

Sea Salt Aerosol from Blowing Snow above Sea Ice - Production Mechanisms and Parametrisations

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1: Introduction

**Why we believe sea ice surface is a direct source of sea salt aerosol?
any evidence?**



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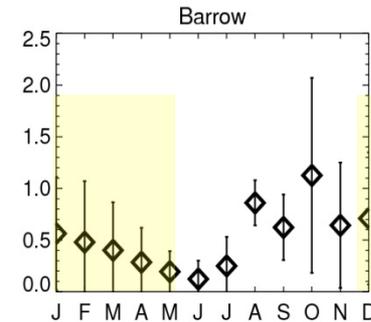
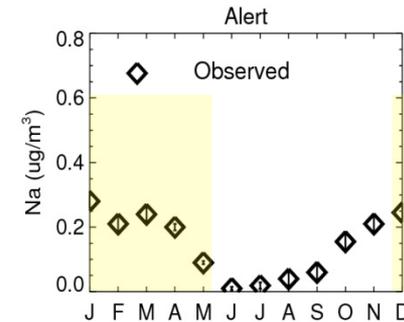
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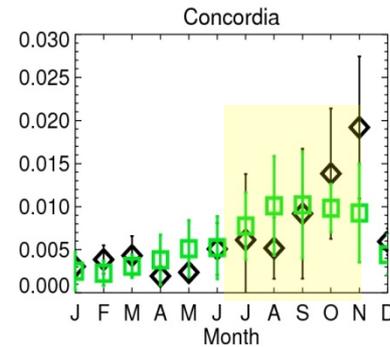
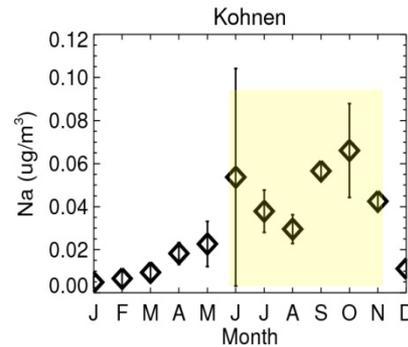
i) Polar SSA has its annual maximum in winter and minimum in summer

Which is out of the phase with the distance to the open ocean but **in phase with sea ice coverage**.

indicating either there is a sea ice source or an enhancement of large scale dynamical transport from summer to winter.



N.H.



S.H.

Legrand et al. JGR, 2016, doi:10.1002/2015JD024066

ii) Na^+ in ice cores has its maximum during glacial and minimum during interglacial period

- Which is out of the phase with the distance to the open ocean **but in phase with sea ice coverage.**

- indicating either sea ice is a source of SSA or there is a significant enhancement of large scale dynamics during glacial periods.

