



Atmospheric bromine deposition as a source of seasonal snowpack bromide reservoirs for Arctic bromine explosion events: evidence from linking chemistry-climate simulations with snow observations using a layered snow model

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Abstract. Bromine explosion events (BEs) are an important source of reactive bromine in the Arctic boundary layer and contribute to episodic ozone depletion in spring. While bromide-rich sea ice and snow are generally regarded as the primary source, the extent to which atmospheric deposition of bromine can establish and replenish a snowpack bromide reservoir remains poorly constrained. We combine simulations with the ECHAM/MESSy Atmospheric Chemistry model (EMAC), field observations, and laboratory analyses of snow samples collected around Ny-Ålesund (Svalbard) in April 2024 to investigate the role of atmospheric bromine deposition for BEs. To connect atmospheric deposition fluxes with observed snow chemistry, we developed the Snow Model with Evolving Layers (SMELs), a simple offline snow model that tracks bromide accumulation within a dynamically evolving snowpack.

EMAC simulations indicate that bromine dry deposition from very short-lived substances (VSLs) and sea-salt aerosol (SSA) dehalogenation can establish snow bromide reservoirs sufficient to sustain typical Arctic springtime BrO abundances. Bromine species partitioning upon deposition suggests that a lack of HBr deposition may suppress heterogeneous Br₂ production during fall. SMELs reproduces the observed vertical bromide enhancement and depletion patterns and demonstrates that finite snowpit sampling can introduce substantial biases. The strong agreement between modeled and observed normalized bromide profiles suggests that bromine deposition and post-depositional processing operate on regional scales around Ny-Ålesund. Our results identify atmospheric bromine deposition as an important seasonal bromide reservoir and highlight the role of bromine speciation and snowpack processes in controlling Arctic bromine activation.

1 Introduction

Ozone (O₃) is a secondary air pollutant in the troposphere and among the three major greenhouse gases. For about four decades, it has been known that O₃ in the polar regions is subject to large-scale depletion in the springtime boundary layer, during which surface ozone volume mixing ratios (VMR) regularly drop from background values of around 30 ppbv to below 5 ppbv (e.g.,



Bottenheim et al., 1986; Jacobi et al., 2010; Benavent et al., 2022). These so-called Ozone Depletion Events (ODE) have been associated with an exponential increase in bromine monoxide (BrO) (Simpson et al., 2007). The increase in BrO has been identified in satellite vertical column density (VCD) retrievals (Richter et al., 1998, 2002), which is why the phenomenon is also referred to as a Bromine Explosion (BE). BEs provided the evidence that the observed catalytic ozone depletion in the Arctic spring is largely bromine-driven (Barrie et al., 1988; McConnell et al., 1992; Platt and Hönniger, 2003), while iodine monoxide IO can also be an important contributor (e.g., Benavent et al., 2022).

Ozone, in conjunction with the hydroxyl (OH) radical and hydrogen peroxide (H₂O₂), strongly alters the oxidative capacity of the polar boundary layer and, thus, the atmospheric trace gas composition (Thompson, 1992). In particular, the formation of toxic, oxidized mercury (Brooks et al., 2006; Wang et al., 2019b), that accumulates up the food chain and causes serious health issues, is affected.

To initiate BEs, a transformation of inorganic (Br_y) reservoir species such as HBr, HOBr, and BrNO₃ is necessary. Multi-phase chemistry – involving reactants in both gas- and aqueous-phase – has been identified as driver of bromine emission and recycling on salty snow (Abbatt et al., 2012). Gas-phase ozone depositing onto snow may act as a trigger (Oum et al., 1998), activating bromide dissolved in the disordered air–ice interface, often called quasi-liquid layer (Bartels-Rausch et al., 2014). Inorganic bromine species, mainly Br₂, are then released into the gas-phase and photolyzed, given the presence of light. These bromine atoms (Br) then start the catalytic ozone depletion cycle, which terminates with the production of the named reservoir species.

A parametrization of bromide activation and recycling of Br_y in the snowpack, proposed by Toyota et al. (2011), is the most common representation of inorganic bromine emission leading to ODEs in global and regional chemistry-climate (CCMs) and chemistry-transport models (CTMs). But these emissions are usually not considered in the default model setups (Whaley et al., 2023).

A key assumption of the bromide activation mechanism is the presence of an effectively infinite bromide source originating from oceanic NaBr and supplied through first-year sea ice. In contrast, salt-depleted multi-year sea ice and terrestrial snow lack a sustained bromide source and therefore only permit recycling of HOBr and BrNO₃ in the presence of HBr as schematically shown in Fig. 1. This recycling assumption is in-line with an experimentally confirmed barrier-free reaction of HOBr with HBr_{aq} (Voegelé et al., 2003)



the formation of HOBr by BrNO₃ dilution in water



and ozone induced formation of HOBr



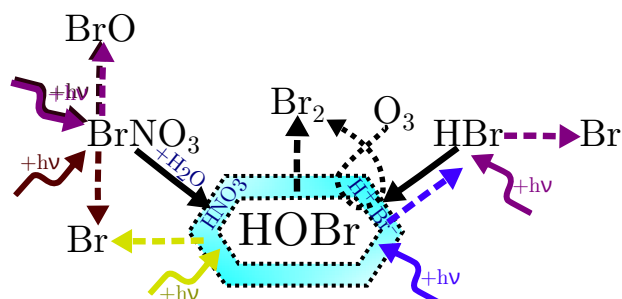


Figure 1. Schematic view of multi-phase and photochemical reactions on the disordered air–ice interface centered around HOBr when assuming no infinite bromide source from the ocean through first-year sea ice. The colors of the curly arrows indicate the photodissociation wavelengths of the respective photochemical reaction (see Burkholder et al., 2020, Section 4G). In the absence of light, the release of Br₂ and Br is limited by the availability of Br[−] on the disordered air–ice interface.

In the absence of light, the release of Br₂ or Br is limited by the availability of Br[−] at the disordered air–ice interface. These reactions suggest that HOBr acts as the main reservoir species of bromine in snow. The photolysis pathways of HOBr in air (Burkholder et al., 2020, Section 4G) are:



Analogous to organic nitrates at the disordered air–ice interface, the quantum yields for above photochemical reactions may be smaller than in air due to the solvent cage effect trapping the products between the molecule structure of the solvent (González-Sánchez et al., 2023). Concerning the photochemical activation of reservoir HOBr, the e-folding depth – the distance over which the light flux is attenuated to e^{-1} – in snow in dependency of grain size and snow density has to be considered. The e-folding depth, depending on snow grain size and density, maximizes between (400 – 450 nm) and can reach up to 55 cm in fresh snow ($\rho = 120 \text{ kg m}^{-3}$) with grain diameters of $d = 0.35 \text{ mm}$ and drops to 10 cm in hard packed snow ($\rho = 350 \text{ kg m}^{-3}$, $d = 0.1 \text{ mm}$) (Kokhanovsky, 2022). This transmittance maximum coincides with the observed spectral maximum of incident sunlight in the Arctic between 450 – 550 nm (Grenfell and Perovich, 2008). Given that the bromide reservoir in snow is indeed build by HOBr at the disordered air–ice interface, these maxima also coincide with the photodissociation wavelength of HOBr (R4).

The roles of multi-year sea ice and snow cover appear to be understated in this mechanism (Falk et al., 2025) as regions covered by multi-year sea ice may serve as a more significant source of reactive bromine than previously assumed (Peterson et al., 2019). This is further backed up by back-trajectory calculations for air masses with observed BrO column enhancements at Ny-Ålesund that correlate more strongly with multi-year sea ice than first-year sea ice (Li et al., 2026).

The major source of bromide in snow on sea ice is upward brine migration from the snow-sea ice interface to a height of about 20 cm (Domine et al., 2004). This depth is comparable to, or even exceeds, the average spring snow depth over first-year sea ice



($15.1 \pm 4.6 \dots 17.6 \pm 8.3$) cm, but is generally smaller than that over multi-year sea ice ($24.2 \pm 6.9 \dots 26.8 \pm 8.5$) cm (Kwok et al., 2020), indicating that direct brine influence may extend throughout much of the snowpack over first-year sea ice but is likely confined to the lower layers over multi-year sea ice. The overlying snowpack is primarily influenced by deposition of sea salt aerosols (SSA) and gaseous Br_y , occurring on both marine and coastal snow (Domine et al., 2004). In laboratory experiments using artificial snow and sea ice, Huang et al. (2025) demonstrated that snow stratification resulting from variations in grain size and degree of metamorphism can further restrict the vertical extent of brine migration. Despite high bromide concentrations, Pratt et al. (2013) found no evidence for Br_2 production directly from sea ice, brine icicles, and basal snow under O_3 treatment, but for both snow on sea ice and coastal surface snow. Lab experiments confirmed that the heterogeneous reactivity of bromide with ozone is quickly lost during snow aging (Edebeli et al., 2020).

The primary source of atmospheric Br_y is sea salt aerosol dehalogenation, whereby multiphase chemical reactions release halogens from aerosol particles (Sander et al., 2003). Both primary SSA and Br_y can then be deposited onto snow after which secondary SSA are formed in blowing snow conditions with wind speeds exceeding 13 m s^{-1} (Yang et al., 2005). The accompanying strong electric fields might promote electrochemical reactions affecting the in-snow ion chemistry (Tkachenko and Jacobi, 2024). Depending on the aerosol size, up to 30% of the initial bromide content would form gaseous Br_2 and thus be lost from the aerosol particle, while smaller aerosol particles would gain bromide from the gas-phase during coagulation (Yang et al., 2005, 2008). Li et al. (2026) found indications that airborne aerosols are substantial in sustaining elevated BrO particle number densities both as halide source and reactive surface. Other minor contributors to the atmospheric bromine load are very short-lived organic bromine substances from anthropogenic or oceanic sources (Falk et al., 2017).

The sodium to bromide ratio in standard seawater is $\text{Na} : \text{Br} = 162$ (Millero et al., 2008). An observed bromide depletion in snow samples compared to this seawater reference would suggest a local bromine release (Br or Br_2), while an enhancement is usually interpreted as deposition of Br_y from gas-phase originating from BEs (e.g., Jacobi et al., 2012).

Combining both bromine release from blowing snow and the bulk snow, modeling studies showed that blowing snow only provides a minor contribution to reactive bromine in the Arctic troposphere (Marelle et al., 2021; Swanson et al., 2022). For the snow bulk emission, recent modeling studies (Zhai et al., 2023; Gong et al., 2025; Falk et al., 2025) suggest a better representation of BEs and ODEs when activation/deactivation of bulk emissions by fresh snow/melting at the end of the season and more realistic multi-year sea ice distributions were considered. Long-term ozone monitoring data in the Arctic indicate that the Arctic sea ice retreat and loss of multi-year sea ice cover induced by climate warming led to a significant decrease in frequency and strength of ODEs post the 2007 major decline in multi-year Arctic sea ice cover (Falk et al., 2025), whereas satellite-derived BrO VCD show an increasing trend (Bougoudis et al., 2020).

Taking these results into consideration, we reconsidered the role of snow acting as a reservoir for reactive bromine species responsible for BEs. Therefore, we explore whether gaseous inorganic bromine deposition has the potential to replenish bromide in fresh snow and provide sufficient bromide to enable bromine explosions and ozone depletion events at larger-scales. To constrain the availability of this reservoir bromide, we consider its vertical distribution based on model simulations and field observations. Furthermore, we investigate the spatio-temporal chemical partitioning of bromine dry deposition over the



pan-Arctic region in the context of the seasonality of bromine explosions. With our improved understanding of the underlying mechanism we address the question, why BEs occur in spring, but not in fall.

To investigate these processes, we combine specified-dynamics chemistry-climate model simulations with observational data. The simulations were performed with the ECHAM/MESSy Atmospheric Chemistry (EMAC) model (Jöckel et al., 2005, 2016) (Section 2.1), while the observational dataset comprises the chemical analyses of Arctic snow samples collected during a field campaign around Ny-Ålesund (Svalbard) in April 2024, complemented by regularly sampled snow from Gruvebadet (Ny-Ålesund) analyzed for ion concentrations (Section 2.2). A simple offline steady-state snow model with dynamically evolving layers (SMELs) was developed to compare modeled bromine deposition with bromide concentrations in our snow samples (Section 2.3). In Section 3, we will first investigate the modeled pan-Arctic spatio-temporal partitioning of Br_y and Br_{org} dry deposition (Section 3.1) and present the bromide profiles from the field measurements (Section 3.2). Results of SMELs driven by CCM simulations are compared to the observations (Section 3.3) to identify a bromine explosion signal (Section 3.4). Finally, we discuss (Section ??) and summarize our findings in Section 4.

