Ny-Ålesund Atmosphere Flagship Online Seminar

Tropospheric bromine monoxide in Ny-Ålesund: source analysis and impacts on atmospheric chemistry

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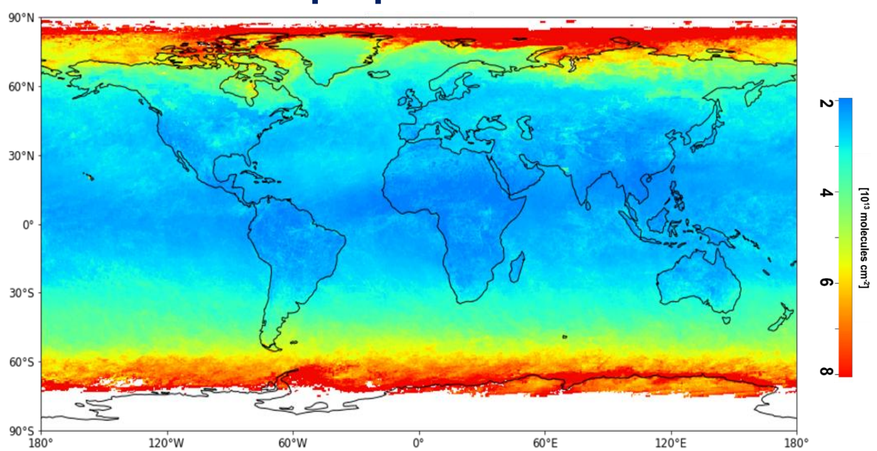
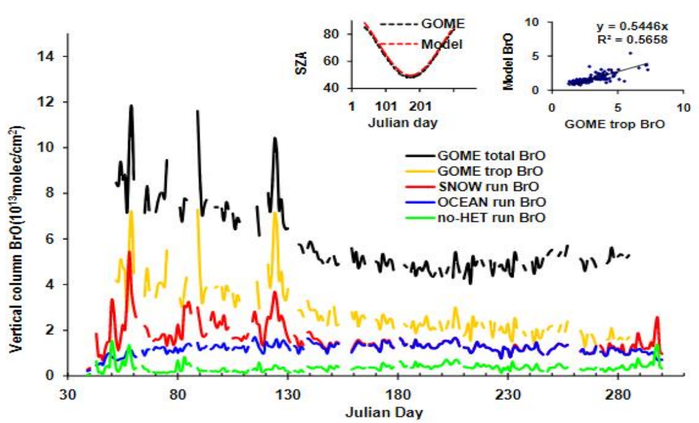
Introduction

- **Background: Global Warming & Arctic Amplification**
- **The total amount of Reactive Halogens in Polar Regions is greatly underestimated.**

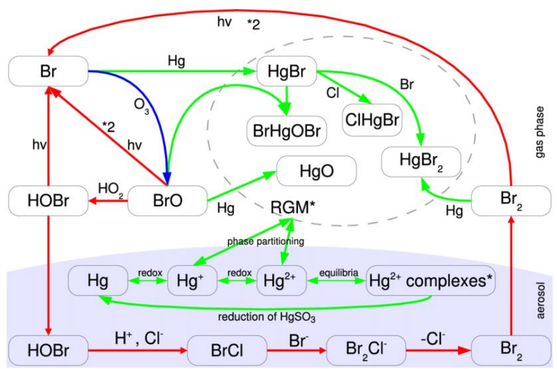
Global tropospheric BrO Column





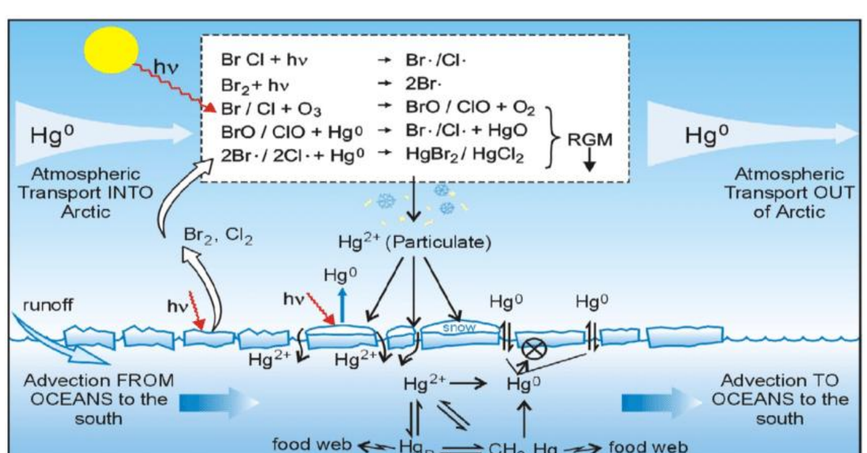
Yang et al., ACP, 2010

Bromine Explosion can lead to severe ozone depletion and gaseous mercury deposition.



The autocatalytic cycle reaction makes bromine atoms grow exponentially.

Xie et al., ACP, 2008

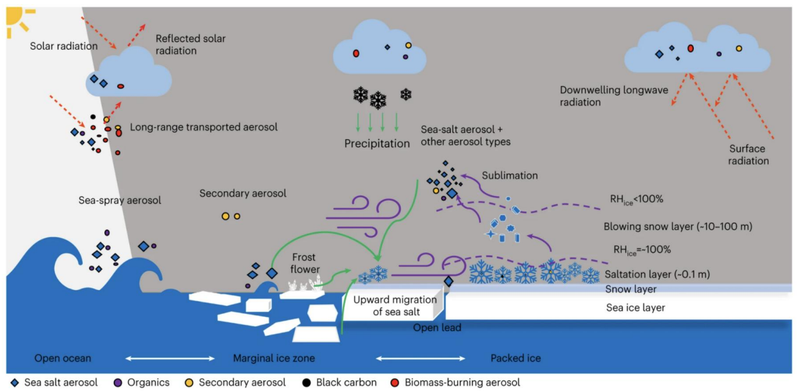


Steffen et al., ACP, 2008

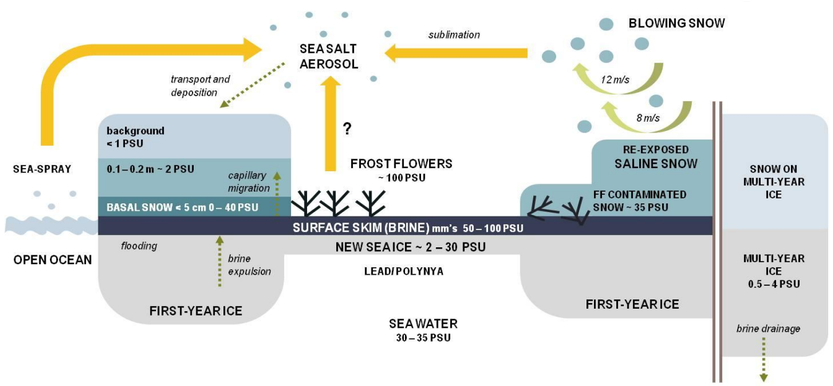
Introduction

- **Due to insufficient observation and model uncertainty, the source contribution of reactive bromine in different regions and meteorological conditions is still unclear.**

  - Open ocean sea spray (Sander et al., 2003)
  - Bromocarbons degradation (Warwick et al., 2006)
  - First year sea ice surface (Simpson et al., 2005; 2007; Abbatt et al., 2012)
  - Frost flowers (Kaleschke, et al., 2004; Piot and von Glasow, 2008))
  - Open leads/polynyas (Peterson et al., 2016; Kirpes et al., 2019; Criscitiello et al., 2021)
  - **Snowpack photochemistry** (Pratt et al., 2013; Custard et al., 2017; Peterson et al., 2019; Thomas et al., 2011; Zhai et sal., 2023).
  - **Blowing-snow sourced sea salt aerosol** (Yang et al., 2008; 2019; 2020;2024; Frey et al., 2020; Huang et al., 2020； Li et al., 2026)



Gong et al., Nature Geoscience, 2023



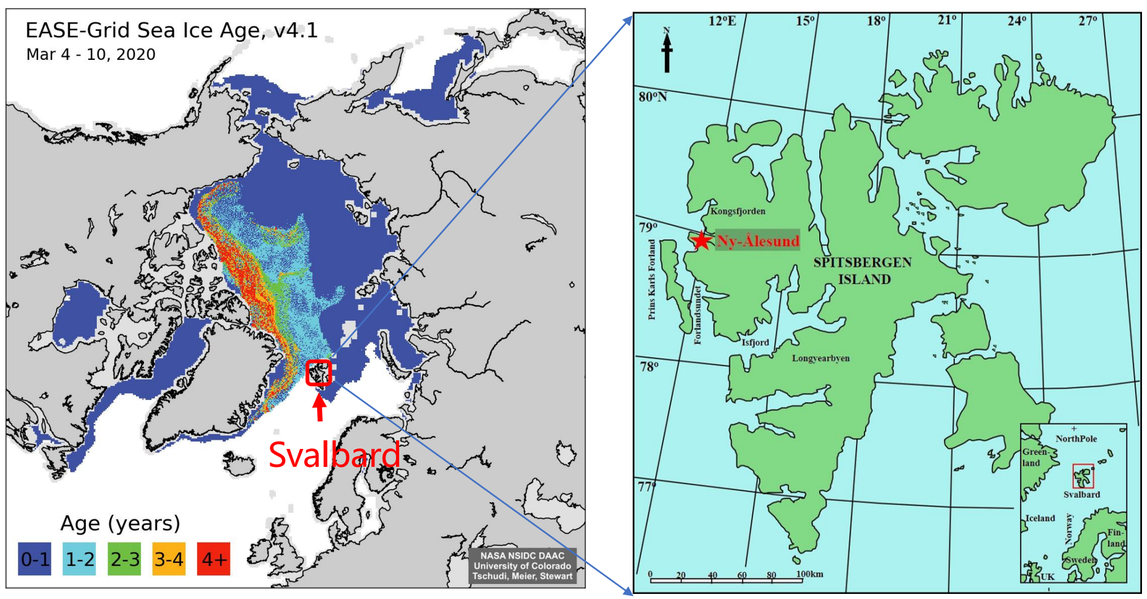
Abbatt et al., 2012

This study: based on long-term observations in Ny-Ålesund Arctic and optimized model to quantify the relative contribution of sea ice (multi-year/one-year sea ice) to the BEEs in Ny-Ålesund.