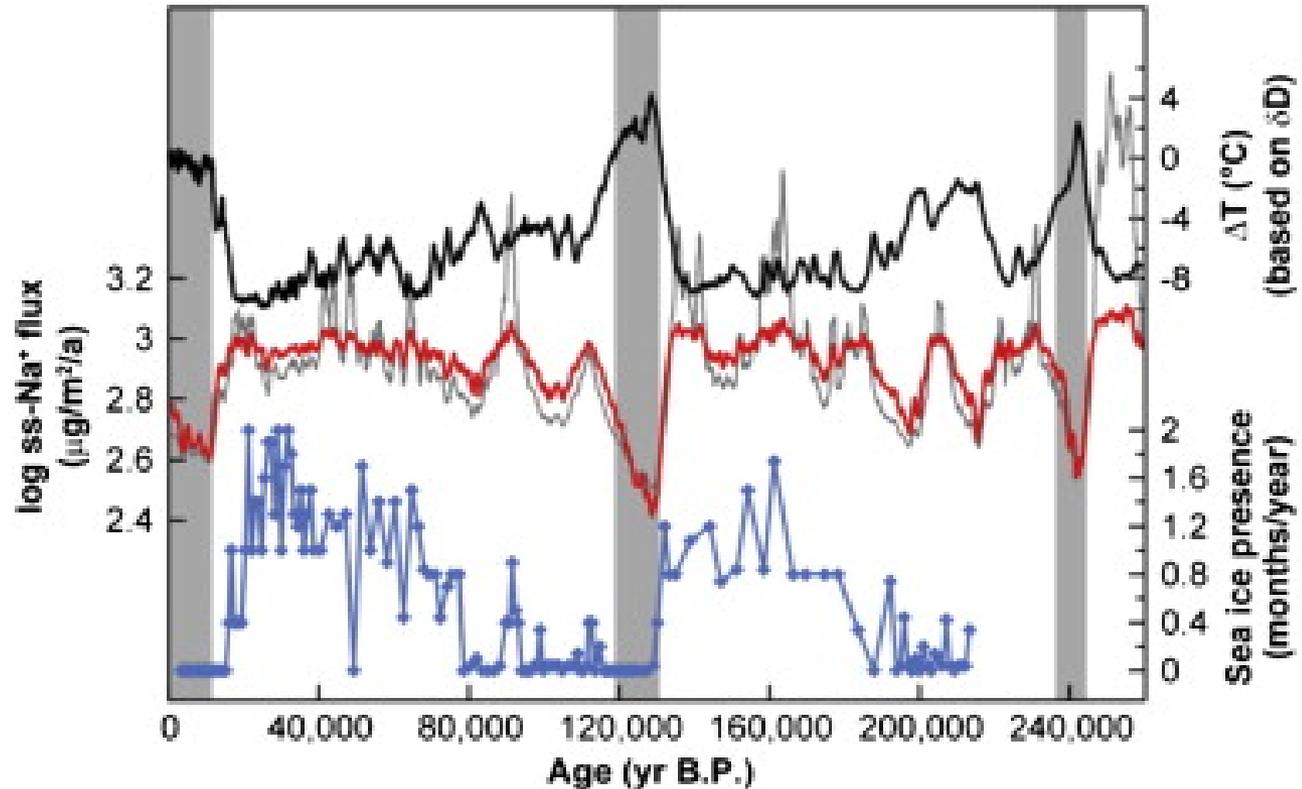
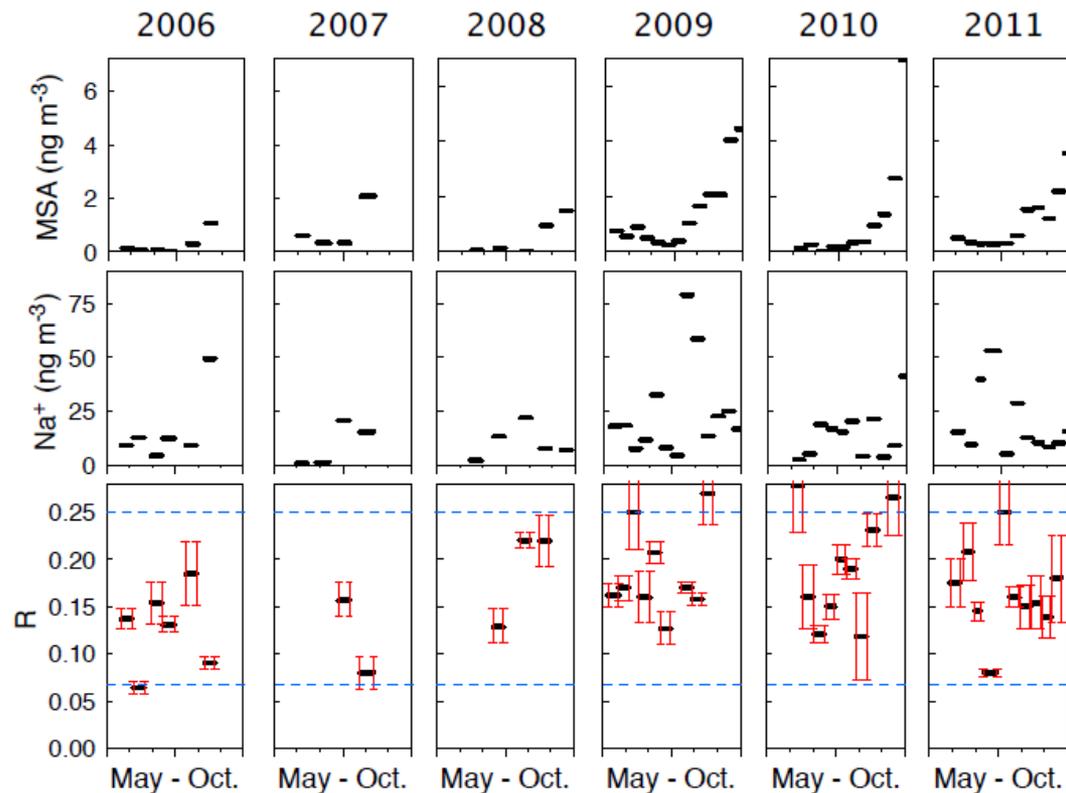