2 Methods and data

This study combines chemistry-climate model simulations with chemical analyses of Arctic snow samples. Section 2.1 describes the EMAC model setup and simulation experiments, while Sect. 2.2 presents the snow sampling strategy and analytical procedures. To facilitate a direct comparison between simulated atmospheric composition and observed snow chemistry, Sect. 2.3 introduces the offline steady-state snow model with dynamically evolving layers (SMELs).

2.1 Chemistry-climate model description and setup

The simulations were conducted with the Modular Earth Submodel System (MESSy, version 2.55.2) coupled to the ECHAM5.2 basemodel (ECHAM/MESSy), hereafter referred to as EMAC, at T42L90MA resolution. MESSy provides a modular framework for the integration of Earth system components, including the atmosphere, ocean, land surface, and their associated subsystems (Jöckel et al., 2005, 2016). Owing to its modular architecture, identical numerical representations of geophysical and chemical processes, as well as their parameterizations, can be applied across different basemodels. Atmospheric chemistry is represented by the Module Efficiently Calculating the Chemistry of the Atmosphere (MECCA) (Sander et al., 2019) using the CCMI-base-02 chemical mechanism. Within this setup, iodine and mercury chemistry are disabled. The employed mechanism includes 261 gas-phase reactions, 12 heterogeneous reactions, and 80 photolysis processes. The exchange of seawater-derived trace gases with the atmosphere, including dimethylsulfate (DMS), bromoform (CHBr_3), and dibromomethane (CH_2Br_2), is calculated by the AIRSEA submodel (Pozzer et al., 2006). Air-sea fluxes are determined from the concentration difference between the uppermost ocean layer and the lowermost atmospheric layer, with the solubility of each compound prescribed by its temperature dependent Henry's law coefficients. Oceanic concentrations of brominated very short-lived substances (VSLs) are adopted from the climatology of Wang et al. (2019a). Emissions of the less abundant VSL species (CHCl_2Br , CHClBr_2 , and CH_2ClBr) follow the inventory of Warwick et al. (2006). Surface mixing ratios of the long-lived brominated compounds



CF₃Br, CF₂ClBr, and CH₃Br are constrained towards observational climatologies using the TNUDGE submodel. For the representation of bromine explosion events, we apply the EMAC implementation of the bromine release and recycling mechanism proposed by Toyota et al. (2011) and implemented into EMAC by Falk and Sinnhuber (2018). Consistent with an earlier study (Falk et al., 2025), bromine activation is restricted to temperatures below the threshold value of $T_{\text{crit}} = -10^\circ\text{C}$.

The present study extends the model configuration and experimental design described by Falk et al. (2025). In particular, the simulation that incorporates bromine explosions together with a simplified parameterization of SSA conversion to gaseous Br₂ emissions and brominated VSLs was continued through June 2024 to enable comparison with the field measurements (*sfa017*→*sfa028*). An additional experiment, *sfa025*, was performed that accounts for both SSA-derived Br₂ emissions and brominated VSLs emissions with BEs switched off (Table 1). All model experiments were performed in specified-dynamics mode, in which meteorological fields are nudged towards reanalysis data while atmospheric chemistry evolves interactively. European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5) (Hersbach et al., 2020) was used to generate the nudging data.

Table 1. List of model experiments. Indicated are whether bromine explosion mechanism, sea-salt aerosol dehalogenation parameterization, or brominated very short-lived substances were used as bromine source. We use MESSy v2.55.2 modifications described in Falk et al. (2025) nudged to ERA5 for all model experiments.

Exp.	Period	BE	SSA	VSLs	Alias
sfa017 [†]	2019-01–2020-07	on	on	on	Br _y (VSLs, SSA, BE) + Br _{org}
sfa025	2019-01–2024-07	off	on	on	Br _y (VSLs, SSA) + Br _{org}
sfa028	2020-07–2024-07	on	on	on	Br _y (VSLs, SSA, BE) + Br _{org}

[†] Simulation originally performed for Falk et al. (2025).

2.2 Snow samples

Snow sampling was conducted from April 18 to 27, 2024 close to Ny-Ålesund, a research village at 78°55'N, located in northwestern Spitsbergen, south of the Kongsfjorden (Fig. 2). Sampling locations included the Gruebadet site, where long-term monitoring of snow properties is performed, as well as the two glaciers, Austre Brøggerbreen and Austre Lovénbreen. The sampling at the Gruebadet site was done in the frame of the long-term monitoring of physical and chemical properties of the seasonal snowpack. The sampling sites on the glaciers were located close to the mass balance points of the glaciers. The general characteristics of the three sites are listed in Table 2.

Preceding the sampling, weather conditions at Ny-Ålesund were below freezing, with daily mean temperatures ($\overline{T}_{\text{air}}$) ranging from -24°C to -4°C . One snowfall event on 4–5 April led to the accumulation of around 22 to 25 cm of fresh snow resulting in a snow depth of 61 cm at Ny-Ålesund research station (SN99910, 8 m a.s.l.) and 90 cm at the Bayelva monitoring station (SN99917, 25 m a.s.l.; source: <https://seklima.met.no/>, last accessed 2026-07-10). Freezing conditions persisted until April 19, when the passage of a low-pressure system advected warm and moist air masses to the region and was accompanied by wind



Table 2. Overview of snow sampling at three sites around Ny-Ålesund research station in April 2024.

Location	Date	Time	Snow height (cm)	T_{air} (°C)	No. samples
Austre Brøggerbreen [†]	2024-04-18	12:15–13:35	160	-6.9	11
Gruvebadet	2024-04-23	15:00–16:00	54	0.9	5
Austre Lovénbreen [‡]	2024-04-27	11:00	179	-3.5	10

[†] Uphill the last mass balance post; [‡] at point H3CD.

speeds of up to 18 m s^{-1} . As air temperatures subsequently increased to $+4^\circ\text{C}$, blowing snow quickly transitioned into rainfall. Temperatures generally exceeded freezing during daytime and dropped below freezing during the evening and nighttime hours until the end of the experiments. During this period, reported snow depths decreased to 23 cm at Ny-Ålesund and 56 cm at Bayelva. The sampling at Austre Brøggerbreen took place before the warm-air intrusion of April 19, whereas samples from Gruvebadet and Austre Lovénbreen were collected afterwards. The sampled snowpack at Gruvebadet had become water-saturated, resulting in slush-like conditions and substantially altered snow physical properties, while the thicker snowpack on the Austre Lovénbreen was still below freezing temperature.

All samples were taken with 50 mL precleaned sampling tubes. At Austre Brøggerbreen and Austre Lovénbreen, the uppermost 10 cm were sampled as a cross-section. All other samples were taken at the center within a snow bin of defined depth. The bin depths were 15 cm at Austre Brøggerbreen and 20 cm at Austre Lovénbreen. At Gruvebadet the sampling was performed in accordance to the snow stratification.

All samples were stored at -20°C in Ny-Ålesund, during shipment from Ny-Ålesund to Grenoble, and at Grenoble. Prior to chemical analysis, the samples were melted at 5°C in a refrigerator and kept in an autosampler at 5°C until analysis. Anions and cations were measured using ion chromatography (e.g., Jacobi et al., 2019) and were analyzed with a combined suppressed conductivity *ThermoScientific Integrion* instrument using an AS11HS-4 μm column with potassium hydroxide (KOH) gradient eluent for anions and a CS16-4 μm column with methanesulfonic acid (MSA) isocratic eluent for cations. Calibration solutions were prepared from individual elemental solution and diluted to a 6-level calibration curve adjusted to the concentration range of the samples. The typical detection limit is below 1 ppbv ($= 0.0125 \mu\text{mol L}^{-1}$), while the analytical precision is around 1 %. Temperature and density profiles as well as determined sodium and bromide concentrations at the three sites are tabulated in Appendix Tables B1–B5. The results are presented in Section 3.2.

2.3 Dynamic snow layer model

While Toyota et al. (2014, a) developed a one-dimensional snow model that explicitly describes chemical and mass-transfer processes within the interstitial air of the snowpack and successfully applied it to Arctic ozone and mercury depletion events (Toyota et al., 2014, b), current CCMs generally do not resolve snowpack processes. Instead, bromine activation is typically parameterized at the snow–atmosphere interface, with snow physical structure and in-snow chemical transformations remaining unresolved (e.g., Toyota et al., 2011). Detailed snowpack models capable of resolving the physical evolution of individual



Figure 2. Approximate locations of snow sampling around Ny-Ålesund reserach station, April 2024. The map was retrieved from <https://toposvalbard.npolar.no/> on 2026-05-26 provided by the Norwegian Polar Institute.

snow layers have long been available (Bartelt and Lehning, 2002; Vionnet et al., 2012) and are widely applied in operational avalanche forecasting as well as climate and hydrological research. Several studies have extended such models to account for the effects of deposited impurities, primarily light-absorbing impurities (LAIs) such as black carbon and mineral dust, to improve simulations of snow albedo. In most cases, however, impurity concentrations were prescribed from field observations and did not evolve dynamically with deposition (Jacobi et al., 2015; Niwano et al., 2012). A first coupling between atmospheric deposition and a detailed snow model was achieved by Tuzet et al. (2017), who integrated LAI deposition calculated by an atmospheric model into the CROCUS snowpack model. For sea-salt species, Jacobi et al. (2019) combined CROCUS simulations with dry and wet deposition estimates derived from atmospheric and precipitation measurements. However, these deposition fluxes were applied a posteriori to the simulated snow layers rather than being incorporated into a temporally evolving snowpack.

Therefore, we developed a simple offline steady-state snow model with dynamically evolving snow layers (SMELs). The dynamically evolving layers L_i account for wet deposition by tracking atmospheric bromine species deposition during snow fall ($m_{Br}^{L_i}$) combined with the snow accumulation per layer over time ($m_{snow}^{L_i}$) as well as dry deposition to the snow surface ($m_{Br}^{I_i}$) without snow fall. This provides a direct link between CCM output and snowpit observations by enabling resampling of the modeled snowpack according to the field sampling strategy. As a result, we can (i) quantify sampling-induced biases in bromide concentrations and (ii) distinguish a bromine explosion signal from the underlying atmospheric bromine background.

To simulate the seasonal accumulation of bromide-containing snow, SMELs requires hourly snow precipitation fluxes (Φ_{snow}^m), organic and inorganic bromine dry deposition fluxes (Φ_{Br}^m), and surface air temperature (T_{air}) from the CCM as input. The model is intentionally designed as a simplified framework and therefore relies on a minimal set of steady-state

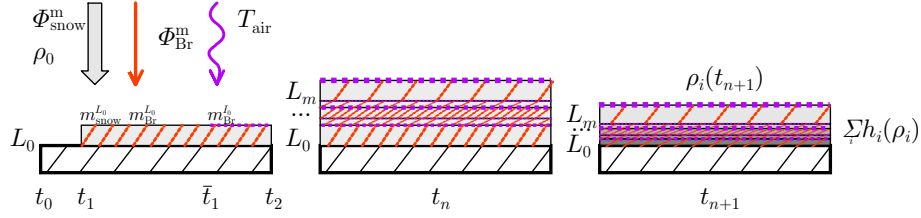


Figure 3. Schematic of dynamic-layer SMELs. An active Layer L_i is defined between the beginning of two snowfall events. During snowfall ($t_i \rightarrow \bar{t}_i$), snow mass ($m_{\text{snow}}^{L_i}$) and bromide mass in the snow ($m_{\text{Br}}^{L_i}$) are accumulated in l sub-layers. An active layer is concluded by accumulation of bromide on the snow interface ($m_{\text{Br}}^{L_i}$) until the beginning of the next snowfall event ($\bar{t}_i \rightarrow t_{i+1}$). At the evaluation time t_{n+1} , the total snowpack height $\sum_i h_i$ is computed using a snow age and temperature dependent density function $\rho_i(t_{n+1}, T_i)$ on each layer.

assumptions. The lateral redistribution of snow is neglected, implying that the local snow mass balance is solely controlled by deposition and accumulation. The snow mass is conserved after deposition, i.e. losses through sublimation or melting are not represented. The liquid-water-driven snow metamorphism and associated vertical transport of dissolved ions are neglected by excluding percolation processes. This means that bromide deposited within a snow layer is assumed to remain fixed to that layer, such that no ion mobility occurs within the snowpack. Neglecting lateral redistribution is a reasonable approximation at the T42 model resolution ($2.7851^\circ \times 2.8125^\circ$), where subgrid-scale transport processes are assumed to balance on average. In contrast, the omission of sublimation, melting, and percolation processes is expected to result in a positive bias in simulated snow accumulation and snowpack height, particularly during periods with above-freezing temperatures or rain-on-snow events.

As shown in Fig. 3, an active layer L_i is defined between the start date and time of two snowfall events ($t_i \rightarrow t_{i+1}$). From the start to the end of snowfall ($t_i \rightarrow \bar{t}_i$), snow mass ($m_{\text{snow}}^{L_i}$) and bromide mass in the snow ($m_{\text{Br}}^{L_i}$) are accumulated in l sub-layers depending on the temporal resolution of the CCM output. An active layer is concluded by accumulation of bromide on the snow interface ($m_{\text{Br}}^{L_i}$) until the start of the next snowfall event ($\bar{t}_i \rightarrow t_{i+1}$).