Method

➢**Location**: Yellow River Station (78.92°N, 11.93°E) in Ny-Ålesund, Svalbard.

➢**Duration**: 2017-2023 (From 2015 to present)



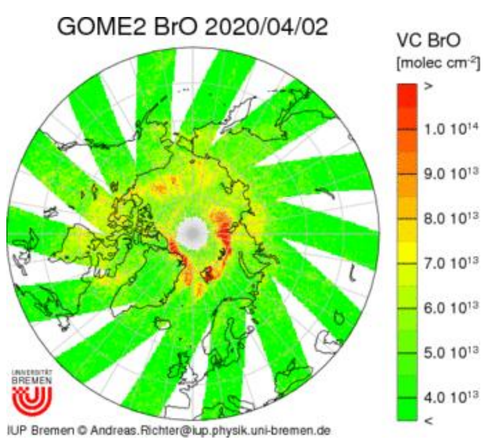
Ground-based MAX-DOAS Observations at Yellow River Station

➢**Observations**:

Ground-based MAX-DOAS (temporal resolution: ~15 min)

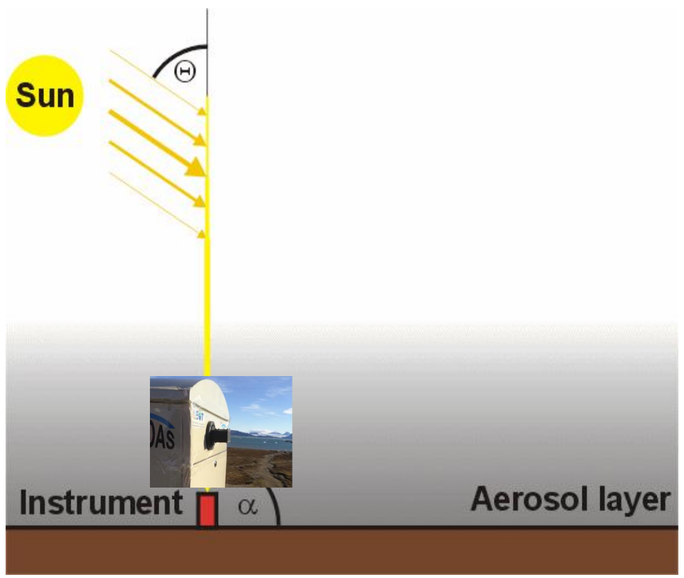
Satellite: GOME-2B tropospheric BrO product (80 km × 40 km per day)

(provided by Bianca Zilker and Andreas Richter from Bremen University)

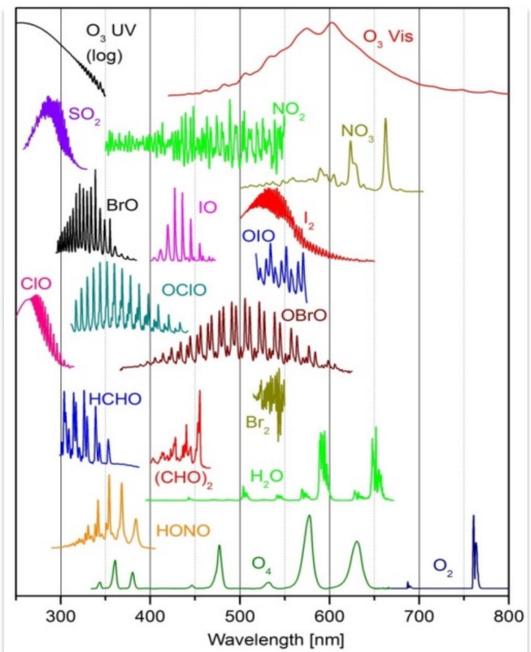


Method

◆ Passive MAX-DOAS: trace gas column concentration and profile distribution



Spectral database



Basic Principle: Lambert Beer's law

$$I(\lambda) = I_0(\lambda) \cdot exp(-\sigma(\lambda) \cdot c \cdot L)$$

$$D' = \ln\left(\frac{I_0(\lambda)}{I(\lambda)}\right) = L \cdot \sum_j \sigma'_j(\lambda) \cdot c_j$$

$$\mathbf{DSCD_{BrO}} = (\mathbf{SCD}_\alpha - \mathbf{SCD}_{FRS}) - (\mathbf{SCD_{90}} - \mathbf{SCD}_{FRS}) = \mathbf{SCD}_\alpha - \mathbf{SCD_{90}}$$

$$\mathbf{VCD_{BrO}} = \mathbf{DSCD_{BrO}} \,/\, \mathbf{DAMF_{BrO}}$$

MAX-DOAS spectral setting for BrO and O4 analysis.

Parameters	BrO	O_4
O_3_223K (Bogumil et al., 2003)	✓	✓
O_3_243K (Bogumil et al., 2003)	✓	✓
NO_2_298K (Vandaele et al., 1998)	✓	✓
NO_2_220K (Vandaele et al., 1998)	✓	✓
O_4_273K (Thalman and Volkamer, 2013)	✓	✓
BrO_298K (Fleischmann et al., 2004)	✓	n/a
OClO_233K (Kromminga et al., 2003)	✓	n/a
Ring (Calculated with QDOAS)	✓	✓
Wavelength	336.5–359 nm	340–370 nm
Polynomial	Fifth order	Fifth order

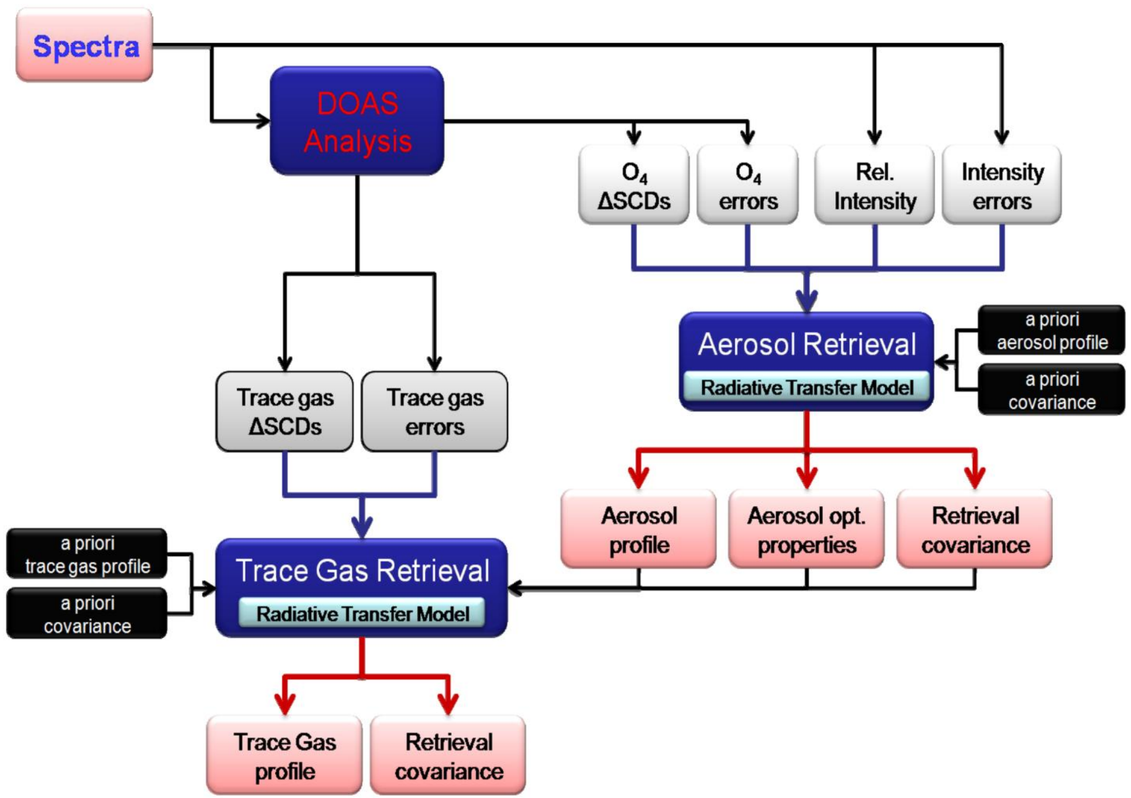
Advantages: accurate recognition, multi-component, stereo detection, real-time, high resolution