Fig. 4. Comparison of **temperature (black)** and **sea salt flux (red)** at Dome C, Antarctica, over the last two glacial cycles (Wolff et al., 2006; Jouzel et al., 2007) with a marine diatom-based reconstruction of **sea ice presence (blue)** at site SO136-111 (Crosta et al., 2004), offshore of Dome C. Grey curve indicates a rescaled sea salt flux, approximating the non-linear relationship between sea ice extent and sea salt flux to Dome C. Grey bars denote interglacial. After [Röthlisberger et al. \(2010\)](#).

iii) Sulfate/sodium ratio ($R=[\text{SO}_4^{2-}/\text{Na}^+]$) in ice cores and particulates is below that of sea water ($R\sim 0.25$) at inland sites

due to the effect of **mirabilite** ($\text{Na}_2\text{SO}_4\cdot 10\text{H}_2\text{O}$) precipitate from brine when temperature drops below -8°C [Wagenbach et al., 1998; Jourdain et al., 2008], e.g. via sea ice formation

$\text{Na}_2\text{SO}_4\cdot 10\text{H}_2\text{O}$ formation has significant impact on sulfate, but relatively weak impact on sodium amount in saline.



Multi-year records of particulate sulfate/sodium ratio R at Dome C (Legrand et al., 2017 ACPD).

2: Mechanism of SSA production from blowing snow

How SSA is produced from sea ice ?