As Φ_{snow}^m could become infinitesimal small (very light snow fall) in EMAC, we introduced a snow precipitation flux threshold $\Phi_{\text{snow}}^{\text{crit}}$ in order to define the start and end of a snowfall event. To keep the amount of unaccounted snow mass accumulation below 0.2%, we used $\Phi_{\text{snow}}^{\text{crit}} = 8.4 \cdot 10^{-7} \text{ kg m}^{-2} \text{ s}^{-1}$ resulting in a critical snow accumulation threshold of $\Sigma h_{\text{snow}}^{\text{crit}} \approx 0.03024 \text{ mm h}^{-1}$. Similarly, Liston et al. (2018) defined a snow accumulation threshold of 0.03 mm in 3 h to account for an overestimation of very light snow fall when using MERRA-2 reanalysis data to force their snow model.

At the evaluation time t_{n+1} , the total snowpack height $\sum_i h_i$ is computed using the snow age ($\Delta t_i = t_{n+1} - \bar{t}_i$) and temperature T_i dependent density function $\rho_i(t_{n+1}, T_i)$ for each layer. First, the snowpack settling is approximated by a simple exponential aging function for the snow density $\rho_i(t_i)$:

$$\rho_i(t_i) = (1 - e^{-\Delta t_i \cdot \tau}) \cdot (\rho_{\text{lim}} - \rho_0), \quad (1)$$

with the decay rate $\tau = \frac{\rho_{\text{lim}} - \rho_0}{t_s}$ in h^{-1} , the empirical densities of aged snow $\rho_{\text{lim}} = 400 \text{ kg m}^{-3}$ and fresh snow $\rho_0 = 100 \text{ kg m}^{-3}$, and an empirically estimated time t_s to reach ρ_{lim} of approximately 4 months in hours.



230 Furthermore, we estimate the snow temperature T by the *frozen-in* air temperature T_{air} during snow fall to account for surface melt without mass loss. For the active snow layer L_i in contact with air, we use a diffusive thermalization from the air–snow interface during times of no snow fall by computing a nearest-neighbor average iteratively over all l_i sub-layers. No thermal conductivity between the snow layers is considered as snow has a high thermal insulation capacity. The resulting sub-layer temperatures are then used to emulate a melting-refreezing-cycle in the snow density function ($\rho_i(t_{n+1}) \rightarrow \rho_i(t_{n+1}, T)$).
 235 This means, that the density of each sub-layer with $T > T_{\text{melt}}$ is set to the density of liquid water $\rho_{\text{water}} = 1000 \text{ kg m}^{-3}$. The average over all sub-layer densities then defines the temperature dependent snow density for each layer.

In the following, we will refer to the bromide incorporated into the active snow layer during snowfall, $m_{\text{Br}}^{L_i}$, as *bulk* bromide and the bromide deposited onto the surface between snowfall events, $m_{\text{Br}}^{I_i}$, as *interface* bromide.

In Figure 4, the layer-wise build-up of bromide in a snowpack is exemplarily shown for the nearest neighboring grid cell of
 240 Ny-Ålesund evaluated for different dates in winter 2023/2024. Here, we consider the dry deposition of $\text{Br}_y(\text{VSLs, SSA, BE}) + \text{Br}_{\text{org}}$ and the prognostic re-emission of $\text{Br}_2 + \text{BrCl}$ in accordance to the Toyota mechanism for BEs (experiment *sfa028*) for the computation of the total amount of bromide deposited on each layer. The modeled snow height ranged from 21 cm on 1 January to 53 cm on 1 March as well as on 1 April and 56 cm on 1 May, respectively. From the Norwegian Weather Service climate data (available at <https://seklime.met.no/>, last accessed 2026-08-04), the observed daily average snow depth
 245 at the measurement stations at Ny-Ålesund and Bayelva amounted to 22/42, 25/64, 35/70, and 21/55 cm, respectively. This indicates that the variability of snow height in proximity to our measurement site at Gruebadet varies quite substantially and that SMELs captures the average height around sea level reasonably well.

The SMELs simulation indicates several regions with $\rho_i > \rho_{\text{lim}}$ due to melting-refreezing-cycles that might be identified as ice layers in field observations. An ice layer at the bottom of the snowpack can be dated back to early winter, while a second
 250 ice layer coincides with a warm-air intrusion at the end of January.

The bromide area density $\rho_A^{\text{Br}^-}$ in $\mu\text{g m}^{-2}$ for the bulk is shown as histogram with bins of variable size. As no layer depth can be assigned to $\rho_A^{\text{Br}^-}$ on the snow interface, this amount of bromide is indicated with a hatched rectangular of fixed size. The total bromide area density in each active layer L_i is displayed by black crosses. Blue crosses would indicate that more bromine was emitted than was available from the immediate sub-layer.

255 Finally, the modeled snowpack is resampled to match the vertical binning of the snowpit samples, thereby enabling a direct comparison of simulated and observed bromide concentrations and the quantification of sampling biases (Sect. 3.3). SMELs also predicts bromide concentrations in the surface snow layer, where recent atmospheric deposition and bromine activation are most apparent. In the model framework, the BE signal is defined as the bromide enhancement relative to the SSA and VSLs background simulation. An analogous background correction is applied to the observations using the seawater $\text{Na}^+ : \text{Br}^-$ ratio,
 260 allowing a consistent comparison between modeled and observed BE signals (Sect. 3.4).

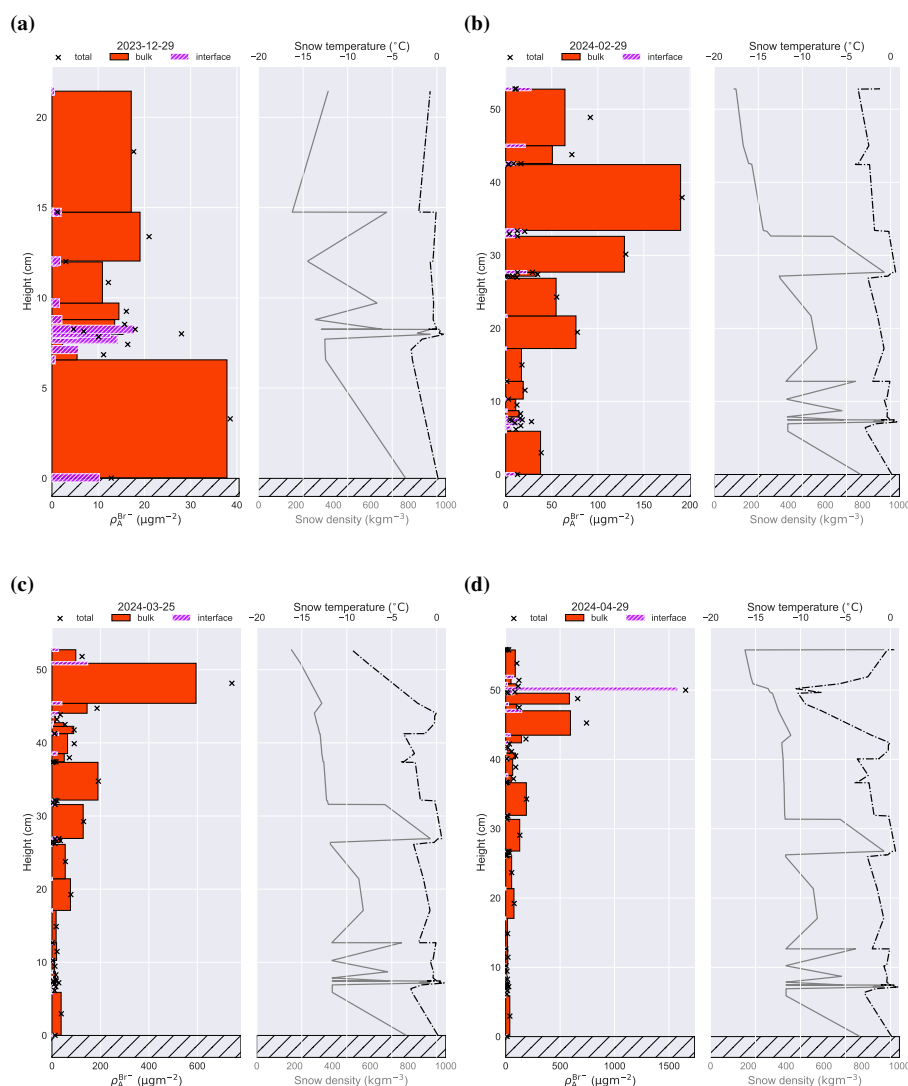


Figure 4. Example build-up of cumulative bromide in a SMELs modeled snowpack at the nearest neighboring grid cell of Ny-Ålesund, Svalbard at different dates in winter 2023/2024: (a) 1 January, (b) 1 March, (c) 1 April, and (d) 1 May. Dry deposition of Br_y (VSLs, SSA, BE) + Br_{org} and re-emission of Br_2 + BrCl due to BEs are considered. Dates displayed in the panels refer to the end date of the last snow fall before evaluation. Layers with $\rho_i > \rho_{\text{lim}}$ indicate ice layers due to a melting-refreezing-cycle.

3 Results

The results are presented from a pan-Arctic to a local scale. We first analyze the spatial and temporal patterns of bromine deposition simulated by EMAC (Sect. 3.1) and subsequently look at local inhomogeneities in bromide concentrations measured in snow samples from the Ny-Ålesund region (Sect. 3.2). Finally, the SMELs model is used to link atmospheric bromine

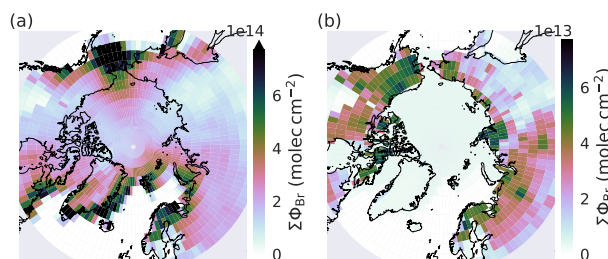


Figure 5. Pan-Arctic spatial distribution of cumulative dry deposition from the EMAC model experiment *sfa025* (excluding BEs). Shown are (a) Br_y and (b) Br_{org} folded with fractional sea ice and snow cover for January–May 2024. Br_y deposition is concentrated over sea ice and coastal regions, while Br_{org} deposition occurs primarily over land. Note the different order of magnitude. Made with Cartopy (Met Office, 2010–2022) and coastlines from Natural Earth.

265 deposition to snowpack bromide concentrations (Sect. 3.3) and to evaluate whether a bromine explosion signal can be discerned in the observations (Sect. 3.4).

3.1 Modeled pan-Arctic bromine deposition

In order to understand BEs based on a limited bromide source better, we first study the spatio-temporal distribution and partitioning of bromine dry deposition from the gas-phase over the snow and ice covered pan-Arctic region. Here, we consider
 270 bromine emissions from VSLS and SSA only (*sfa025* in Table 1).

Because bromine deposited during early winter is likely buried in deeper snow layers by subsequent snowfall or displaced by wind-driven snow transport, it becomes less accessible for reactivation and is therefore unlikely to contribute directly to BEs at the location of its deposition. Bromine deposited from January onward, however, may remain accessible within the upper snowpack and provide a source for BEs during March and late spring. We therefore consider the cumulative dry deposition of
 275 Br_y and Br_{org} between January and May, weighted by fractional sea-ice and snow cover (Fig. 5), as a proxy for the bromine reservoir available for springtime activation.

The cumulative bromine dry deposition displays a distinct spatial pattern: Br_y deposition is concentrated over sea ice and coastal regions, while Br_{org} deposition occurs primarily over land. Inorganic bromine dominates the total deposited bromine budget. Appendix Fig. A1 displays that bromine deposition is strongest and extends furthest from the open ocean in January, with both the deposited amount and spatial coverage steadily declining towards late spring. Integrated over spring 2024, the
 280 amount of bromine deposited from sea-salt aerosol dehalogenation onto Arctic snow and ice surfaces is sufficient, if reactivated, to produce tropospheric BrO VCDs comparable to those typically observed over Arctic sea ice $((1-8) \cdot 10^{13} \text{ molecules cm}^{-2}$; Bougoudis et al., 2020).