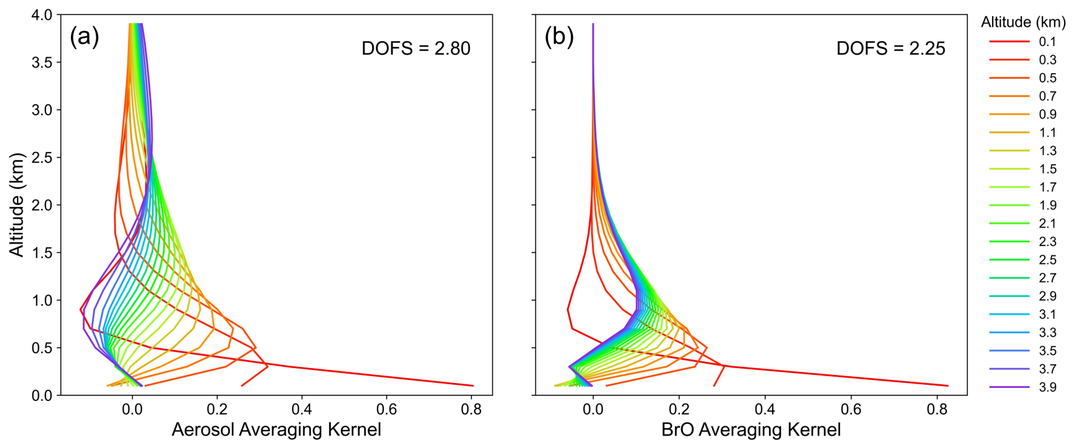
Method

◆ Passive MAX-DOAS: trace gas column concentration and profile distribution

➢**Profile inversion: based on a two-step optimal estimation algorithm HEIPRO (Frieß et al., 2011)**

Profile Inversion Strategy





●average kernel function of retrieved aerosols and BrO

Method

■ p-TOMCAT Model: parallelised-Tropospheric Offline Model of Chemistry and Transport

◆ Detailed Tropospheric Bromine Chemistry Scheme (Yang et al., 2005; 2010;2019;2020)

- Gas phase chemical reaction of bromide
- Heterogeneous reaction
- The photochemical reaction of ozone

◆ Blowing snow:

- Snow Salinity (MOSAiC data, Macfarlane et al., 2023)
- Wind-dependent snow shape parameterization (Ranjithkumar et al., 2025)

◆ Mode resolution:

- Horizontal: 2.825 °× 2.825 °
- Vertical: divided into 31 layers, with the lowest layer ~60 meters and the highest layer ~25 kilometers (10hPa)

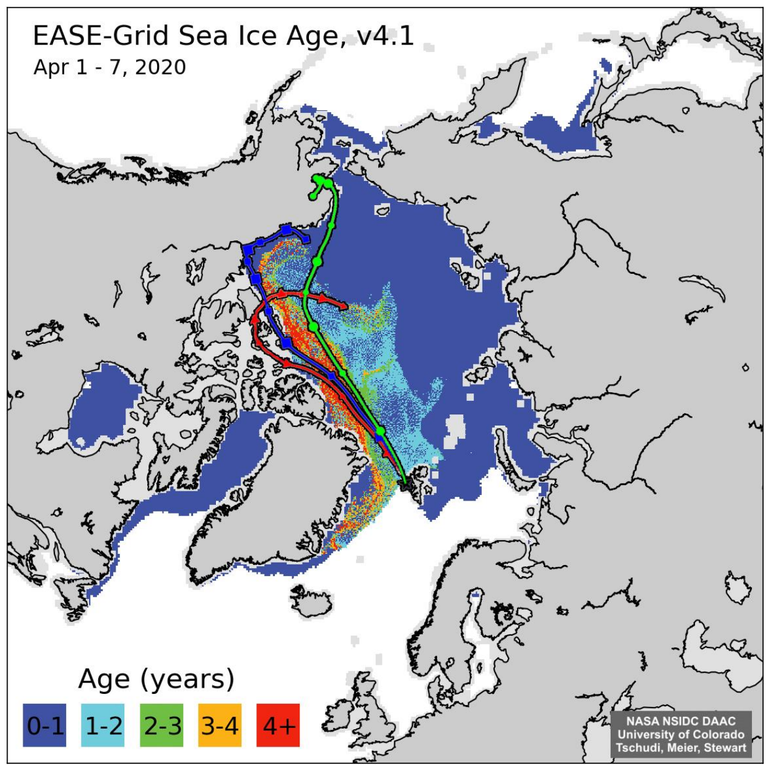
◆ Meteorological field driver:

- 6-hour ERA-5 reanalysis dataset
- The monthly data on sea ice and sea surface temperature : from the HadISST (Rayner et al., 2003) dataset

● Key simulation results: BrO, O_3, SSA

Method

◆ Air mass back-trajectory analysis: HYSPLIT model



➢ Backward trajectories at 10 m, 200 m, and 500 m at 12:00 on 2 April 2020.

➢ BEEs are defined as BrO > 12 pptv (Schofield et al., 2006).

➢ Backward trajectories were **calculated for 120 h** with hourly output, arriving at Ny-Ålesund. **Fifteen vertical levels** from 100 m to 3 km were set at 200 m intervals.

➢ Surface contact: trajectory height < 500 m → effective contact with **sea ice, open ocean, and land**

① **Contact time:** accumulating along each backward trajectory

② **Bromine flux:** accumulating the emission fluxes along each trajectory by assuming an average bromine lifetime of τ =5 d (120 h, Yang et al., 2005)

$$F = \sum_{i=1}^{120} F_{t_i} \times e^{-t_i/\tau}$$

(t_i : hours before arrival)

Method

◆ Parameterizations of reactive bromine emissions

➢ **Sea salt aerosol production from open ocean:** wind speed dependent (Gong et al., 2003; Jaeglé et al., 2011):

$$\frac{dF}{dr} = 1.373u_{10}^{3.41}r^{-A}\left(1 + 0.057r^{3.45}\right) \times 10^{1.607e^{-B^2}}$$

➢ **Sea salt aerosol production from blowing snow over sea ice:** salinity, surface wind speed, temperature, relative humidity, and snow age (Yang et al., 2008; 2019):

$$Q_{seasalt} = \frac{Q_s}{1000}\int_0^\infty \int_0^\infty f(d_i)\varsigma\psi(\varsigma)d(d_i)d\varsigma,$$

- Br release: $Q_{Br} = Q_{seasalt} * R * DF$

a) R: 0.00223 kg/kg is the mass ratio of Br to NaCl (sodium chloride) in sea salt
b) DF: bromine depletion factor

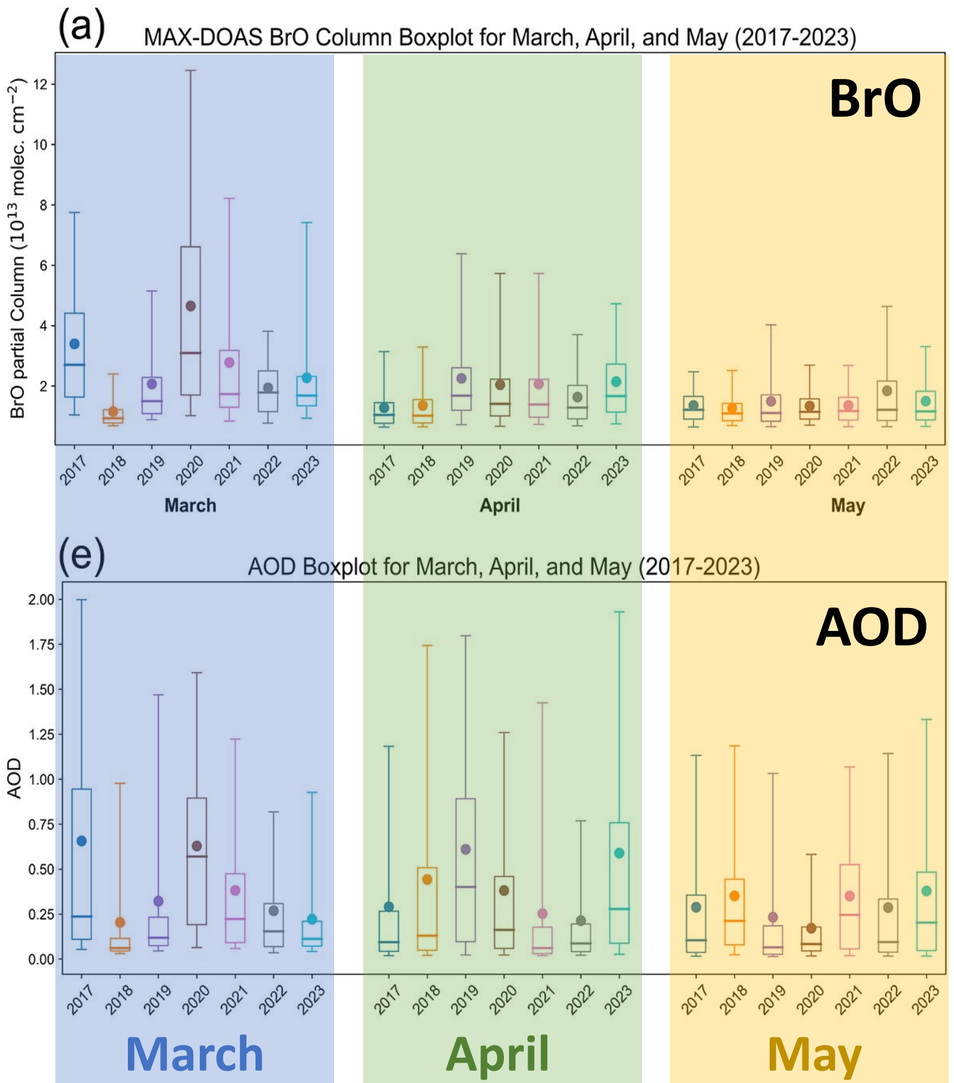
➢ **Bromine flux from snowpack over sea ice:** ozone deposition velocity, temperature, solar zenith angle (Toyota et al., 2011):