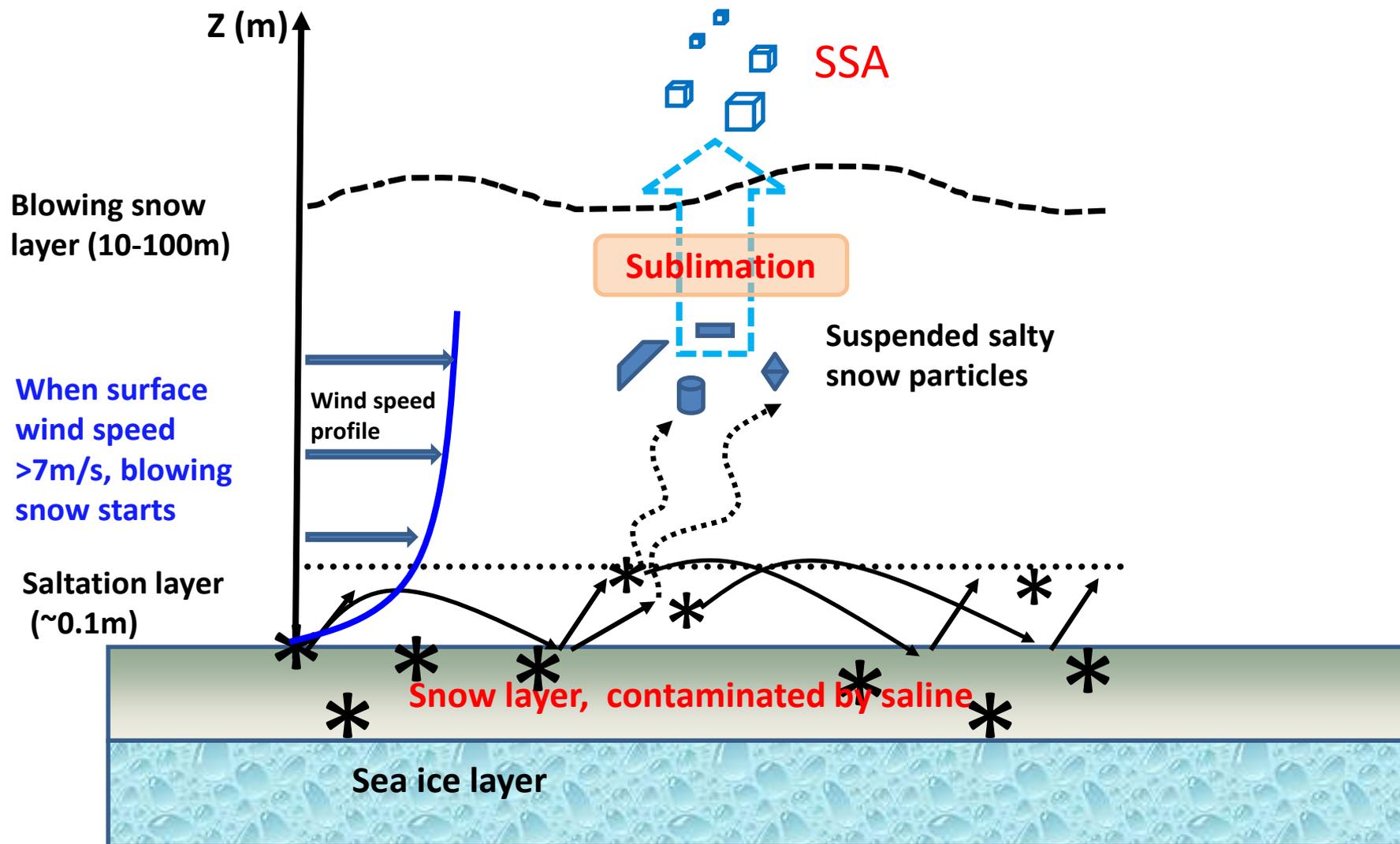


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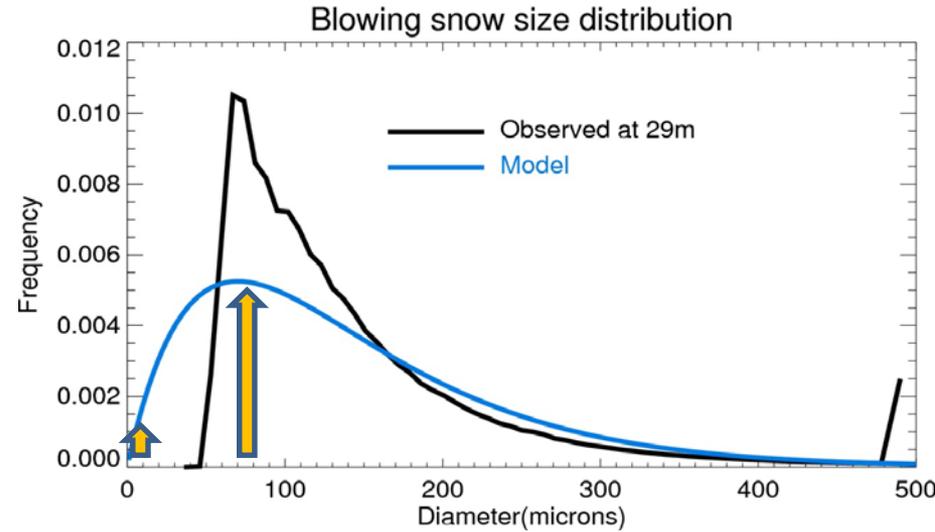
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Schematic plot of mechanism for sea-salt aerosol production from wind-blown snow on sea ice (Yang et al. GRL, 2008)



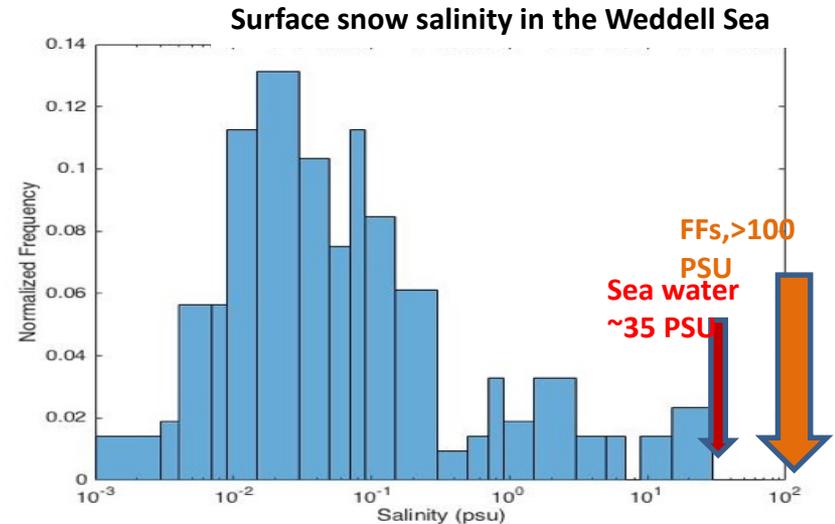
Comparing to frost flowers, surface snows have much lower salinity but with larger coverage