However, not all of this deposited bromine is photochemically available for springtime reactivation. In the absence of light,
 285 dissolved BrNO_3 is converted to HOBr (R2). As long as dissolved Br^- provided by HBr is available, HOBr reacts immediately to form Br_2 (R1), which is released. When all Br^- is consumed a HOBr reservoir builds up on the disordered air–ice

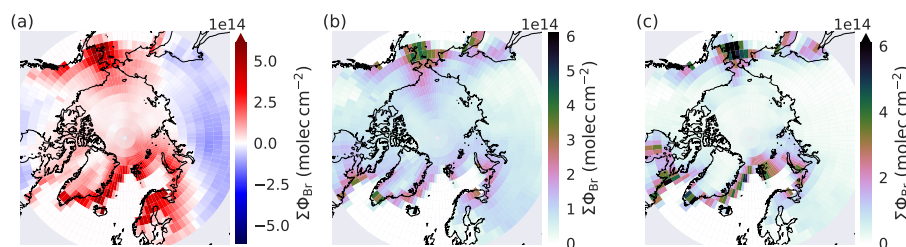


Figure 6. Pan-Arctic spatial distribution of the bromide reservoir in HOBBr and prognostic Br₂ emissions folded with fractional sea ice and snow cover accumulated for January–May 2024 from the EMAC model experiment *sfa025* (excluding BEs). (a) HOBBr reservoir (red), Br⁻ reservoir (blue), (b) Br₂ emission from dark-reaction (R1), and (c) Br₂ emission from reservoir HOBBr multiplied with photochemical reaction rate (J_{HOBBr}) computed for the lowermost grid cell. Made with Cartopy (Met Office, 2010–2022) and coastlines from Natural Earth.

interface of the snow grains, which serves as a proxy for the snowpack reservoir of reactive bromine available for subsequent bromine activation. In this work, we do not consider Br⁻ contributions from SSA deposition.

In Fig. 6a, the cumulative HOBBr reservoir is shown for January–May 2024. Red colors indicate regions with an overall excess of HOBBr compared to HBr while blue colors imply a depletion in HOBBr in comparison with HBr. In the HBr enhanced regions, a dark-reaction with ozone (R3) may trigger a Br₂ release proportional to the amount of available Br⁻, while in the HOBBr enhanced regions a supplemental HBr deposition is necessary for a subsequent release of bromine to the gas-phase.

The HOBBr reservoir can act as a source of Br₂ through both heterogeneous reactions in the dark and photochemical processes under illumination. The cumulative Br₂ production associated with the dark pathway (R1) and the photolytic pathway is shown in Fig. 6b, c, respectively. For the latter, Br₂ emissions were estimated using the HOBBr photolysis frequencies (J_{HOBBr}) calculated by the MESSy submodel *JVAL* for the lowermost atmospheric model level across the pan-Arctic region. These atmospheric photolysis frequencies should be regarded as an upper-limit estimate, as the radiative environment and thus the effective J -values at the disordered air–ice interface are expected to differ from those in the overlying air.

The spatial distributions of the dark- and photolytic emission pathways are very similar. Both exhibit pronounced hotspots along the sea-ice margins of the North Atlantic and North Pacific, particularly in the Bering Sea, Labrador Sea, Sea of Okhotsk, Barents Sea, and Greenland Sea. These regions correspond to areas where the simulated HOBBr reservoir and the associated potential for Br₂ release are largest. In contrast, satellite observations indicate the highest occurrence frequencies of enhanced BrO VCDs over the Chukchi Sea, Laptev Sea, and the Canadian Arctic Archipelago (Seo et al., 2020).

The zonally integrated distributions (Fig. 7) reveal three distinct phases of bromine reactivation. During January and February, a late-winter regime is characterized by the build-up of a substantial HOBBr reservoir north of 60°N and strong Br₂ production through the dark reaction of HOBBr with HBr (Fig. 7a,b). With the return of sunlight, photolytic release becomes increasingly important, leading to pronounced photolytic Br₂ emissions between 75 and 90°N during April and May (Fig. 7c). Another, not explicitly shown, distinct reactivation regime may occur in March when HBr deposition exceeds that of HOBBr.

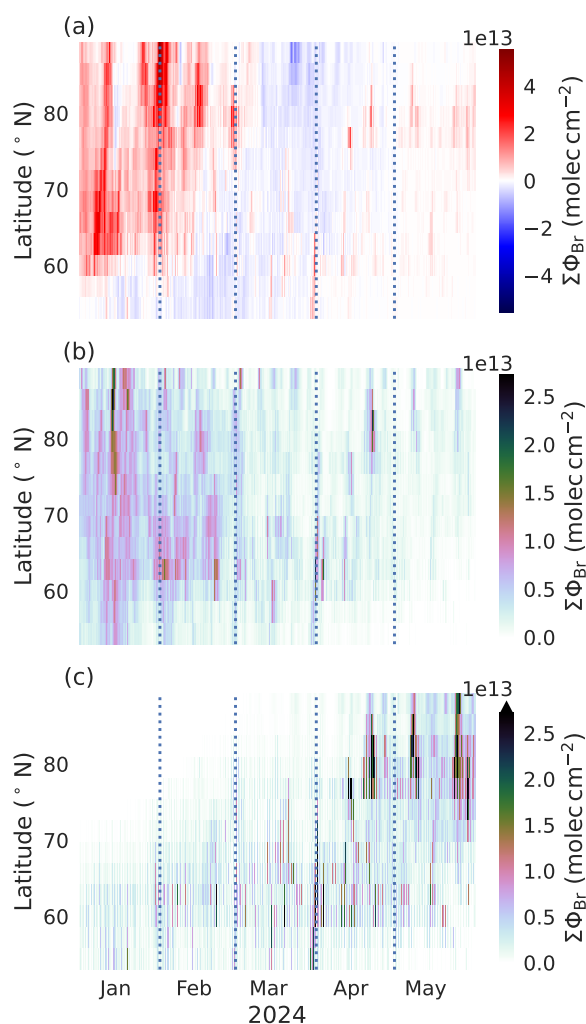


Figure 7. Pan-Arctic zonal-temporal distribution of the bromide reservoir in HOBr and prognostic Br₂ emissions folded with fractional sea ice and snow cover accumulated for January–May 2024 from the EMAC model experiment *sfa025* (excluding BEs). (a) HOBr reservoir (red), Br[−] reservoir (blue), (b) Br₂ emission from dark-reaction (R1), and (c) Br₂ emission from reservoir HOBr multiplied with photochemical reaction rate (J_{HOBr}) computed for the lowermost grid cell.

Under these conditions, bromide can be activated directly through heterogeneous reactions with ozone, rather than by recycling
 310 of the accumulated HOBr reservoir, resulting in an ozone-driven pathway that exhibits a different seasonal behavior.

Bromine released through these pathways is subsequently partitioned among the various Br_y species, transported by the prevailing circulation, and redeposited elsewhere. Therefore, the spatial distribution of enhanced BrO VCDs observed from space is expected to be displaced from the underlying source regions and should be interpreted as the integrated outcome of bromine activation, chemistry, and transport.

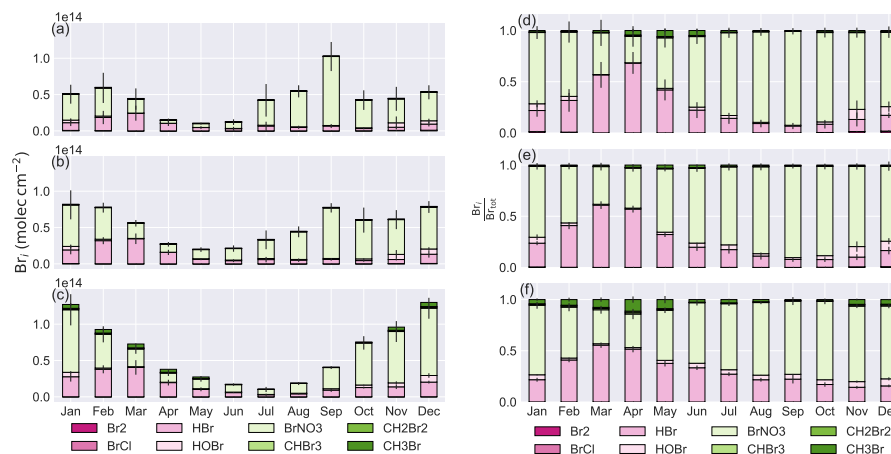


Figure 8. Modeled multi-annual average partitioning of accumulated gas-phase bromine dry deposition ($Br_y(VSLS,SSA) + Br_{org}$) for the years 2019–2024 computed for the (a, d) North Pole, (b, e) grid cells with sea ice cover fraction exceeding 0.8, and (c, f) grid cells with snow cover fraction exceeding 0.8. Absolute values shown in (a–c); values relative to absolute bromine dry deposition displayed in (d–f).

While the previous analysis focused on spring 2024, the pronounced seasonality of bromine explosion events motivates an examination of the full 5.5-year simulation period. Figure 8a–c displays the climatological seasonal cycle of bromine dry deposition species. The total bromine deposition decreases from spring into summer in concert with the retreat of snow and sea-ice cover. Although substantial amounts of $BrNO_3$ are deposited over sea ice during fall, deposition of HBr remains comparatively weak. Because the present experiment does not include bromide recycling within the snowpack nor bromide from SSA, this imbalance suggests that the chemical conditions required for efficient bromine activation are less favorable during fall.

To further investigate this hypothesis, Fig. 8d–f presents the species partitioning normalized by total bromine deposition. All three regions exhibit a remarkably similar seasonal cycle. Only during February–May does the $BrNO_3:HBr$ ratio favor efficient dark Br_2 production through the HOBr–HBr pathway, providing a potential explanation for why BEs predominantly occur in spring rather than fall.

The climatological deposited bromine burden ranges between $(1–13) \cdot 10^{13}$ molecules cm^{-2} per month, which is comparable to typical Arctic tropospheric BrO VCDs of $(1–8) \cdot 10^{13}$ molecules cm^{-2} observed from satellite measurements (Bougoudis et al., 2020). Furthermore, the modeled seasonal cycle, characterized by decreasing values from March to July and increasing values during August and September, closely resembles the observed BrO seasonality (Bougoudis et al., 2020). This agreement suggests that bromine dry deposition and subsequent snowpack storage represent a bromine reservoir of sufficient magnitude to sustain Arctic springtime bromine activation.

In summary, these results indicate that the occurrence of Arctic bromine explosion events is controlled not only by meteorological conditions but also by the chemical composition of the deposited bromine reservoir. Dark Br_2 emissions over sea ice and most coastal regions are generally HBr-limited, while ozone-driven bromine activation may provide an additional source



335 in early spring and inland regions. During April and May, photolytic release becomes increasingly important. The springtime partitioning between BrNO_3 and HBr favours efficient bromine recycling and Br_2 production, whereas the lack of deposited HBr in fall largely inhibits these processes despite comparable BrNO_3 deposition.

3.2 Snow samples

To understand the availability of bromide for dark- and light-reactions, the vertical distribution of bromide in the snowpack
340 and the physical properties of the snow will be investigated in the following.

In Figure 9, the observed physical snow properties, density ρ and temperature T over snow height, are shown together with the measured bromide concentrations. Snow heights varied between 160 cm at Austre Brøggerbreen, 54 cm at Gruvebadet, and 173 cm at Austre Lovénbreen (Table 2). Snow densities in the lower snow layers at Austre Brøggerbreen (Fig. 9a) are comparable to those observed at Gruvebadet, with mean values of $\langle \rho \rangle \approx 367 \text{ kg m}^{-3}$ and $\langle \rho \rangle \approx 428 \text{ kg m}^{-3}$, respectively. The
345 uppermost 40 cm at Austre Brøggerbreen can be categorized as fresh or aged snow with densities ranging between 71 – 262 kg m^{-3} . No density profile was retrieved from Austre Lovénbreen.

The snow temperatures were in line with the varying air temperatures (Fig. 9b). The coldest snowpack was found at Austre Brøggerbreen. While the surface layer temperature was close to the air temperature, the underlying fresh snow reached a minimum temperature of $T = -12.5^\circ\text{C}$, followed by an approximately linear increase to $T = -6.9^\circ\text{C}$ towards the base of
350 the snowpack. Due to the warmer air temperatures, the snow temperature at Austre Lovénbreen was higher and was close to $T = -6^\circ\text{C}$ throughout the snow pit. At Gruvebadet, the snowpack was at $T = 0^\circ\text{C}$.

Both at Austre Brøggerbreen and Austre Lovénbreen, high concentrations of bromide were found in the uppermost 25 cm, with maximum concentrations of $[\text{Br}^-] = 0.122 \mu\text{mol L}^{-1}$ and $[\text{Br}^-] = 0.12 \mu\text{mol L}^{-1}$, respectively. Similar amounts have been measured at Gruvebadet ($[\text{Br}^-] = 0.134 \mu\text{mol L}^{-1}$) at a depth of 4 – 10 cm. In contrast to Austre Brøggerbreen, Austre
355 Lovénbreen data display a major enhancement of bromide concentration ($[\text{Br}^-] = 0.256 \mu\text{mol L}^{-1}$) at a depth of 50 cm.