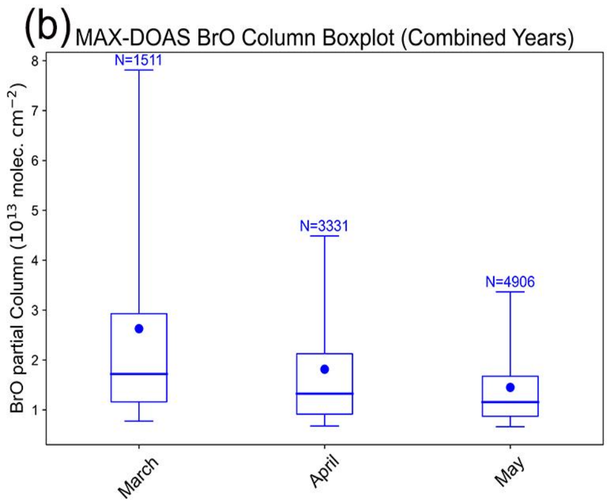
$$F_{Br2} = v_d \cdot [O_3] \cdot Y_{Br2}$$

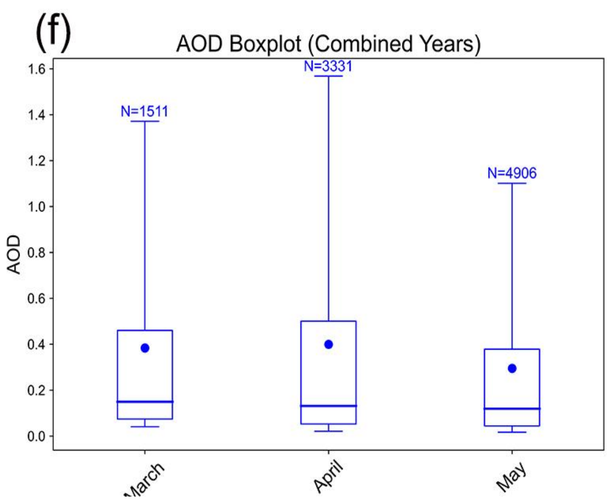
(v_d is the ozone deposition velocity; Y_{Br2} is the yield, which depends on solar zenith angle)

Results

◆BrO vs AOD (Aerosol Optical Depth) of seven years （2017-2023）



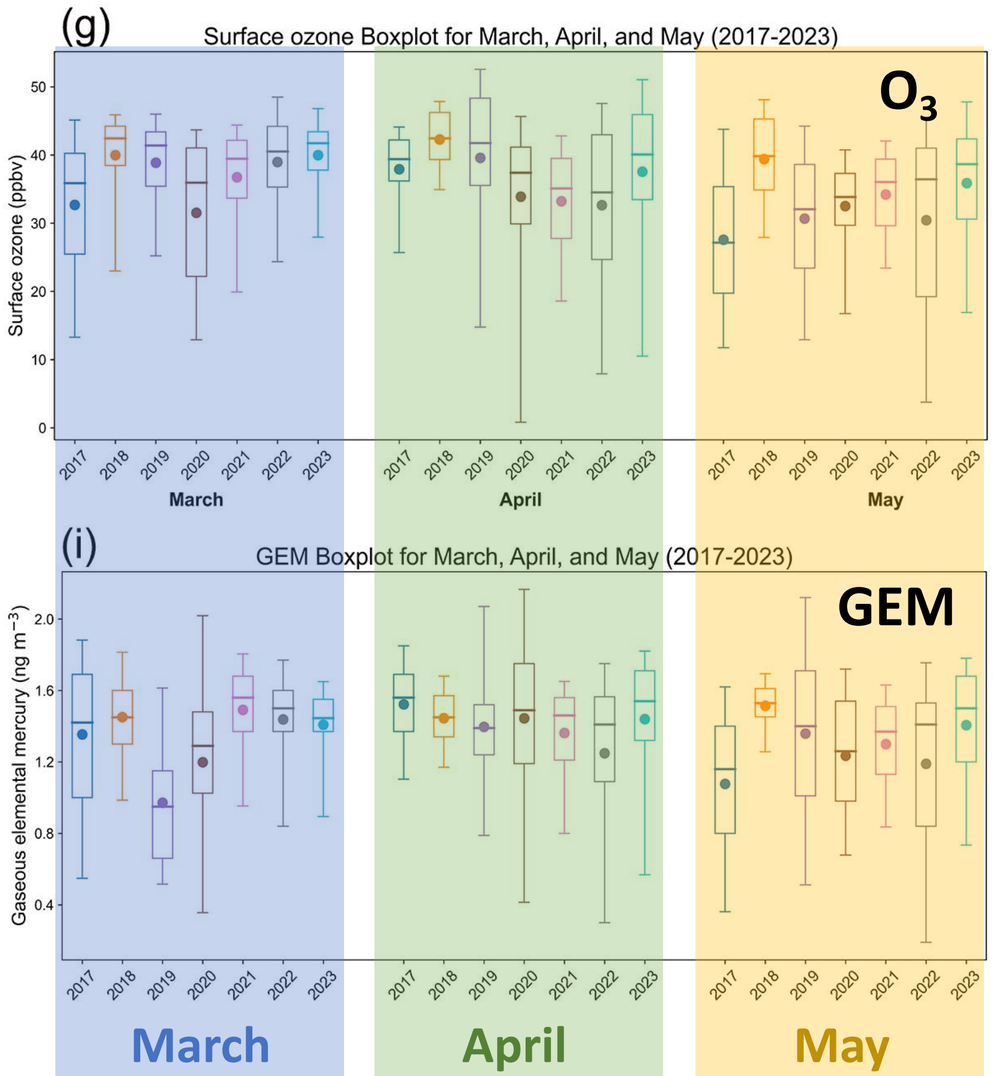


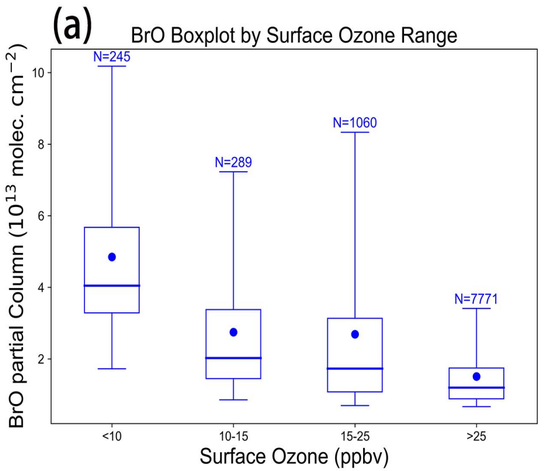


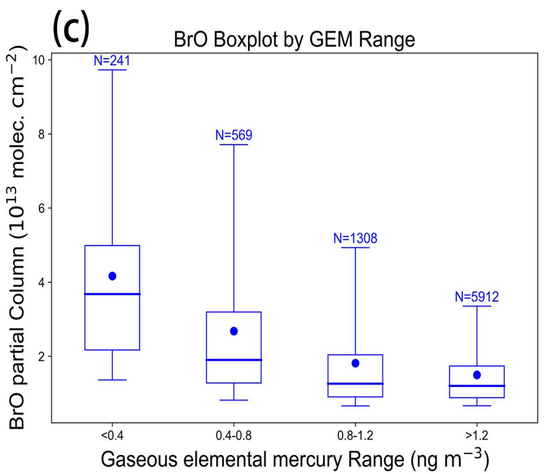
- In March, the overall BrO was the highest, but AOD did not show a consistent change;
- The interannual variation of BrO varies greatly.

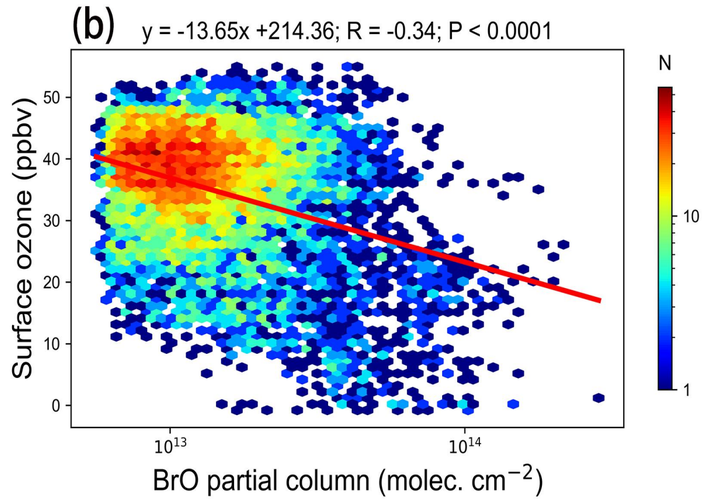
Results

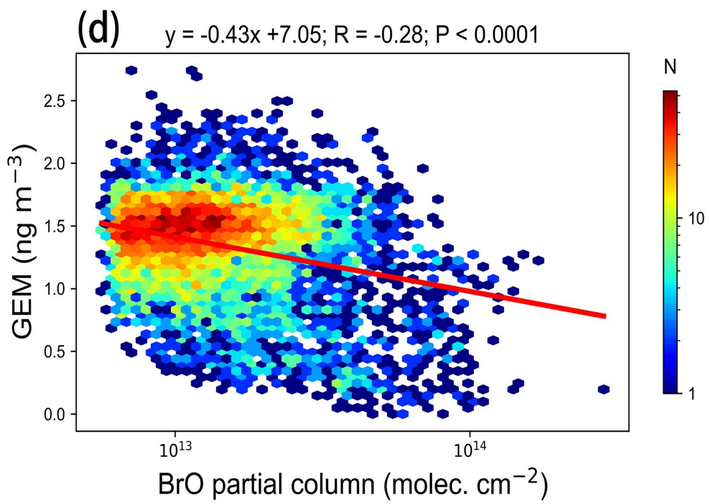
➢ Enhanced bromine drives both surface ozone and GEM depletion.