Corresponding dry NaCl size (μm) after sublimation can be calculated when salinity of ζ (in PSU) is known. Where ρ_{ice} and ρ_{NaCl} are densities of ice and NaCl, respectively.

$$r_{dry} = r_i \left(\frac{\zeta \rho_{ice}}{1000 \rho_{NaCl}} \right)^{1/3}$$

Initial snow size (1 st column), and salinity (1 st row)	100 psu	1 psu	0.06 psu	0.01 psu	0.001 psu
70 μm (peak)	24.3	5.2	2.0	1.1	0.5
10 μm	3.5	0.75	0.29	0.16	0.074



Parameterisation of SSA production from blowing snow

(Yang, Pyle and Cox, 2008)

The sea salt aerosol production flux can be expressed as:

$$Q_{\text{seasalt}} = \frac{Q_s}{1000} \int \int f(d_i) \zeta \psi(\zeta) d(d_i) d\zeta$$

As can be seen, SSA flux is proportional to blowing snow **sublimation flux** Q_s , which is a function of wind speed, RH , temperature (following Déry and Yau [1999; 2001] bulk mode).

The double integration is over **snow salinity** $d\zeta$ and **snow particle size** $d(d_i)$.

$\psi(\zeta)$ is the snow salinity frequency distribution (as shown before).

$f(d_i)$ is size distribution of the suspended snow particles (as shown previously).

Note: there are two assumptions applied in the above equation:

- 1) only one SSA forms per single blown-snow particle;
- 2) particle's sublimation rate follows **dr/dt being proportional to $1/r^2$ (the curvature effect), or equivalent to $dm/dt = \text{constant}$** , to allow more water coming from smaller snow particles.

3: Comparison to SSA Observations to validate the parameterisation



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Modelling SSA in pTOMCAT:

pTOMCAT is an offline global chemistry transport model (CTM). A process-based sea salt aerosol scheme has been implemented in the model (Levine et al., 2014) based on the scheme by Reader and McFarlane (2003). The forcing meteorology fields are ECMWF ERA-interim data. Horizontal resolution is $2.8^{\circ} \times 2.8^{\circ}$, with top layer $\sim 30\text{km}$.

Some updates in recent studies (Legrand et al., 2016; Rhodes et al., 2017):