For the observations, we expect the major source of bromide in the snow from SSA deposition. The amount of SSA and, thus, the concentration of SSA bromide, is proportional to the sodium ion concentration in the snow samples ($[\text{Na}^+]$). We define the observed relative bromide enhancement $[\text{Br}^-]_{\text{rel}}^{\text{obs}}$ as:

$$[\text{Br}^-]_{\text{rel}}^{\text{obs}} = \frac{[\text{Br}^-] - [\text{nss}]}{[\text{Br}^-]}, \quad (2)$$

360 with the SSA bromide background ($[\text{nss}]$) and the observed $[\text{Br}^-]$. We find a similar pattern at all probed sites (Fig. 10a): The surface layers display a pronounced depletion in bromide as do the lowest layers that date back to early winter. At the glacial sites also the mid-region in the snowpit is depleted for bromide. Probably due to the lower vertical resolution this cannot be seen at Gruvebadet. The average relative bromide enhancement between the areas of bromide depletion is remarkably similar at all sites and amounts to $\langle [\text{Br}^-]_{\text{rel}} \rangle = 0.35 \pm 0.15 \mu\text{mol L}^{-1}$.

365 Normalized by the maximum snow depth (Fig. 10b), the bromide profiles exhibit remarkably similar enhancement and depletion patterns across the three sites. Comparable gradients are found in the uppermost snow layers at all locations and

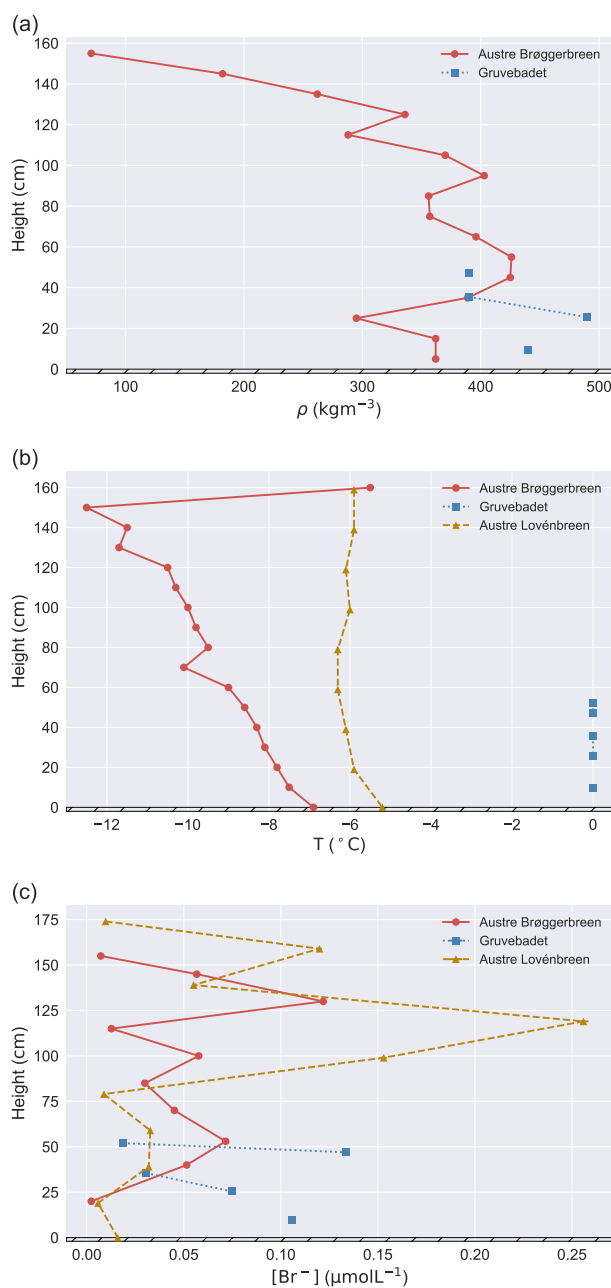


Figure 9. Measured physical properties of the snowpits around Ny-Ålesund in April 2024: (a) Snow density and (b) snow temperature. (c) Bromide concentrations from the laboratory analysis of the retrieved snow samples. Snow height was measured from the ground (solid ice layer) indicated by the hatched area to the snow surface.

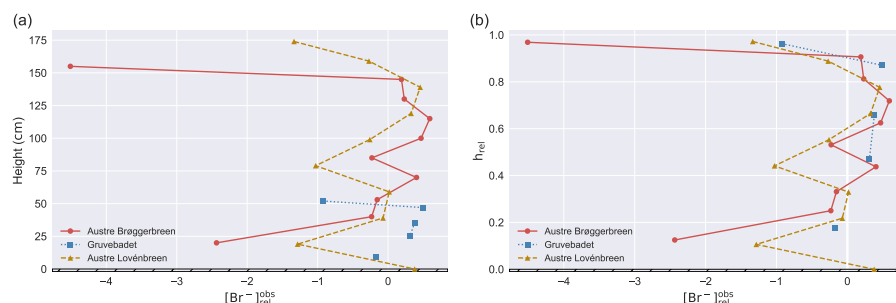


Figure 10. Observed relative bromide enhancement with respect to the expected bromide concentration from the Na : Br ratio in seawater ($[\text{Br}^-]_{\text{rel}}^{\text{obs}}$). Negative values indicate a depletion compared to the deposition of SSA. Ordinate axis is shown as (a) absolute height over ground and (b) relative height, normalized by the maximum snow depth.

in the lowermost layers at the two glacier sites. The most notable difference occurs between relative heights of 0.4 and 0.6, where bromide is enriched at Gruvebadet and Austre Brøggerbreen but depleted at Austre Lovénbreen. The overall agreement suggests that Gruvebadet and Austre Brøggerbreen experienced similar bromine deposition histories, whereas local emission
 370 processes may have had a larger influence at Austre Lovénbreen.

3.3 Dynamic snow layer model

Before analyzing the simulated bromide distributions, we evaluate the ability of SMELs to reproduce the observed snowpack conditions. On April 23 2024, the date of snow sampling at Gruvebadet, the simulated snow height was 54 cm. This agrees closely with the observed snow depth at Gruvebadet (54 cm; Appendix Table B4) and with the snow depth reported for Bayelva
 375 (56 cm), providing confidence in the modeled snowpack evolution prior to sampling.

A comparison of simulated and observed snow stratigraphy indicates that SMELs captures the overall snowpack structure at Gruvebadet reasonably well (Fig. 11a–c). The model produces two dense ice-rich layers ($\rho > 400 \text{ kg m}^{-3}$), one near the snowpack base (0–10 cm) associated with an early-winter melt-freeze event and a second at 25–30 cm. These layers are consistent with the observed basal ice layer and the ice layer at 19–21 cm depth. Minor differences in the simulated snowpack
 380 structure between the EMAC experiments are apparent, but such variability is expected even in a specified-dynamics setup and does not alter the overall correspondence with the observed snow stratigraphy.

However, the observed upper ice layer at 41–44 cm is absent from the simulation. A plausible explanation is the warm-air intrusion during the field campaign, which was accompanied by rainfall. As percolation processes are not represented in SMELs, the model cannot account for rainwater infiltration and refreezing within the snowpack. In reality, percolat-
 385 ing meltwater may have accumulated above less permeable layers, forming water-saturated slush snow before refreezing in colder parts of the snowpack. The lowest simulated snow temperatures occurred within the underlying settled snow layer ($200 \text{ kg m}^{-3} < \rho < 400 \text{ kg m}^{-3}$) at a height of approximately 45–52 cm, suggesting that refreezing of infiltrating water could have produced the observed upper ice layer.

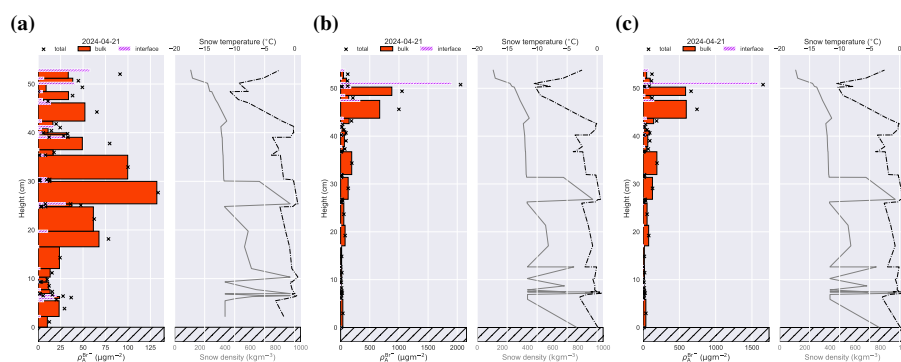


Figure 11. SMELs modeled snowpack and vertical bromide profiles evaluated at the nearest neighboring grid cell of Ny-Ålesund, Svalbard on 23 April 2024, considering model dry deposition of (a) $\text{Br}_y(\text{VSLS, SSA}) + \text{Br}_{\text{org}} (\text{sfa025})$; (b) $\text{Br}_y(\text{VSLS, SSA, BE}) + \text{Br}_{\text{org}} (\text{sfa028})$; (c) $\text{Br}_y(\text{VSLS, SSA, BE}) + \text{Br}_{\text{org}} - (\text{Br}_2 + \text{BrCl}) (\text{sfa028})$. Snow densities above 400 kg m^{-3} indicate that the snow has undergone a melting-refreezing-cycle.

The left panel of Fig. 11a displays the accumulation of bromide in the snowpack resulting from the deposition of Br_y originating from VSLS and SSA and Br_{org} . Deposited bromine is assumed to be retained quantitatively as bromide in the snow, such that the simulated bromide distribution reflects the cumulative atmospheric bromine deposition. Bromine deposition occurred mainly during snowfall events and only occasionally onto the snow–air interface. The maximum bromide area density ($\rho_A^{\text{Br}^-} \approx 130 \mu\text{g m}^{-2}$) is located at a height of approximately 28 cm above ground. A second enhancement is visible during and after the warm-air intrusion. In early winter, corresponding to the deeper snow layers, bromine is deposited predominantly together with snowfall, whereas deposition directly onto the snow surface becomes increasingly important during spring.

Figure 11b, c displays the simulated bromide accumulation when BE source and product gases are included in the deposition budget. In Fig. 11c, the cumulative dry deposition is additionally corrected for local Br_2 and BrCl emissions diagnosed by the Toyota bromine explosion scheme. These emissions are applied as a net loss term to the accumulated deposition budget and should therefore not be interpreted as an explicit representation of bromine recycling within the snowpack. The vertical bromide profiles including BEs differ substantially from the VSLS and SSA background experiment. Maximum bromide area densities of approximately $\rho_A^{\text{Br}^-} \approx 2000 \mu\text{g m}^{-2}$ without re-emission and $\rho_A^{\text{Br}^-} \approx 1600 \mu\text{g m}^{-2}$ with re-emission occur at a snow depth of 5 – 10 cm. These bromide-rich layers originated from deposition onto the snow surface during periods with temperatures below -10°C , corresponding to the threshold temperature applied in the Toyota scheme. The peak area densities exceed those of the VSLS and SSA background experiment by more than one order of magnitude. In contrast, the bromide inventories in the deeper snow layers, representing deposition during early winter, remain of the same order of magnitude as in the background simulation.

The total snow column bromide mass concentrations amount to 6, 25, and 20 ng g^{-1} , respectively. However, as bromide from SSA deposition was not traced, about 50 % of SSA related bromide is not accounted for.

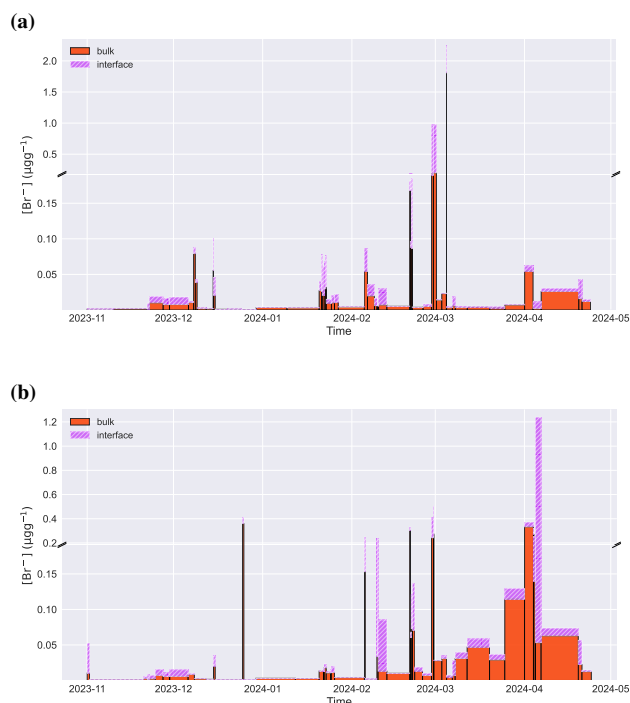


Figure 12. SMELs modeled evolution of bromide content in the uppermost 1 cm of the snowpack over time in winter 2023/24 including (a) $\text{Br}_y(\text{VLS}, \text{SSA}) + \text{Br}_{\text{org}}$ (b) $\text{Br}_y(\text{VLS}, \text{SSA}, \text{BE}) + \text{Br}_{\text{org}} - (\text{Br}_2 + \text{BrCl})$. For better readability, the ordinate axis is broken at $0.19 \mu\text{g g}^{-1}$.