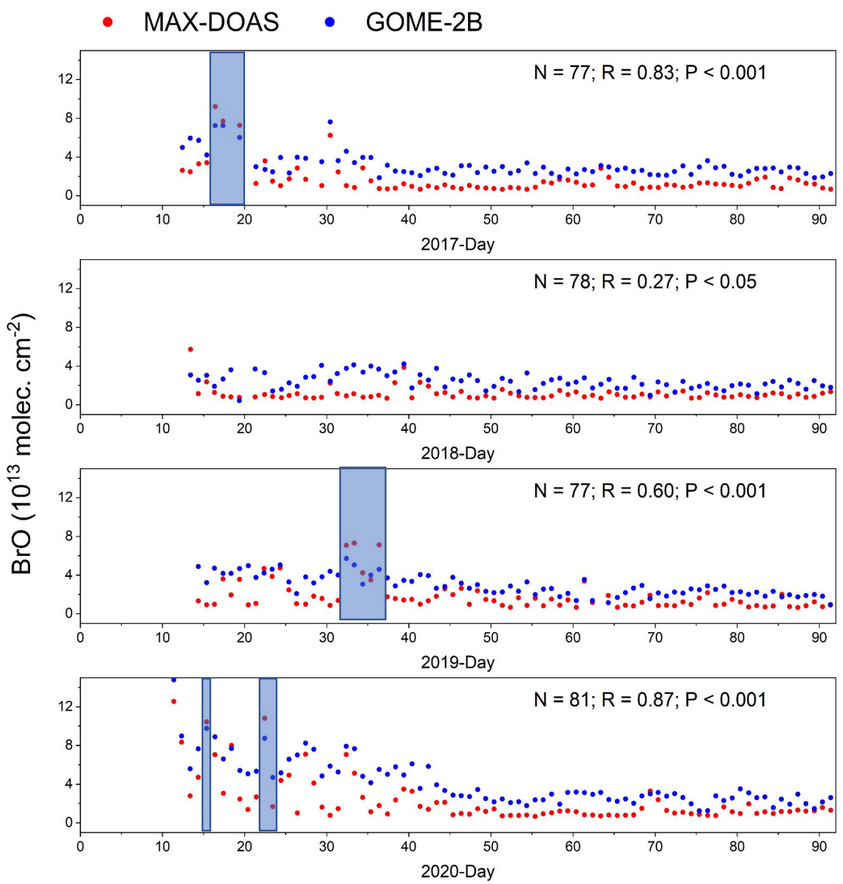


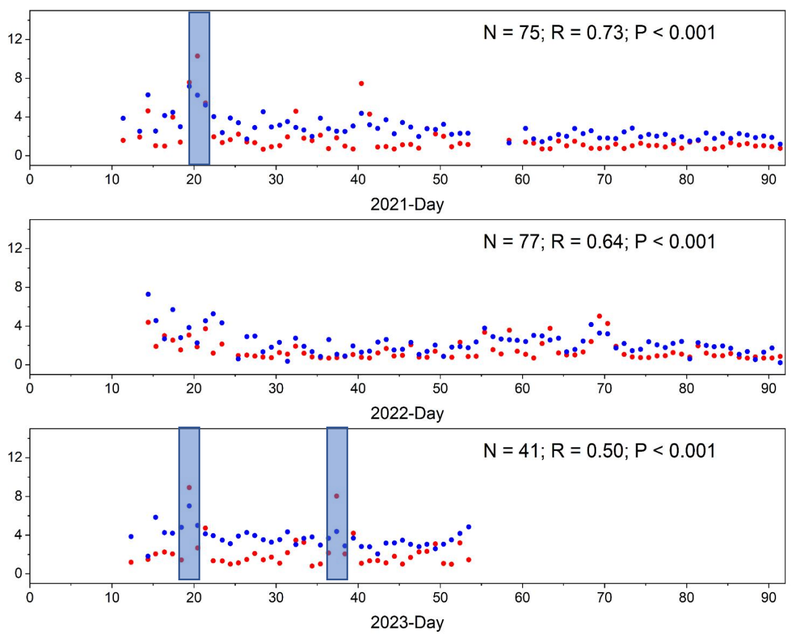




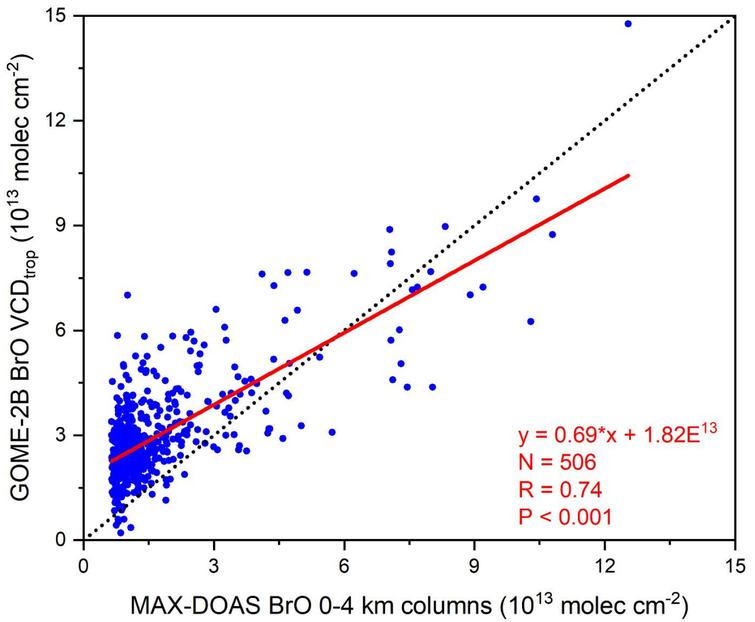


Results: Data Comparison with satellite





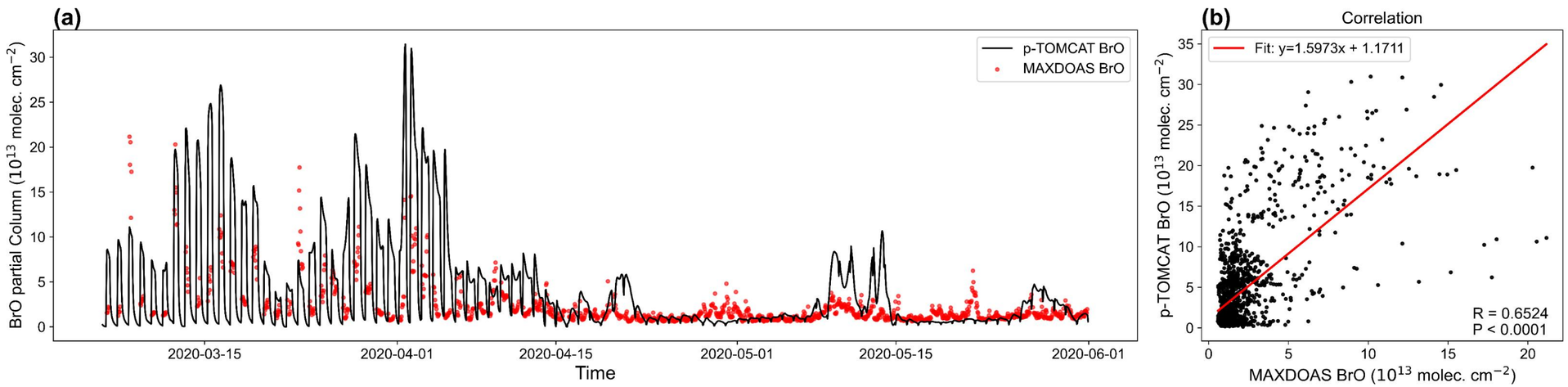
- Daily MAX-DOAS BrO partial columns (red scatters)
- GOME-2B tropospheric BrO columns (blue scatters)

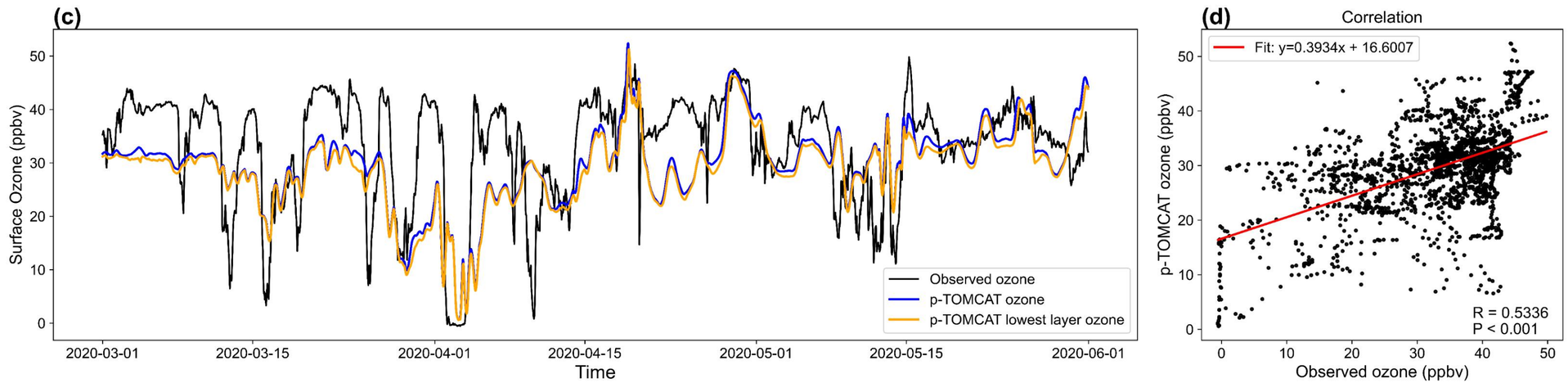


- The GOME-2B BrO VCD_{trop} were slightly higher than the MAX-DOAS BrO partial columns.
- During periods of BrO enhancement, the MAX-DOAS BrO partial columns exceeded the GOME-2B BrO VCD_{trop}.