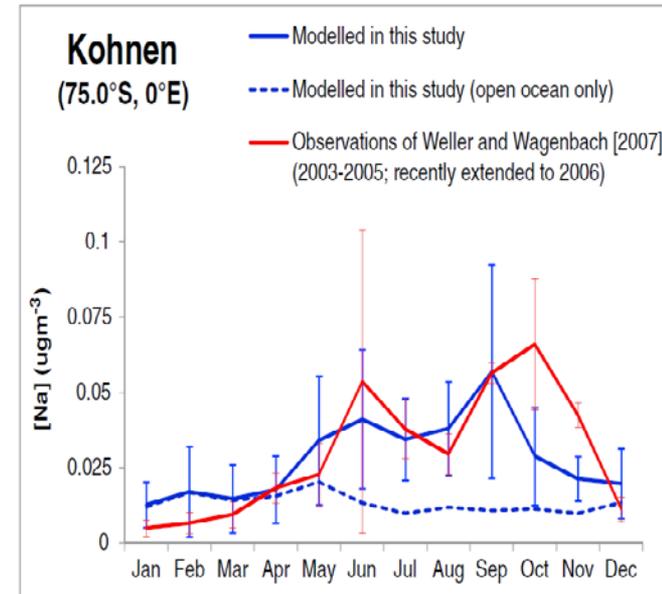
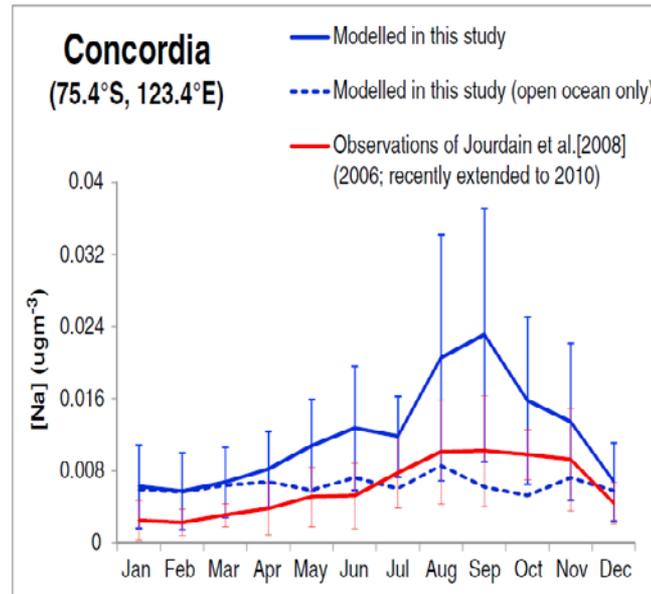
- improved **wet deposition scheme** by introducing monthly climatology precipitation data (from the Global Precipitation Climatology Project (GPCP)) to force model rainfall amount close to the climatology.
- **open ocean sea salt production scheme following Jaeglé et al. (2011) scheme** to allow a reduced SSA production flux at lower SSTs region.
- Using **surface snow salinity** (collected in this study), instead of the Massom et al. (2001) column mean data, \rightarrow salinity lower by e.g. $>$ one order of magnitude.
- Minimum SSA size bin down to 10 nm



SSA massive concentrations (in the S.H.)

Open ocean sourced SSA is flat all year round.

When sea-ice sourced SSA included, the winter peaks reproduced.

