{Br}^- < \text{I}^- < \text{Na}^+$), indicating that both bromine and sodium exhibit a broadly similar elution sensitivity to melt events.

In addition to chemical elements remobilization in the snowpack, we also considered the influence of mineral dust on the glacier surface in modulating Br_{enr} levels. If a glacier is subjected to mineral dust depositions, the total sodium concentration in the snow (Na_{total}) results from both a sea-salt component (ssNa) and an additional crustal

Table 1

Annual Average Values of Sodium (Na), Bromine (Br), and Bromine Enrichment (Br_{enr}) in Seasonal Snow Pits and Shallow Cores Stacked Record

Year	Sodium (Na)		Bromine (Br)		Bromine enrichment (Br_{enr})	
	Snow pit [$\text{ng} \cdot \text{g}^{-1}$]	Core [$\text{ng} \cdot \text{g}^{-1}$]	Snow pit [$\text{ng} \cdot \text{g}^{-1}$]	Core [$\text{ng} \cdot \text{g}^{-1}$]	Snow pit -	Core -
2012	562	85 (0.15)	3.16	0.69 (0.22)	1.82	1.39 (0.76)
2013	332	153 (0.46)	2.74	1.08 (0.39)	2.28	1.20 (0.53)
2015	753	124 (0.16)	4.72	0.76 (0.16)	1.63	1.08 (0.66)
2016	508	125 (0.25)	3.32	0.84 (0.25)	1.37	1.25 (0.91)

Note. Values in bold indicate normalized concentrations, calculated as the ratio between each chemical's annual value in the seasonal snow pit and the corresponding value in the stacked record.

contribution (nssNa). In general, the non-sea-salt contribution of sodium in the snow is determined by employing elements such as aluminum (Al) (Boutron et al., 1991), calcium (Ca) (Schüpbach et al., 2018), magnesium (Mg) (Maffezzoli et al., 2021), iron (Fe), or direct dust measurements (Vallelonga et al., 2013). Using the reference mass ratio of sodium and iron in the Earth's upper continental crust, the marine sodium contribution and the magnitude of the nssNa in the annual snowpack were calculated as follows:

$$\text{ssNa} = \text{Na}_{\text{total}} - \left[\text{Fe}_{\text{total}} \cdot \left(\frac{\text{Na}}{\text{Fe}} \right)_t \right] = \text{Na}_{\text{total}} - [\text{Fe}_{\text{total}} \cdot 0.65] \quad (2)$$

ssNa accounted for approximately 97% of the total sodium in the snow pits, with nssNa—calculated using sodium-to-iron ratios from Rudnick and Gao (2014) ($\text{Na}/\text{Fe}_t \approx 0.65$)—contributing less than 3%. Because of the importance of appropriately selecting elemental ratios, we undertook the same exercise by solving Equation 2 for aluminum. The results were consistent ($\text{ssNa} \approx 97 - 99\%$), confirming the minimal contribution of non-sea-salt sodium. In conclusion, although we might not exclude post-depositional effects on Br and Na, their similar washout results in a marginal influence on the overall Br_{enr} signal in the shallow cores and, to some extent, also in the deeper ice.

3.4. Bromine Enrichment and Seasonal Sea Ice

By correlating firn cores' Br_{enr} with SIE variability observed within the PBSA, a positive but non-significant correlation ($r = 0.57$, $p\text{-value} > 0.05$) was obtained. However, the correlation increases and becomes statistically significant ($r = 0.62$, $p\text{-value} = 0.04$) excluding Br_{enr} value for 2013, which, among the three cores considered, shows the highest loss of Br_{enr} between shallow cores and snow pits (Table 1). To evaluate the influence of sea ice age on the HDF firn cores' Br_{enr} signal, a Pearson correlation analysis was performed considering different sea ice age categories extracted from the *EASE-Grid Sea Ice Age, Version 4* data set by Tschudi et al. (2020). Similarly, excluding 2013, the only statistically significant correlation found ($r = 0.83$, $p\text{-value} = 0.002$) is with freshly formed, first-year sea ice (Figure 4a). Weaker or not-statistically significant correlations are instead obtained between Br_{enr} and other sea ice types (Figures 4b–4d). The positive correlation between FYSI extent variability within the identified PBSA over 2005–2016 and the stacked Br_{enr} from HDF cores, highlights newly formed, seasonal sea ice as an effective substrate for springtime bromine explosion events. This in turn, supports the reliability of Br_{enr} as a proxy for reconstructing past seasonal sea ice fluctuations. Considering Br_{enr} absolute values, $Br_{\text{enr}} \approx 1$ indicate either open-ocean conditions or that the seasonal sea ice within the PBSA is too limited in extent to be fully captured by the ice cores-based proxy. Based on the FYSI- Br_{enr} regression ($\text{FYSI} = 2.45 \cdot 10^4 \cdot \log_2 Br_{\text{enr}} + 5.48 \cdot 10^4$), the HDF detection limit for sea ice extent is $\approx 5.48 \cdot 10^4 \text{ km}^2$. Below this threshold, Br_{enr} in HDF firn and ice cores may not be sensitive enough to past seasonal sea ice variations in the identified source regions.