To investigate the timing of bromine deposition, we examine the simulated bromide concentrations in the near-surface snow, defined here as the uppermost 1 cm of the snowpack (Fig. 12). Figure 12a displays the evolution of surface bromide concentrations resulting solely from VLS and SSA bromine deposition, whereas Fig. 12b additionally includes BE source and product gases together with local re-emission. Owing to the large concentration enhancements particularly associated with BEs, the ordinate axis in Fig. 12b is broken at $0.19 \mu\text{g g}^{-1}$.

Typical simulated bromide background concentrations resulting from VLS and SSA deposition range between 0.01 and $0.2 \mu\text{g g}^{-1}$. Both the background and BE experiments occasionally exceed this range. However, the temporal characteristics differ: exceedances in the VLS and SSA background experiment are short-lived and associated with individual deposition events, whereas bromine explosions produce sustained bromide enhancements that persist over substantially longer periods. In the experiment including BEs, the strongest and longest-lasting bromide enhancement related to snowfall is simulated in early April, coinciding with the major snowfall event of 4–5 April observed at Ny-Ålesund. Consequently, the snow layers located between approximately 45 and 50 cm in the simulated snowpack can be attributed to this event. In the subsequent fair weather conditions a strong enhancement is found corresponding to a simulated snow height of approximately 51 cm in Fig. 11b, c.



3.4 Bromine explosion signal

In this section, we investigate whether a bromine explosion signal can be discerned in the snowpit observations. For this purpose, the modeled snowpack is resampled to match the vertical resolution of the sampled snowpits. The comparison is performed using (i) absolute bromide concentrations at Gruebadet, (ii) relative bromide enhancements over the SSA- and VLSL-derived background, and (iii) normalized bromide profiles relative to the total snow depth at all sampling sites. In addition, we examine the temporal evolution of bromide concentrations in the uppermost 20 cm of snow at Gruebadet to assess the timing and persistence of potential BE signals.

For the model, the BE signal is defined as the relative bromide enhancement over the SSA- and VLSL-derived background taking bromine re-emission into account. For the observations, an analogous background estimate is derived from sodium concentrations and the seawater $\text{Na}^+ : \text{Br}^-$ ratio (Sect. 3.2).

The simulated bromide concentrations are resampled in two ways. In the first approach, the true bromide concentration of a sample bin is obtained by averaging over the entire sampled depth interval (*model truth*). Rather than placing this value at the geometric center of the bin, it is assigned to the mean depth of the contributing SMELs layers weighted by their bromide content. Error bars indicate the corresponding weighted standard deviation and therefore quantify how broadly the bromide is distributed within the sampled depth interval. The second mimics a point measurement at the geometric center of the bin (*model sampling bias*). Error bars indicate the concentration range within $\pm 10\%$ of the bin width around the bin center. In the following, we use a bin width of 10 cm which is overall consistent with the sampling strategy applied in the field.

For smooth bromide profiles, as obtained in the $\text{Br}_y(\text{VLSL}, \text{SSA}) + \text{Br}_{\text{org}}$ experiment (Fig. 13a), both approaches produce nearly identical concentrations. In contrast, bromine explosions generate sharp vertical concentration gradients, causing the *model sampling bias* to deviate substantially from the *model truth* (Fig. 13b, c). Depending on the local shape of the simulated profile, this bias can lead to either an underestimation or an overestimation of bromide concentrations.

The SSA- and VLSL-derived bromide background concentration amounts to $\langle [\text{Br}^-] \rangle = (0.015 \pm 0.009) \mu\text{mol L}^{-1}$ for the *model truth* and $\langle [\text{Br}^-] \rangle = (0.031 \pm 0.018) \mu\text{mol L}^{-1}$ for the *model sampling bias*. Thus, the true background concentration lies within one standard deviation of the value inferred from finite-bin sampling. In the experiment including BEs, a pronounced bromide enhancement develops in the upper snow layer close to the observed third ice layer. If local re-emission is not considered (Fig. 13b), the concentrations amount to $[\text{Br}^-] = 0.59 \mu\text{mol L}^{-1}$ (*model truth*) and $[\text{Br}^-] = (0.68^{+0.06}_{-0.02}) \mu\text{mol L}^{-1}$ (*model sampling bias*), respectively. When local bromine re-emission is considered (Fig. 13c), the resulting concentrations derived from the *model truth* ($[\text{Br}^-] = 0.44 \mu\text{mol L}^{-1}$) and the *model sampling bias* ($[\text{Br}^-] = (0.43^{+0.04}_{-0.01}) \mu\text{mol L}^{-1}$) agree closely.

The observed mean bromide background concentration is $\langle [\text{Br}^-] \rangle = (0.06 \pm 0.03) \mu\text{mol L}^{-1}$. A distinct bromide maximum of $[\text{Br}^-] = 0.135 \mu\text{mol L}^{-1}$ is observed at the depth corresponding to the modeled maximum. This maximum concentration exceeds the estimated background by approximately 2.5σ .

Although the simulated BE-induced bromide enhancement is substantially larger than observed, the coincidence in depth and the statistically significant enhancement above the estimated background suggest that the measured bromide maximum is most likely associated with bromine explosion activity.

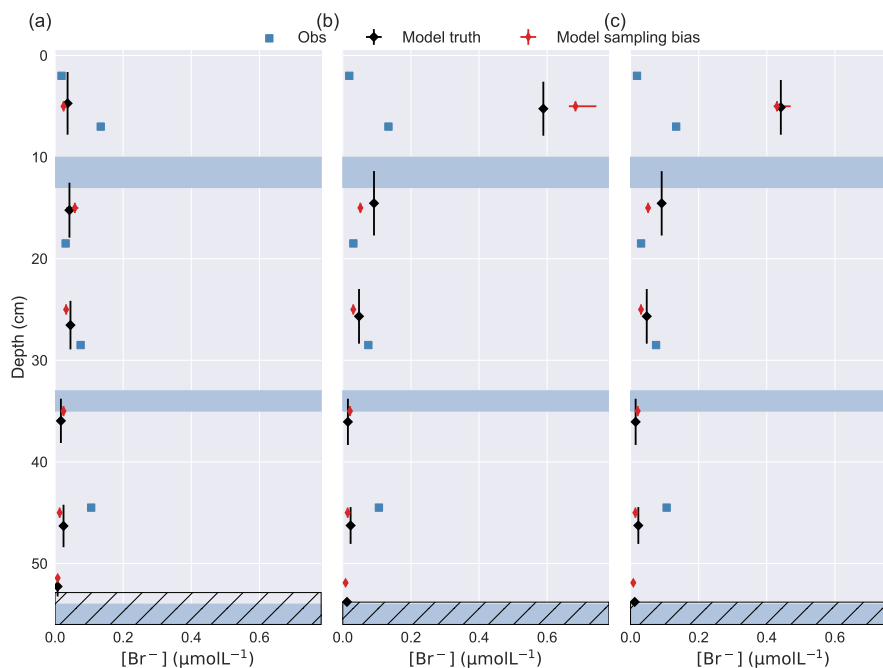


Figure 13. Comparison of observed and modeled bromide distribution in the snowpit at Gruebadet on 23 April 2024, considering modeled dry deposition of (a) $\text{Br}_y(\text{VSLs, SSA}) + \text{Br}_{\text{org}}$, (b) $\text{Br}_y(\text{VSLs, SSA, BE}) + \text{Br}_{\text{org}}$, and (c) $\text{Br}_y(\text{VSLs, SSA, BE}) + \text{Br}_{\text{org}} - (\text{Br}_2 + \text{BrCl})$. Gray-blue areas indicate observed ice layers. For locations of modeled ice layers compare with Fig. 11.

Although, the comparison of absolute bromide concentrations indicates the presence of a BE-related enhancement in the observations, it also reveals substantial differences in magnitude between the modeled and observed signals. We therefore focus next on bromide enhancements relative to the estimated background concentration. This approach removes much of the influence of the absolute bromide burden and allows the vertical structure of the BE signal to be compared more directly.

460 To facilitate a direct comparison with the observations, the modeled relative bromide enhancement $[\text{Br}^-]_{\text{rel}}^{\text{model}}$ is defined as

$$[\text{Br}^-]_{\text{rel}}^{\text{model}} = \frac{[\text{Br}_{\text{BE, VSLs, SSA}}^-] - [\text{Br}_{\text{VSLs, SSA}}^-]}{[\text{Br}_{\text{BE, VSLs, SSA}}^-]} \quad (3)$$

and evaluated for both the *model truth* and the *model sampling bias*. The resulting profiles are compared with the observed relative bromide enhancement derived from the laboratory analysis (Sect. 3.2) and are shown in Fig. 14.

465 The *model truth* reproduces the observed vertical structure remarkably well. Both profiles exhibit bromide enhancements above and below the first observed ice layer and a depletion in the layer between the second and third ice layers. Although the *model sampling bias* produces slightly different enhancement magnitudes, it reproduces the same enhancement-depletion pattern within its uncertainty range. The agreement suggests that the observed vertical bromide redistribution is largely consistent with the deposition history simulated by EMAC and represented by SMELs.

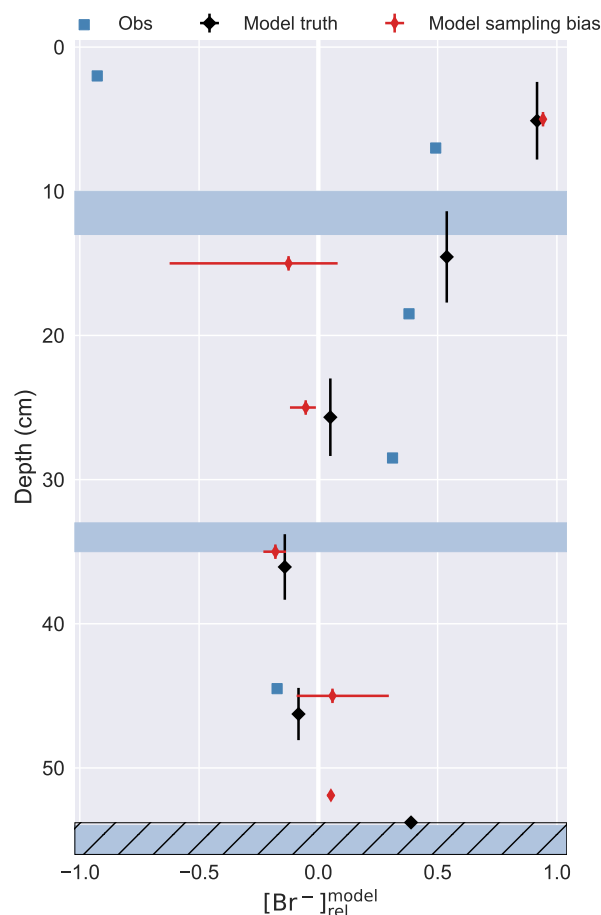


Figure 14. Modeled relative bromide enhancement $[\text{Br}^-]_{\text{rel}}^{\text{model}}$ due to BEs including re-emission of Br_2 and BrCl with VSLS and SSA bromide background subtracted. Negative values indicate a depletion compared to the background. Observed relative bromide enhancement at Gruvebadet ($[\text{Br}^-]_{\text{rel}}^{\text{obs}}$, Sect. 3.2) is shown for reference. Gray-blue areas indicate observed ice layers. The hatched area indicates the maximum depth of the modeled snowpack.

Because snow accumulation in SMELs is initialized after the final rain event of 2023, the depleted layer in the bottom must have formed after November 2023. Given the absence of significant photochemical activity during the polar night, this depletion is unlikely to result from photolytic bromide activation. It could instead indicate either multiphase chemical bromine activation within the snowpack or the deposition of previously dehalogenated sea-salt aerosol, both of which would reduce the bromide content of the affected snow layers.