Results: Data Comparison with model

■ **p-TOMCAT generally captured BEEs and ODEs.**

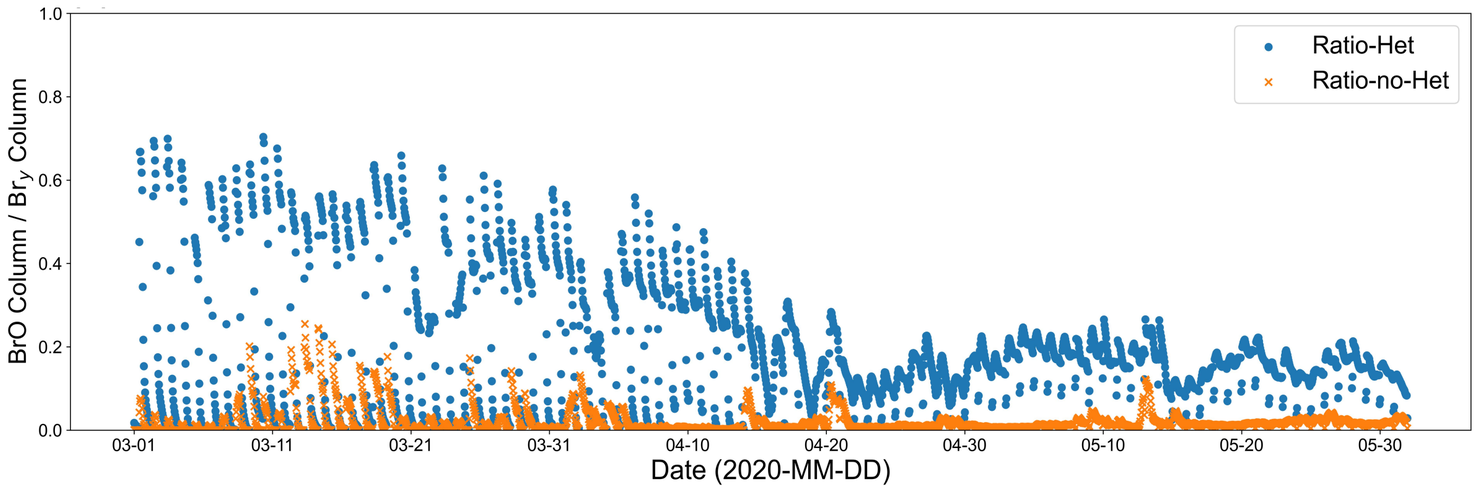


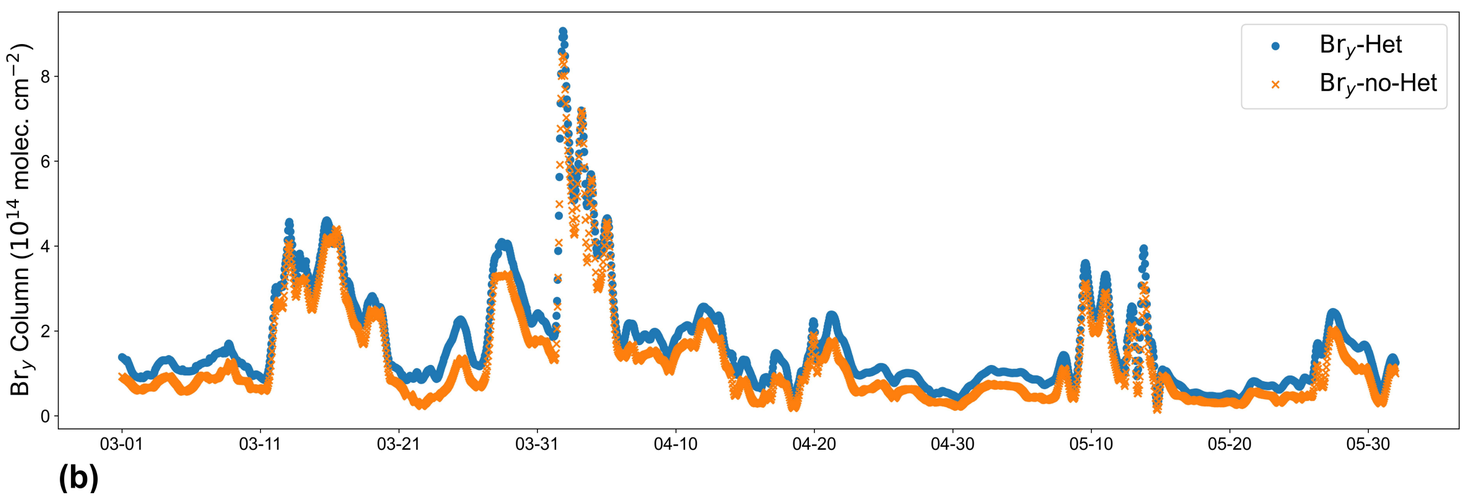


➢ **Good agreement between MAX-DOAS and p-TOMCAT BrO partial columns and ozone observations.**

Disscussion

◆Heterogeneous reactivation significantly enhance BrO partitioning





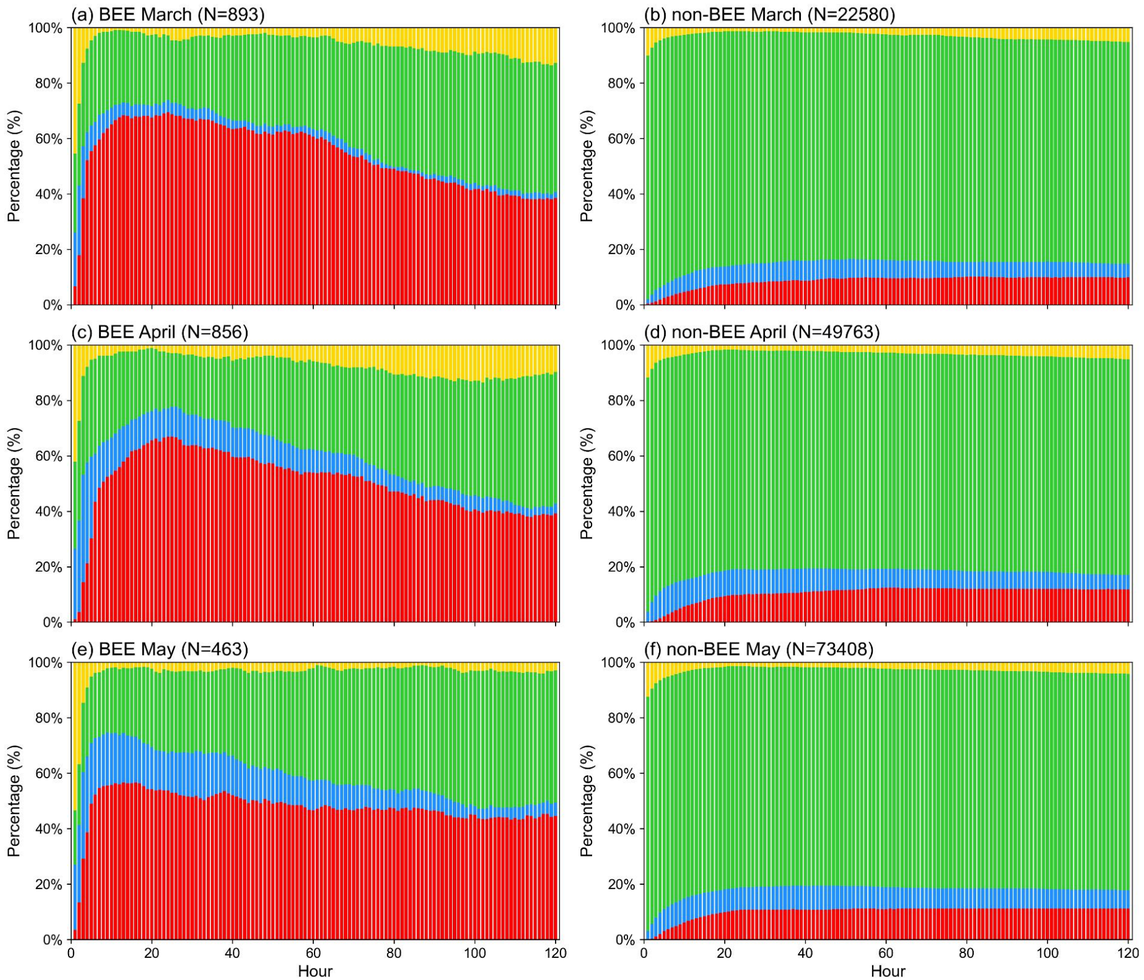
(b)

- **Sensitivity experiment**
  - **Het: heterogeneous reactivation ON**
  - **no-Het: heterogeneous reactivation OFF**
- When heterogeneous reactivation ON, Br$_y$ column increase by 1.2 times; **BrO/Br$_y$ increase by 6.7 times.**

Aerosols activate BrO partitioning in total Br$_y$

Disscussion

◆Surface and Free troposphere contact time during BEEs and non-BEEs



Percentage of Contact Time during BEEs				
	March (N=879)	April (N=835)	May (N=445)	Total (N=2159)
Free	35.69%	32.82%	36.98%	34.85%
Land	6.21%	7.95%	3.50%	6.32%
Sea ice	54.74%	50.88%	48.75%	**52.01%**
Ocean	3.36%	8.35%	10.77%	**6.82%**