In addition to its link with seasonal sea ice fluctuations, Br_{enr} was also evaluated against $\delta^{18}\text{O}$, a commonly used indicator of past climate changes based on water stable isotopes. In this regard, a significant negative correlation

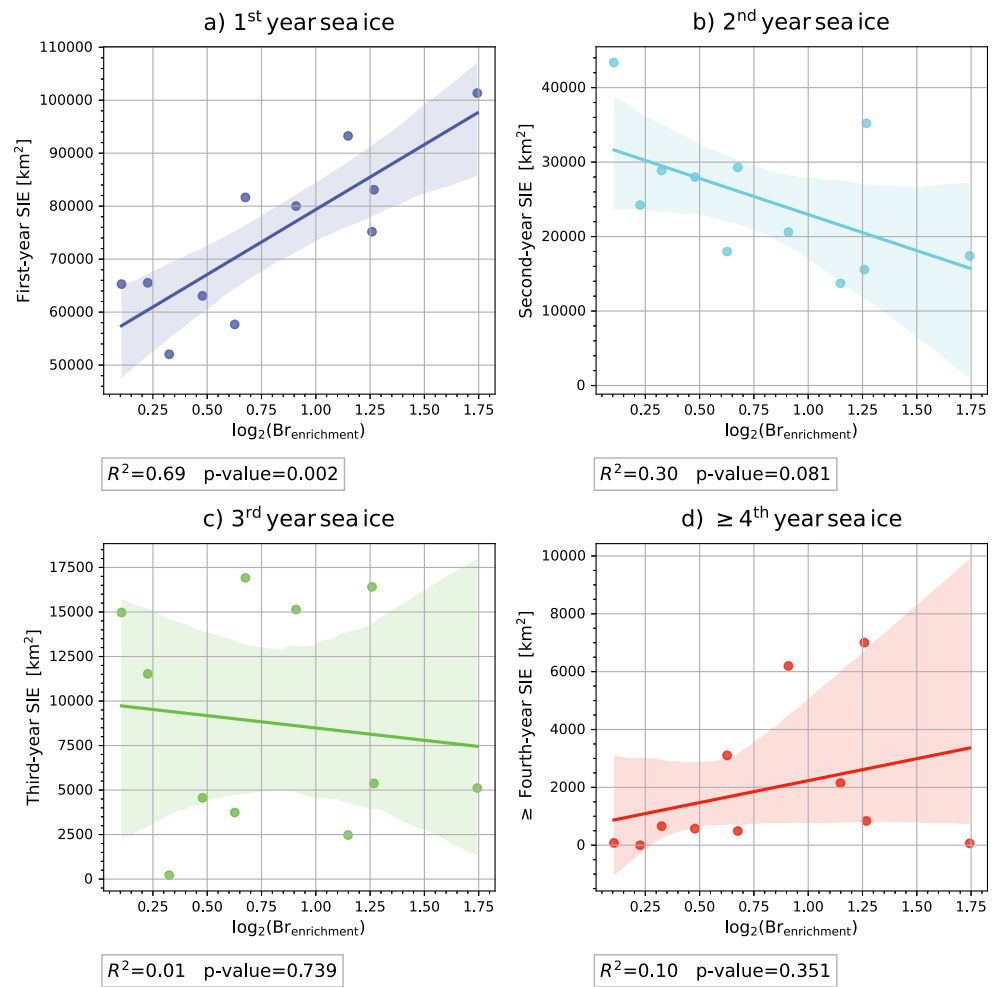


Figure 4. Linear regression analysis between Br_{enr} (expressed on a base-2 logarithmic scale) and sea ice extent within the Potential Bromine Source Area (PBSA), accounted for ice age. The 2013 data point was identified as an outlier and is therefore excluded from the analysis and not shown.