In contrast, the observed depletion in the near-surface layer ($d = 5$ cm) may be linked to photochemical bromine activation. For a snow density of $\rho = 350 \text{ kg m}^{-3}$, comparable to the observed density at Gruvebadet, the e-folding depth at the wavelength of maximum actinic flux is approximately 10 cm (Kokhanovsky, 2022). Consequently, photolytic processing of bromine

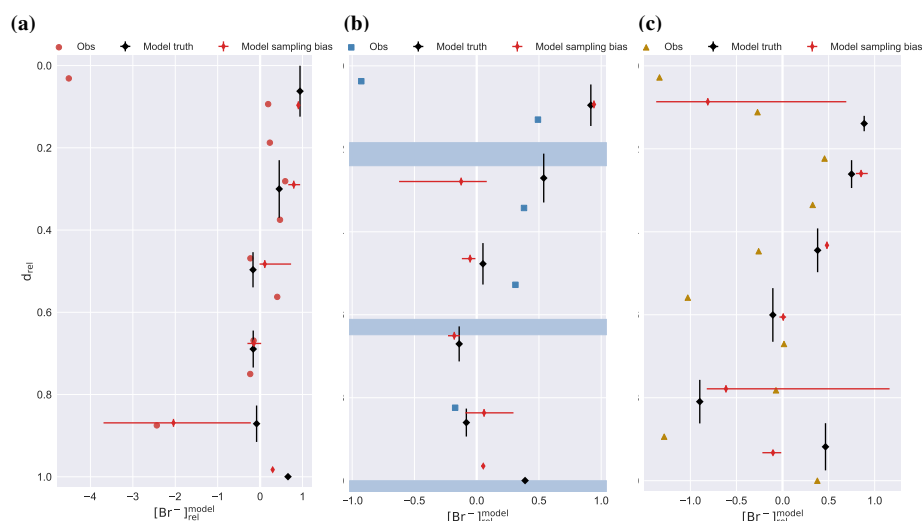


Figure 15. Modeled and observed relative bromide enhancement with respect to sampling depth relative to maximum depth of the snow pit. Model data include BEs with re-emission of Br_2 and BrCl and VSLs and SSA bromide background subtracted. Negative values indicate a depletion compared to the background. (a) Austre Brøggerbreen (18 April 2024); (b) Gruvebadet (23 April 2024); (c) Austre Lovénbreen (27 April 2024). Gray-blue areas indicate observed ice layers at Gruvebadet.

contained within the uppermost snow layers remains possible. This mechanism would be especially effective if bromine were stored as HOBr at the air–ice interface and had not been removed by the rain-induced percolation event. Bromine deposited in deeper layers would be less accessible to photochemical activation, particularly if the intervening ice layer restricted gas exchange between the surface and the underlying snowpack.

The occurrence of similar enhancement and depletion patterns at geographically separated sites (Sect. 3.2) suggests that these features may reflect a regional-scale deposition or processing signal rather than a purely local effect.

As all three sites are contained in a single EMAC grid cell, differences between SMELs results corresponding to the dates of the snowpits sampled in field are expected to origin from the temporal evolution of the modeled snowpack and bromine deposition only. To investigate this further, we study the relative bromide enhancement $[\text{Br}^-]_{\text{rel}}^{\text{model}}$ over normalized depth d_{rel} and compare with the respective $[\text{Br}^-]_{\text{rel}}^{\text{obs}}$ (Fig. 15).

The SMELs simulations reproduce the characteristic S-shaped profile of relative bromide enhancement observed at all three sampling sites. The largest discrepancies between the observations and the *model truth* occur near $d_{\text{rel}} \approx 0.1$ at Austre Lovénbreen and $d_{\text{rel}} \approx 0.8$ at both glacier sites. However, these differences largely fall within the uncertainty associated with the *model sampling bias*. In particular, the large uncertainty range of the *model sampling bias* at $d_{\text{rel}} \approx 0.1$ indicates substantial variability in bromide concentrations over a comparatively small vertical distance.

This finding suggests that a finer vertical sampling resolution, especially within the uppermost 10 cm of the snowpack, would improve the characterization of processes occurring at the snow–air interface. Owing to the higher relative vertical sampling



resolution at Austre Lovénbreen, an additional alternating depletion-enhancement structure is resolved between $d_{\text{rel}} \approx 0.6$ and 1.0. At the same time, the observations exhibit a systematic shift towards lower relative bromide concentrations than simulated by SMELs. As this offset exceeds the uncertainty attributable to sampling bias, it points to enhanced bromide depletion at Austre Lovénbreen that is not represented by the EMAC model. Consequently, while the three snowpits share a common regional-scale bromide enhancement pattern, substantial local variability in snowpack bromine processing must be present.

To investigate the timing of the processes responsible for the observed vertical bromide structure, we finally examine the simulated evolution of bromide concentrations in the uppermost 20 cm of the snowpack at Gruvebadet (Fig. 16).

The observed bromide concentrations in the uppermost 20 cm of the snowpack exhibit a pronounced seasonal cycle. Between November and the end of February, concentrations average $\langle [\text{Br}^-] \rangle = 9 \pm 6 \text{ ng g}^{-1}$. Elevated concentrations of $18 - 29 \text{ ng g}^{-1}$ are observed in late March and early April, after which bromide concentrations decrease to $\langle [\text{Br}^-] \rangle = 5.1 \pm 1.9 \text{ ng g}^{-1}$ for the remainder of the measurement period. Comparison with the simulated SSA- and VSLS-derived bromide background (Fig. 16a) indicates that the model underestimates bromide concentrations between November and February. The missing bromide approximately corresponds to the fraction of sea-salt bromide not represented by the SSA dehalogenation approach. In contrast, modeled and observed bromide concentrations agree well during April and May, suggesting that bromine emissions from the surface snow are of a similar magnitude as the remaining bromide inventory. Some observed concentration maxima may additionally be associated with episodic SSA deposition during the passage of weather systems.

The simulation including bromine explosions and recycling (Fig. 16b) displays a distinct different temporal evolution. The two concentration maxima in November correspond to false bromine explosion events previously identified as a limitation of the Toyota parameterization (Falk and Sinnhuber, 2018; Falk et al., 2025). Apart from these events, modeled and observed concentrations agree reasonably well until the end of February when accounting for the unrepresented SSA bromide contribution. From mid-March onward, however, simulated bromide concentrations exceed the observations by one to two orders of magnitude. This discrepancy suggests that the current bromine explosion parameterization releases excessive amounts of bromine from first-year sea ice and/or does not sufficiently recycle bromide within the snowpack.

This interpretation is further supported by the bromide anomalies relative to the SSA background (Fig. 16c). The observations indicate bromide depletion from November to early January and again from late March through May, whereas enhanced bromide concentrations are observed between mid-February and mid-March. Except the false November events, the modeled and observed anomalies agree reasonably well until the end of February. Both datasets indicate a bromine explosion signal around February 20. Beyond this period, the comparison becomes less conclusive owing to the substantial positive bias in simulated bromine deposition.

In summary, we identified and quantified bromide background concentrations and bromine explosion signals in both the snowpit bromide profiles and the top-20 cm snow time series from Gruvebadet. The SMELs simulations reproduce the observed vertical enhancement and depletion patterns remarkably well and demonstrate that finite-bin sampling can introduce substantial biases in the inferred bromide concentrations. In relative terms, the three sampling sites display a common regional bromide fingerprint, although noticeable local variations are present, particularly at Austre Lovénbreen.

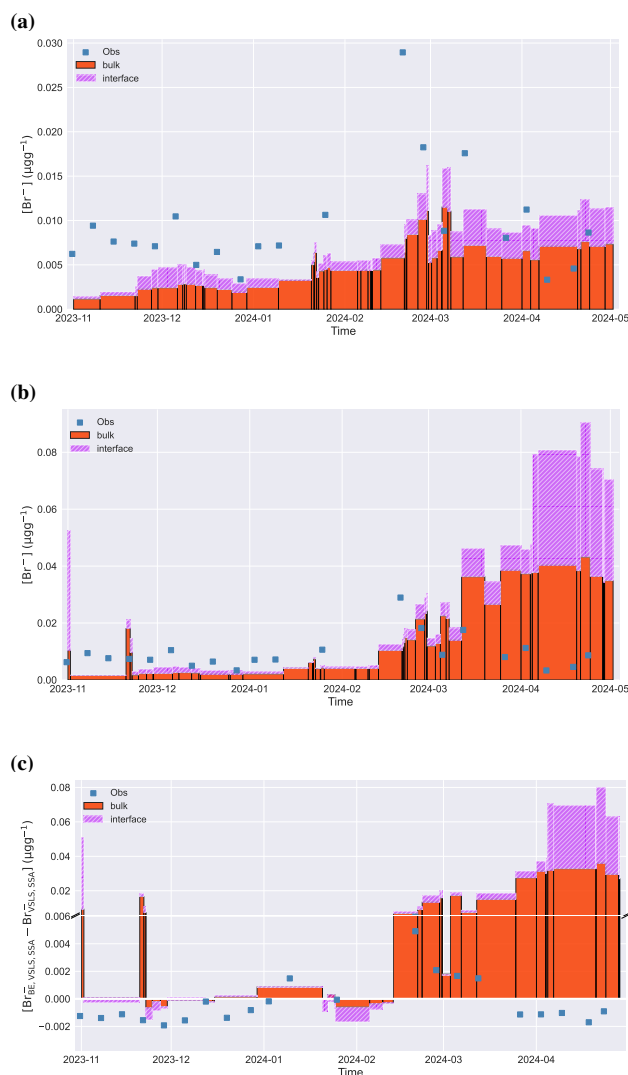


Figure 16. Evolution of modeled and observed bromide content in the uppermost 20 cm of the snowpack over time in winter 2023/24 at Gruebadet including (a) $\text{Br}_y(\text{VSL}, \text{SSA}) + \text{Br}_{\text{org}}$, (b) $\text{Br}_y(\text{VSL}, \text{SSA}, \text{BE}) + \text{Br}_{\text{org}} - (\text{Br}_2 + \text{BrCl})$, and (c) same as (b) with SSA background removed. For better readability, the ordinate axis is broken at $0.006 \mu\text{g g}^{-1}$.

The comparison of modeled and observed surface snow bromide concentrations suggests that either the SSA deposited over the Ny-Ålesund region is more strongly bromide-depleted than assumed or that bromide recycling remains active during the polar night. Furthermore, the substantial overestimation of springtime surface bromide concentrations in the bromine explosion simulations indicates that the current parameterization likely overestimates bromine release from first-year sea ice and/or underestimates bromide recycling within the snowpack.



4 Conclusion and discussion

In this study, we investigated whether dry deposition of atmospheric bromine species can establish and maintain a bromide reservoir in snow on sea ice and land without requiring direct access to an infinite oceanic bromide source. To address this question, we combined chemistry-climate model simulations with field observations and laboratory analyses of Arctic snow samples collected around Ny-Ålesund in spring 2024. To bridge the gap between atmospheric deposition fluxes and snowpit observations, we developed the Snow Model with Evolving Layers (SMELs), a simple offline snow model that tracks the accumulation of bromine in a dynamically evolving snowpack.

Our results indicate that bromine dry deposition originating from both VSLs and SSA dehalogenation can establish a snow bromide reservoir of sufficient magnitude to sustain Arctic bromine explosion events. Integrated bromine deposition is of the same order of magnitude as observed Arctic tropospheric BrO vertical column densities and exhibits a comparable seasonal cycle. The modeled deposition patterns further suggest that deposited bromine provides a seasonal memory of atmospheric bromine processing and may accumulate in the snowpack over several months before being reactivated.

Analysis of bromine species partitioning reveals that the availability of deposited HBr may be a key factor controlling bromine reactivation. While substantial amounts of bromine are deposited already during fall, the low abundance of HBr largely suppresses efficient heterogeneous production of Br₂ in the absence of primary SSA bromide. In contrast, springtime deposition favors a bromine speciation to facilitate bromine activation. This finding provides a potential explanation for the pronounced seasonality of Arctic BEs despite broadly similar meteorological conditions in fall and spring.

The pan-Arctic simulations identify three distinct bromine reactivation regimes. During winter, deposited bromine may accumulate predominantly as a HOBr reservoir within the snowpack. In early spring, bromine activation may proceed via dark heterogeneous reactions involving ozone and the snow bromine reservoir, particularly in regions where HBr deposition exceeds that of HOBr. Following the return of sunlight, photolytic activation of deposited bromine becomes increasingly important and dominates during late spring. Together, these results suggest that the timing of bromine activation is governed by both bromine speciation and the seasonal evolution of illumination.

The comparison between SMELs and snowpit observations demonstrates that bromide concentrations measured in the field are strongly influenced by snow stratigraphy and finite sampling resolution. Depending on the vertical distribution of bromide within the snowpack, sampling biases may either enhance or suppress apparent bromide signals. Nevertheless, the observed and modeled relative bromide enhancement and depletion profiles show remarkably good agreement, supporting the interpretation that the observed bromide distribution reflects the deposition and subsequent processing of atmospheric bromine. Beyond the comparison at Gruvebadet, the normalized bromide profiles exhibit a striking similarity among all three sampling sites, particularly in the upper snowpack and in the overall pattern of relative enrichment and depletion. This consistency suggests that bromine deposition and post-depositional processing operate on regional scales around Ny-Ålesund rather than being purely controlled by local snowpack conditions. In particular, the close agreement between the Gruvebadet and Austre Brøggerbreen profiles indicates a common deposition history, while the somewhat larger deviations at Austre Lovénbreen may reflect differences in local meteorology, snowpack evolution, or transport pathways.