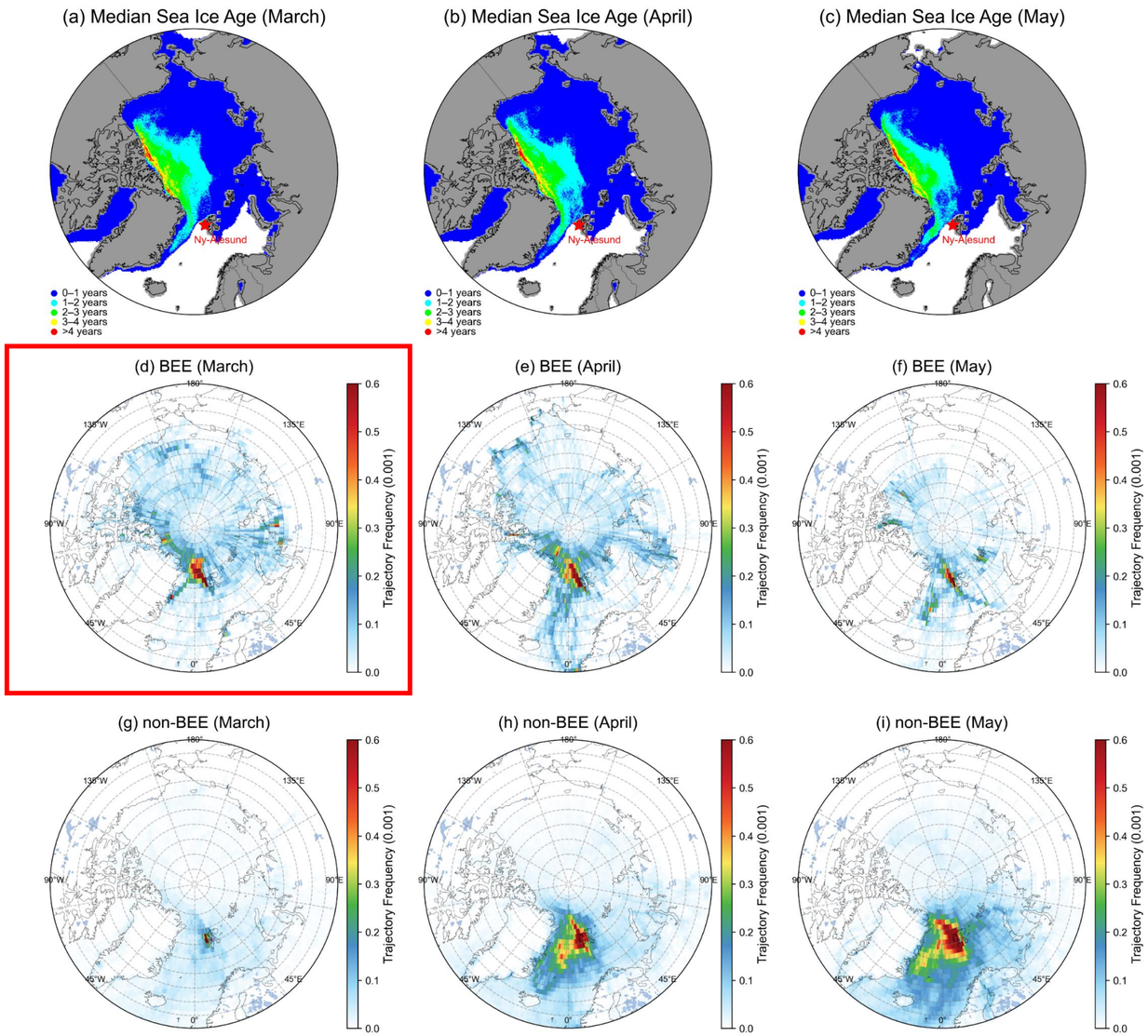
- **Ratios of contact time between the backward trajectories of air masses associated with BEEs in Ny-Ålesund during 2017–2023**

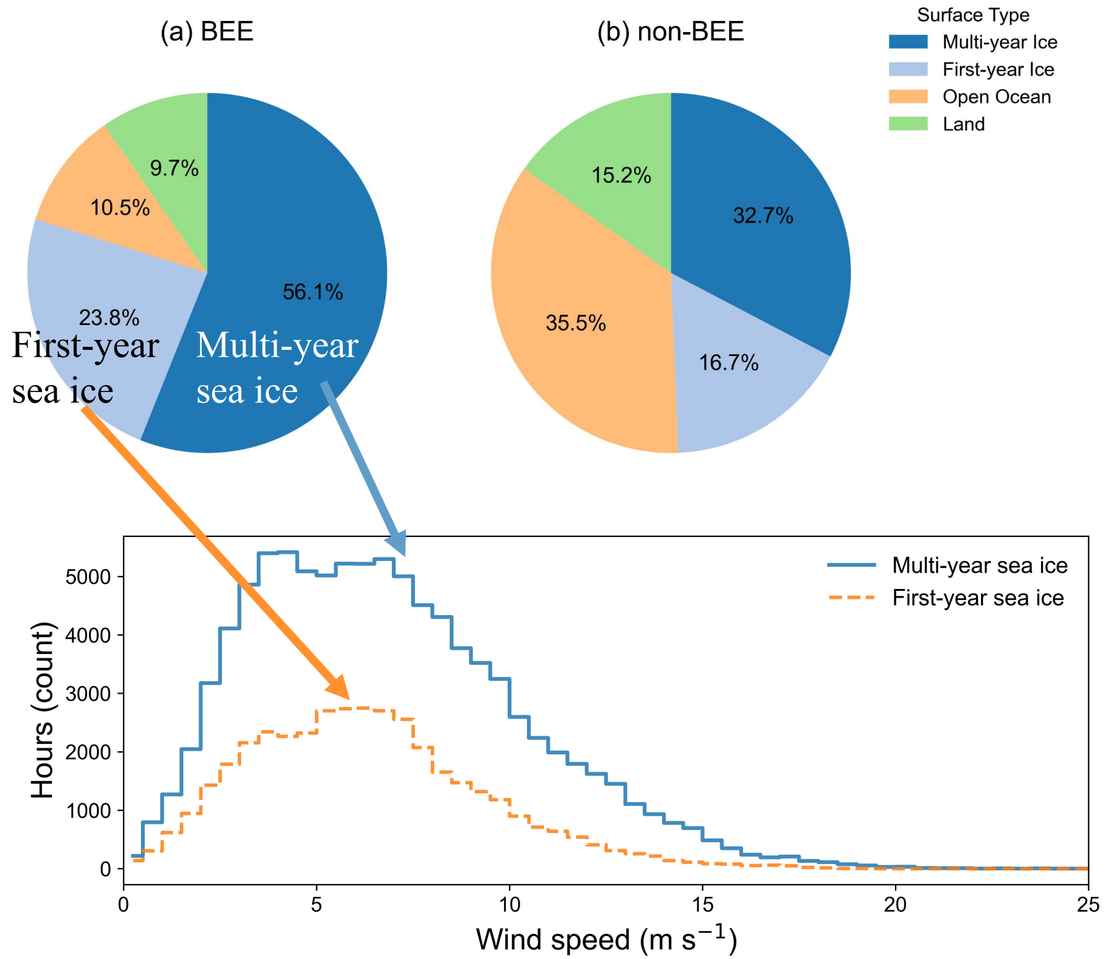
✓ **The contact time of BEE-related air masses with sea ice is more than 50% and with the open ocean is less than 10%.**

✓ From March to May, contact time with the open ocean gradually increases, but contact with sea ice remains dominant.

Disscussion

◆Sea ice surface contact time BEE vs non-BEE

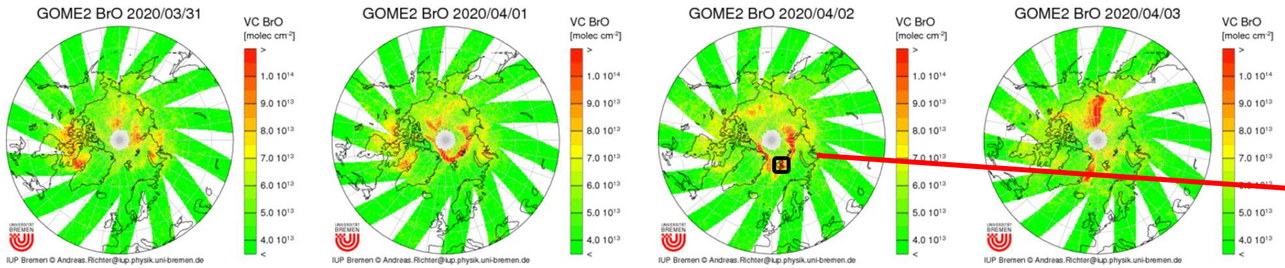




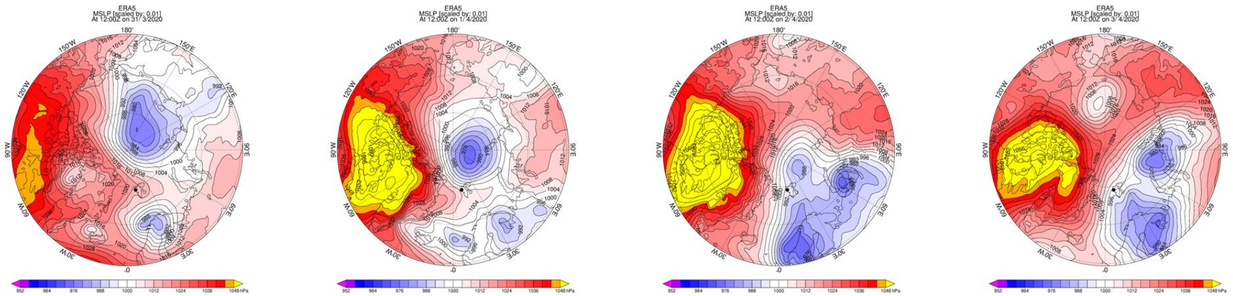
➢During BEEs at Ny-Ålesund, air masses spend about **2.4 times longer in contact with multi-year sea ice (56.1%)** than with first-year sea ice (23.8%).