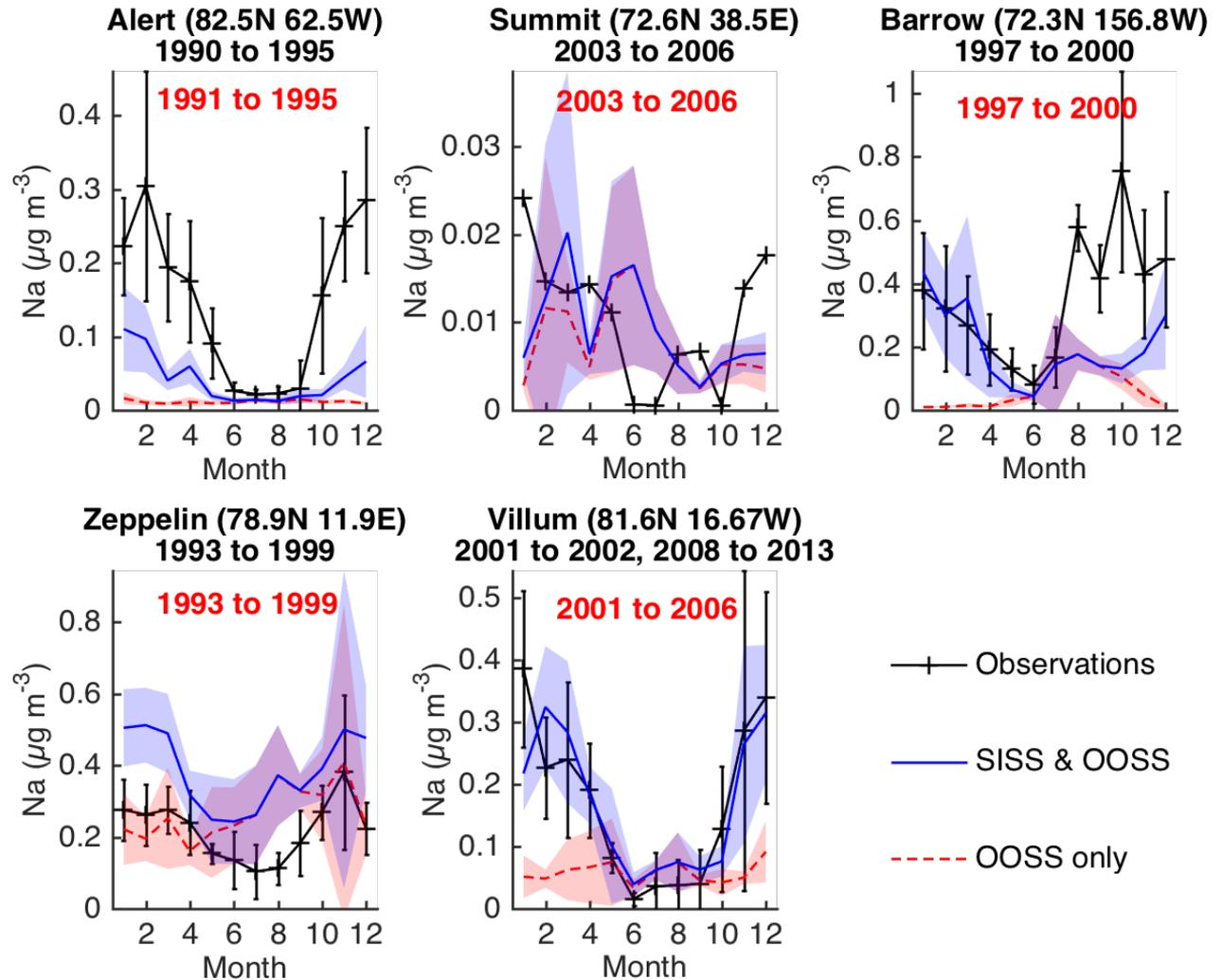


Sea salt (Na^+) concentrations at inland Antarctic sites simulated by pTOMCAT (Levine et al., 2014).

SSA massive concentrations (in the N.H.)

Open ocean sourced SSA could not explain the winter peaks observed.

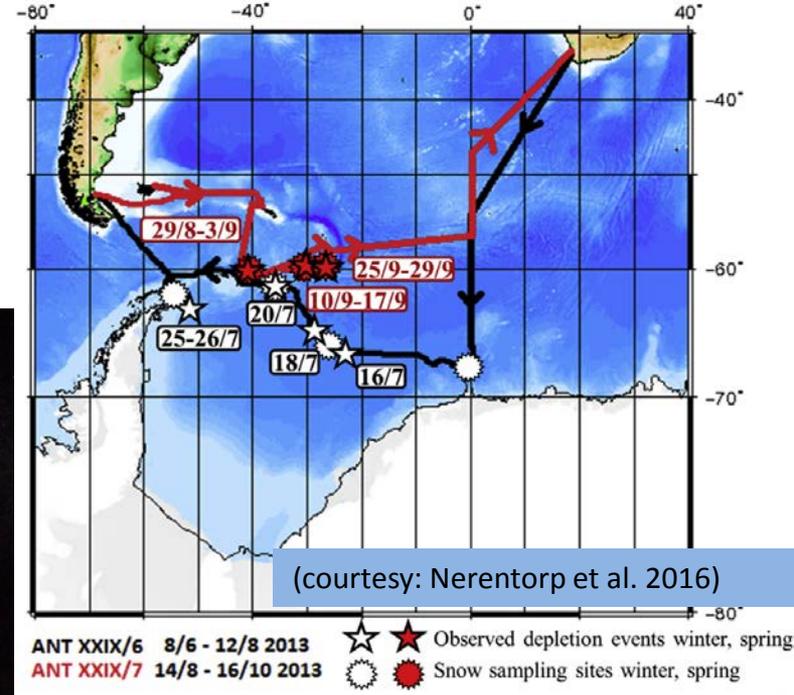
When sea-ice sourced SSA included, the winter SSA simulations are improved.



Sea salt (Na⁺) concentrations at Arctic locations simulated by pTOMCAT. Observations and model results are mean monthly values with uncertainty bars or shaded bounds representing $\pm 1 \sigma$ of the inter-annual variability. (Rhodes et al., 2017)

Aerosol number densities:

Both blowing snow particles (using SPC, size range 40-500 μm) and aerosol particles (using CLASP, size range 0.4-10 μm) were continuously counted at Polarstern's crow nest (~29m above surface) during June-August, 2013 (first leg in black).