The persistent depletion observed in the uppermost snow layer is consistent with photochemical processing within the surface snowpack. For the observed snow densities at Gruebadet, the estimated e-folding depth of approximately 10 cm coincides with the depth over which photolysis of HOBr may remain effective, suggesting that this process could contribute to springtime bromine release from snow.

Several uncertainties remain. The relative contributions of primary SSA bromide and recycled atmospheric bromine, e.g. from SSA aging, to snowpack bromide inventories are still poorly constrained. The major natural source of reactive halogens in the polar boundary layer is the dehalogenation of SSA (Saiz-Lopez and von Glasow, 2012). The efficiency of this process depends on the SSA emission flux, the chemical composition of the boundary layer (Sommariva and von Glasow, 2012), aerosol size distributions (Yang et al., 2005, 2008), and the amount of adsorbed water available for heterogeneous reactions (Finlayson-Pitts and Hemminger, 2000). Consequently, both the bromide enrichment of SSA and the resulting bromine deposition are expected to exhibit pronounced spatial and seasonal variability (Zhu et al., 2019). Furthermore, global estimates of SSA burdens, emissions, and deposition remain highly uncertain and are typically constrained indirectly using satellite-derived aerosol optical depth (AOD) in combination with ground-based observations (Gliß et al., 2021; Farmer et al., 2021). The simplified conversion of SSA bromide to gas-phase bromine applied in this study, assuming an instantaneous release of 50 % of the available SSA bromide independent of aerosol size or mode, should therefore be regarded as an upper-limit estimate. Explicitly representing SSA aging, bromine release, transport, and subsequent incorporation into the snowpack would be an important next step towards quantifying the relative contributions of primary SSA bromide and recycled atmospheric bromine to Arctic snowpack bromide inventories.

An additional uncertainty concerns the physicochemical form in which bromine is stored within the snowpack. Salinity and bromide concentrations generally decrease with increasing distance from the coast and are typically highest in basal snow layers over sea ice, where bromide-rich brine may migrate upward from the underlying ice (Domine et al., 2004; Yang et al., 2024). However, the mere presence of bromide does not necessarily imply chemical availability. Although laboratory experiments demonstrated bromine activation from seawater ice exposed to ozone (Oum et al., 1998), Pratt et al. (2013) found no evidence for significant Br₂ production from sea ice, brine icicles, or basal snow under ozone and light treatment. Similarly, Yang et al. (2024) observed strong bromide enrichment in the uppermost millimeter of the snowpack near Eureka, while the snowpack itself acted only as a weak source of reactive bromine. Together, these studies suggest that the chemical form of deposited bromine may play a decisive role in determining its reactivity. In particular, bromide originating from primary SSA may be less accessible for heterogeneous recycling than bromine deposited as reactive gas-phase species, especially under conditions where only limited amounts of liquid water are available at the ice surface (Finlayson-Pitts and Hemminger, 2000).

Snow physical properties may further constrain bromine activation. Snow depth, stratigraphy, and metamorphism influence both ventilation of the snowpack (Toyota et al., 2014a,b) and the penetration of ultraviolet radiation (Kokhanovsky, 2022). For typical Arctic snow densities, photochemically active layers are largely confined to the uppermost ~ 10 cm of the snowpack, while dense ice layers may additionally inhibit gas exchange between surface and deeper snow layers. Our observations at Gruebadet, together with the missing upper ice layer in SMELs resulting from unresolved rain-percolation processes, highlight the potential importance of snow metamorphism for the vertical redistribution and accessibility of bromine. Consequently, only



a fraction of the bromine stored within the seasonal snowpack may be available for reactivation, even if the deposited bromine is chemically reactive.

Finally, the representativeness of Svalbard observations for the wider Arctic should be considered. Based on snowpit transects across seven Svalbard glaciers, Barbaro et al. (2021) reported substantial spatial variability in snow ion composition, with the highest concentrations occurring in southern Svalbard and the lowest in the east. Ion concentrations generally increased with altitude, indicating an enhanced influence of long-range aerosol transport. In addition, the maritime setting of western Svalbard exposes the region to frequent intrusions of warm and moist air masses, resulting in rain-on-snow events and snow metamorphism that are less common in the central Arctic. Therefore, the bromide enrichments observed around Ny-Ålesund are likely influenced by both regional Arctic bromine chemistry and local snowpack evolution, which should be considered when extrapolating these findings to other Arctic environments.

In summary, our results demonstrate that the history of bromine deposition and storage in snow is an important component of the Arctic bromine cycle. The successful application of SMELs suggests that even simple snowpack representations can substantially improve the interpretation of snow chemistry observations and provide a physically consistent framework for linking chemistry-climate model simulations with field measurements. Incorporating dynamic snow bromine reservoirs into future atmospheric chemistry modeling studies may therefore help improve our understanding of bromine activation, recycling, and ozone depletion in the polar environment.

Code availability. A SMELs release will be made publically available at zenodo and can be shared upon request during the review process via github.

Additional python analysis scripts used for data processing can be made available through github.

The Modular Earth Submodel System (MESSy) is being continuously further developed and applied by a consortium of institutions. The usage of MESSy and access to the source code is licenced to all affiliates of institutions who are members of the MESSy Consortium. Institutions can become a member of the MESSy Consortium by signing the MESSy Memorandum of Understanding. More information can be found on the MESSy Consortium website (<http://www.messy-interface.org>). The study presented here was performed based on MESSy version 2.55.2. Compared to MESSy v2.55.2, the updated AirSnow algorithm also includes two critical bug fixes concerning the temperature and solar zenith angle thresholds. It has been integrated into the MESSy release candidate and will be available in the next official release (version 2.56). MYSIC based on ICDC Age of Arctic Sea Ice has been contributed to the MESSy community.

Data availability. Model data from the sensitivity studies presented here will be made available at zenodo.

The results contain modified Copernicus Climate Change Service information 2020. Neither the European Commission nor ECMWF is responsible for any use that may be made of the Copernicus information or data it contains.

Sample availability. Snow sample analysis will be made available by H.-W. Jacobi on the EaSy Data portal.



Appendix A: Figures

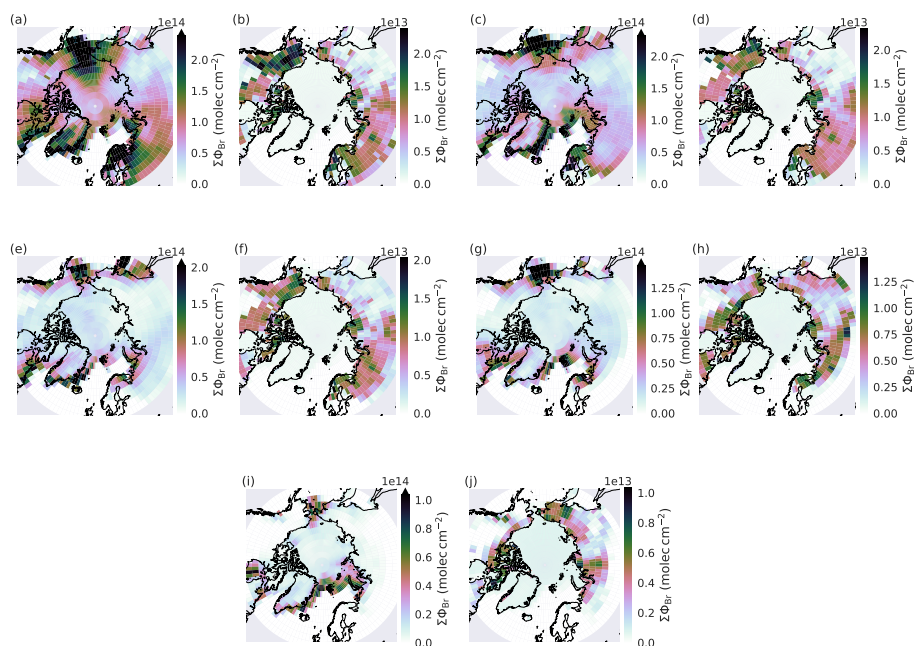


Figure A1. Modeled pan-Arctic spatial distribution of the integrated dry deposition of (a, c, e, g, i) Br_y and (b, d, f, h, j) Br_{org} folded with fractional sea ice and snow cover accumulated monthly: January (a, b), February (c, d), March (e, f), April (g, h), and May (i, j) 2024. Br_y deposition is concentrated over sea ice and coastal regions, while Br_{org} deposition occurs primarily over land. Note the different order of magnitude. Made with Cartopy (Met Office, 2010–2022) and coastlines from Natural Earth.



Appendix B: Tabulated observational data

Table B1. Snow density from the snowpit at Austre Brøggerbreen. Height is measured from the basal ice. Sampling data and time: 18 April 2024, 12:15-13:35.

Height (cm)		Density (g cm ⁻³)
from	to	
160	150	0.071
150	140	0.182
140	130	0.262
130	120	0.336
120	110	0.288
110	100	0.37
100	90	0.403
90	80	0.356
80	70	0.357
70	60	0.396
60	50	0.426
50	40	0.425
40	30	0.389
30	20	0.295
20	10	0.362
10	0	0.362



Table B2. Snow and air temperature for the snowpit at Austre Brøggerbreen. Height is measured from the basal ice. Sampling data and time: 18 April 2024, 12:15-13:35.

Height (cm)	Temperature (° C)
air	-6.9
160	-5.5
150	-12.5
140	-11.5
130	-11.7
120	-10.5
110	-10.3
100	-10
90	-9.8
80	-9.5
70	-10.1
60	-9
50	-8.6
40	-8.3
30	-8.1
20	-7.8
10	-7.5
0	-6.9



Table B3. Bromide concentrations for the snowpit at Austre Brøggerbreen. Height is measured from the basal ice. The uppermost 10 cm of the snowpack have been sampled as cross-section, below, point samples at the given height were taken. Sampling data and time: 18 April 2024, 12:15-13:35.

Height (cm)	$[\text{Br}^-]$ ($\mu\text{mol L}^{-1}$)	$\frac{[\text{Br}^- - \text{nss}]}{[\text{Br}^-]}$
160–150	0.007	-4.510
145	0.057	0.190
130	0.122	0.230
115	0.013	0.592
100	0.058	0.469
85	0.030	-0.229
70	0.045	0.404
53	0.072	-0.154
40	0.051	-0.233
20	0.002	-2.435

Table B4. Snow properties and bromide concentration of the snowpit at Gruvebadet as part of the regular snow sampling. Height is measured from the basal ice. Point samples at the given height were taken. The measured probe mass (g) is converted to snow densities (kg m^{-3}) using $\rho_{\text{snow}} = (m_{\text{probe}} - 140) \cdot 10$. Sampling data and time: 23 April 2024, 15:00-16:00.

Height (cm)		Temperature (° C)	Mass (g)	$[\text{Br}^-]$ ($\mu\text{mol L}^{-1}$)	$\frac{[\text{Br}^- - \text{nss}]}{[\text{Br}^-]}$
from	to				
54	50	0		0.019	-0.927
50	44	0	180	0.134	0.492
44	41		ice		
41	30	0	180	0.031	0.380
30	21	0	190	0.075	0.311
21	19		ice		
19	0	0	185	0.106	-0.173



Table B5. Snow and air temperature and bromide concentration for the snowpit at Austre Lovénbreen. Height is measured from the basal ice. The uppermost 10 cm of the snowpack have been sampled as cross-section, below, point samples at the given height were taken. Sampling data and time: 27 April 2024, 11:00.

Height (cm)	Temperature (° C)	[Br ⁻] (μmol L ⁻¹)	$\frac{[\text{Br}^- - \text{nss}]}{[\text{Br}^-]}$
179–169		0.010	-1.335
159	-5.9	0.120	-0.271
139	-5.9	0.055	0.456
119	-6.1	0.256	0.327
99	-6	0.153	-0.259
79	-6.3	0.009	-1.028
59	-6.3	0.033	0.016
39	-6.1	0.032	-0.071
19	-5.9	0.006	-1.284
0	-5.2	0.016	0.378



Author contributions. SF wrote and edited the manuscript, performed the CCM model simulations, developed SMELs, and analyzed the model and observational results. HWJ contribution to the methodology, contribution to the formal analysis, provision of snow physics and chemistry data, writing of parts of the manuscript, approval and correction of the manuscript. HEM realization of the chemical analysis, approval of the manuscript. PG realization of the chemical analysis, approval of the manuscript. BMS proposed the project ‘BromoPole’ and contributed with insights and ideas and proofreading.

Competing interests. There are not competing interests.

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