($r = 0.83$, $p\text{-value} < 0.005$; Figure S5 in Supporting Information S1) was found between Br_{enr} and the $\delta^{18}\text{O}$ record (Spolaor et al., 2024), which reflects interannual temperature variability across the three cores. Colder periods shown in the isotopic record (more negative $\delta^{18}\text{O}$) are associated with higher Br_{enr} (more sea ice), while warmer periods correspond to lower Br_{enr} values (Figure 3a). Generally, years characterized by extensive sea ice across the PBSA sectors—reflected in higher Br_{enr} levels—exhibit more negative $\delta^{18}\text{O}$ values. Conversely, periods of decreasing sea ice concentration point out less negative $\delta^{18}\text{O}$ values and so warmer temperatures. Despite post-depositional processes that may alter the original signal, the correlation appears robust indicating a period of predominant FYSI conditions with respect to perennial ice. In the context of paleoclimate reconstructions, glacial periods—characterized by extensive multi-year sea ice cover—may alter the observed negative $\text{Br}_{\text{enr}} - \delta^{18}\text{O}$ relationship, as also suggested in earlier studies (Spolaor, Vallenga, et al., 2016). Low bromine enrichment values could indicate either open water or multi-year sea ice conditions, each associated with distinct temperature signatures. These varying climate conditions could therefore complicate the interpretation of the relationship, as different sea ice influence the signals in different ways. In our study, we observe a negative correlation, likely because our record is dominated by seasonal sea ice, whereas Spolaor, Vallenga, et al. (2016) report a positive correlation, likely driven by a record characterized also by perennial sea ice regime. While the possibility of a spurious relationship cannot be entirely excluded, integrating the $\delta^{18}\text{O}$ temperature proxy with Br_{enr} may help disentangle the signals of temperature and sea ice, offering a more refined understanding of overall sea ice

variability. This integrated approach, especially in the context of paleoclimate sea ice reconstructions, could help distinguish between periods dominated by seasonal sea ice cover (high Br_{enr}), open water (low Br_{enr} and less negative $\delta^{18}\text{O}$), and MYSI conditions (low Br_{enr} and more negative $\delta^{18}\text{O}$ values). Extending the Br_{enr} record, such as through the 2023 deep HDF core drilling, could further clarify the extent of meltwater percolation and the role of sea ice age in shaping these signals, providing deeper insights into sea ice dynamics during past climatic intervals.

4. Conclusions

The positive statistically significant correlation between firn cores Br_{enr} and first-year sea ice variability supports the key role of newly formed, seasonal sea ice in modulating springtime bromine depositions in the Svalbard archipelago. Moreover, the comparison of chemical records from the shallow cores and those of temporally corresponding annual snow pits showed a similar loss of both Na and Br, resulting in relatively stable Br_{enr} values over time. In turn, these empirical findings suggest the Br_{enr} record at the summit area of the Holtedahlfonna is likely preserved given a similar degree of elution of Na and Br induced by meltwater percolation. Considering the current rate of warming, future research, based on coupled multi-layer snow chemical-physical models, is needed to achieve a more comprehensive parametrization of the chemical elution during snow melting. Beyond sea-spray aerosol, the methodological approach proposed could be further applied to assess the impact of meltwater percolation on crustal elements linked with dust depositions. Finally, the observed negative correlation between Br_{enr} and $\delta^{18}\text{O}$ highlights the sensitivity of Br_{enr} to overall climate variability. In this perspective, the coupling of water stable isotopes with the bromine-based sea ice proxy can supply further indications in discriminating between past open ocean and perennial sea ice conditions. Although the results reported in this study are based on a relatively short period, they provide a valuable basis for interpreting the long-term 2023 Holtedahlfonna deep ice core record, which aims to reconstruct regional sea ice fluctuations over the last 300 years.

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Acronyms

Br_{enr}	Bromine enrichment
BTs	Back Trajectories
FYSI	First Year Sea Ice
HDF	Holtedahlfonna
MAM	March-April-May
MYSI	Multi Year Sea Ice
PBSA	Potential Bromine Source Area
SIE	Sea Ice Extent

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

Sodium (Na) and (Br) data are available at Biscaro et al. (2026).

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