Disscussion

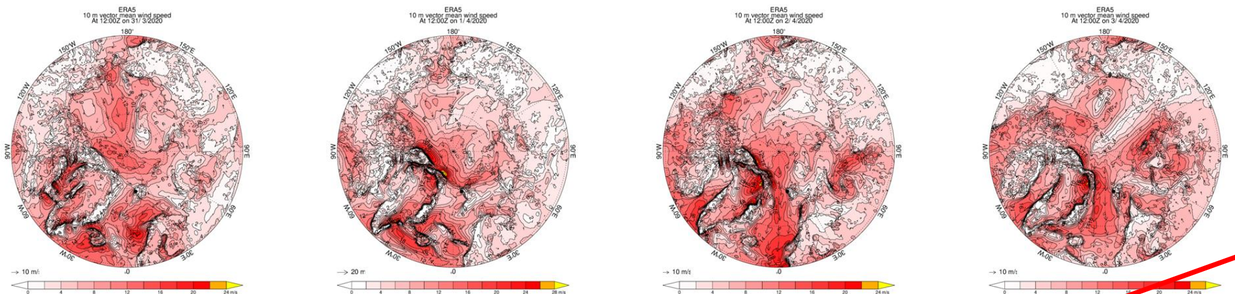
GOME-2B tropospheric BrO columns



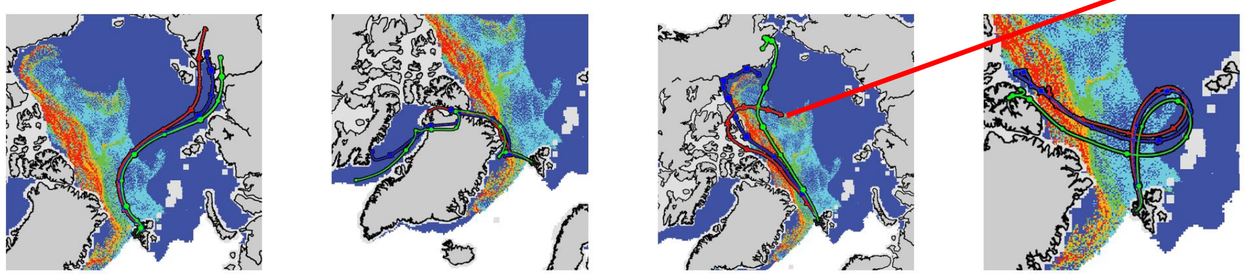
Mean Sea Level Pressure



Wind Speed

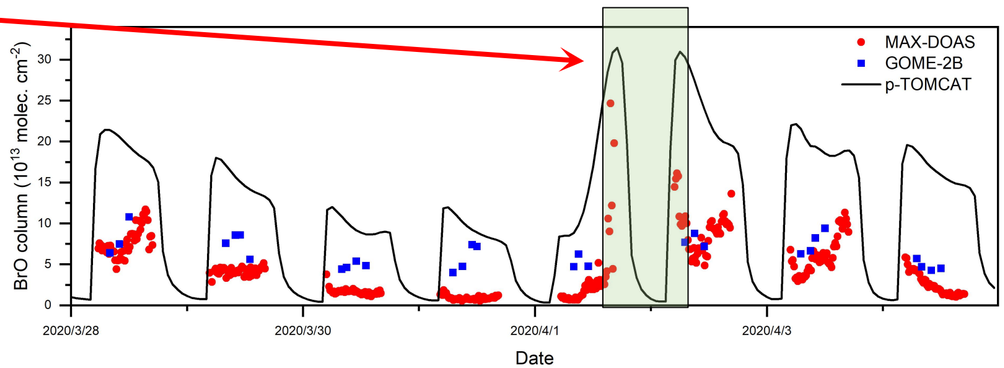


Backward trajectory (10m, 200m, 500m)



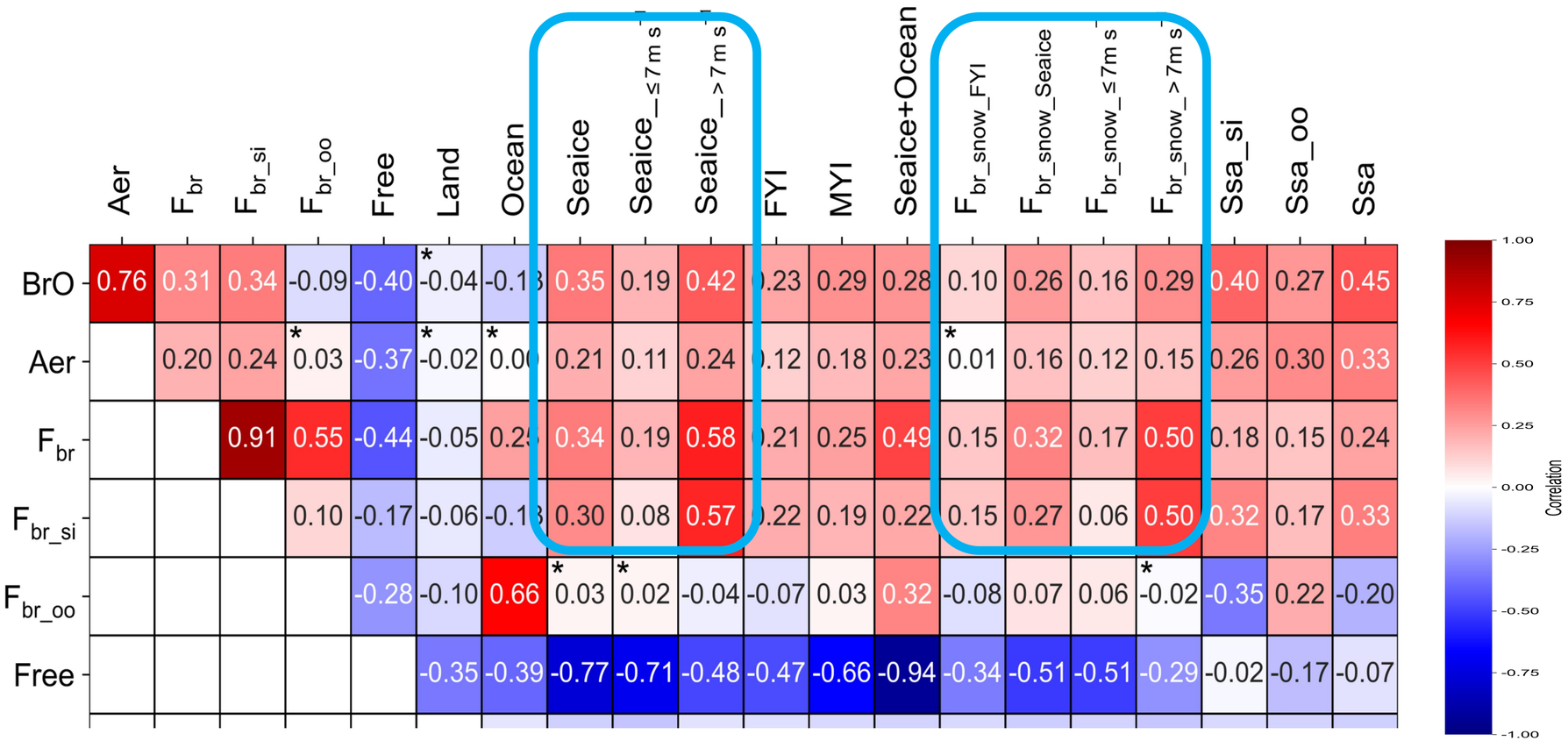
2020/03/31 12:00 | 2020/04/01 12:00 | 2020/04/02 12:00 | 2020/04/03 12:00

◆ A case of BEE from Multi-year sea ice



- A low-pressure system approached Ny-Ålesund from the northeast. Air masses mainly passed over multi-year sea ice, accompanied by high wind speeds.
- The BEE was driven primarily **by high-wind blowing snow** over multi-year sea ice on April 1 and 2.

Disscussion: strong winds effect



- Pearson correlation matrix of MAX-DOAS BrO VMR and related variables for March, based on combined data from 2017 to 2023.

➢ **Under strong wind conditions (> 7 m/s),** the observed BrO shows **stronger correlations** with both sea-ice contact time (R = 0.42) and snowpack bromine emission fluxes (R = 0.29) than under weak wind conditions (R=0.19; 0.16).

Conclusions

- High resolution BrO by MAX-DOAS at Ny-Ålesund, Arctic from 2017-2023;
- ODEs and BEEs were modelled by a chemistry transport model p-TOMCAT;
- The heterogeneous reactivation is important in maintaining high BrO;
- Multi-year sea ice is a dominant source of reactive bromine for Svalbard;
- Strong winds enhance the release of reactive bromine from blowing snow.

Thanks for your attention! Questions are welcome!

Avilable at https://doi.org/10.5194/acp-26-6165-2026 Contact Email: yhluo@aiofm.ac.cn, xinyang55@bas.ac.uk