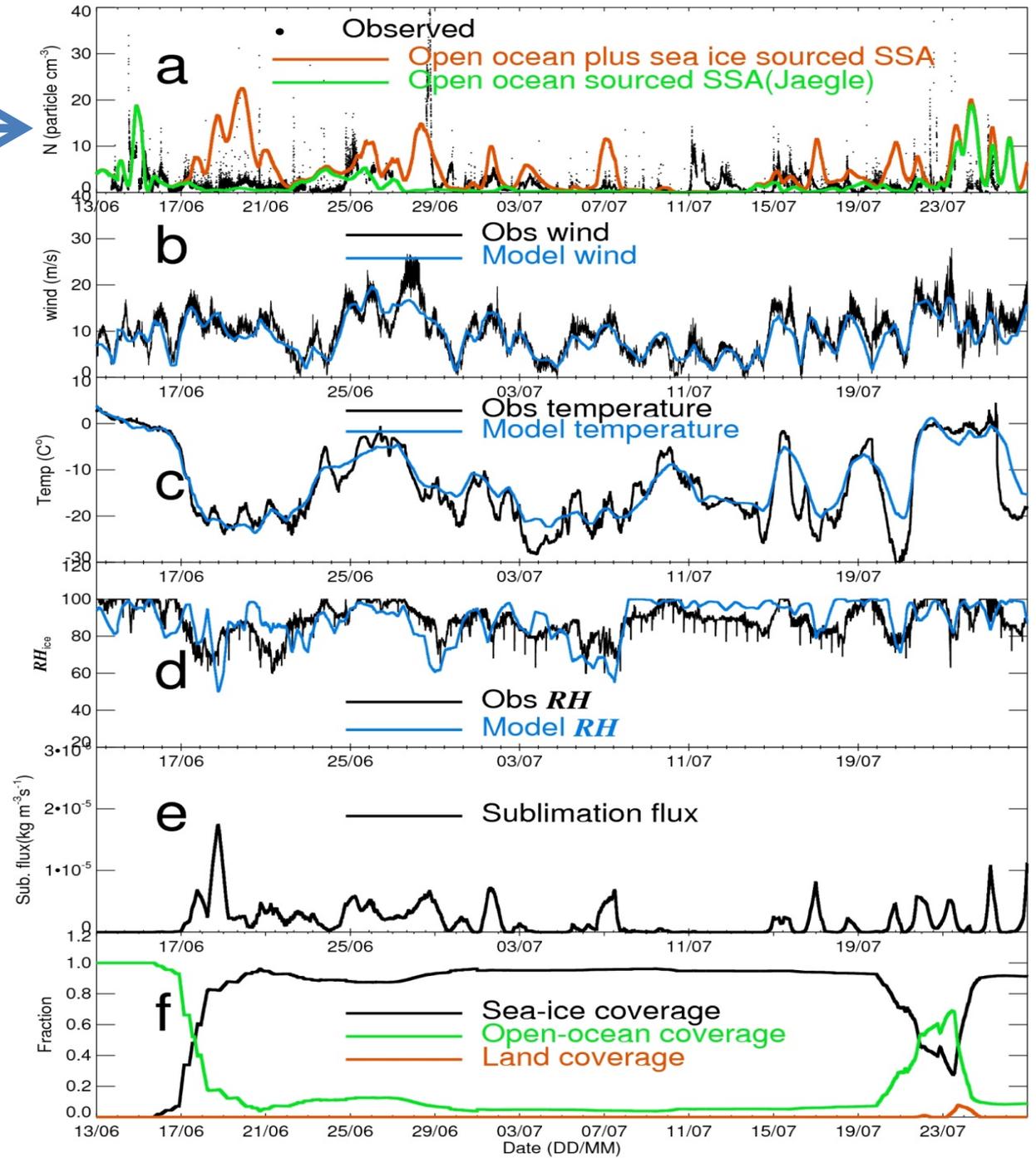
Aerosol number densities



i) Elevated aerosol densities were observed within sea ice covered zone; most of them are associating with strong winds, e.g. > ~10m/s.

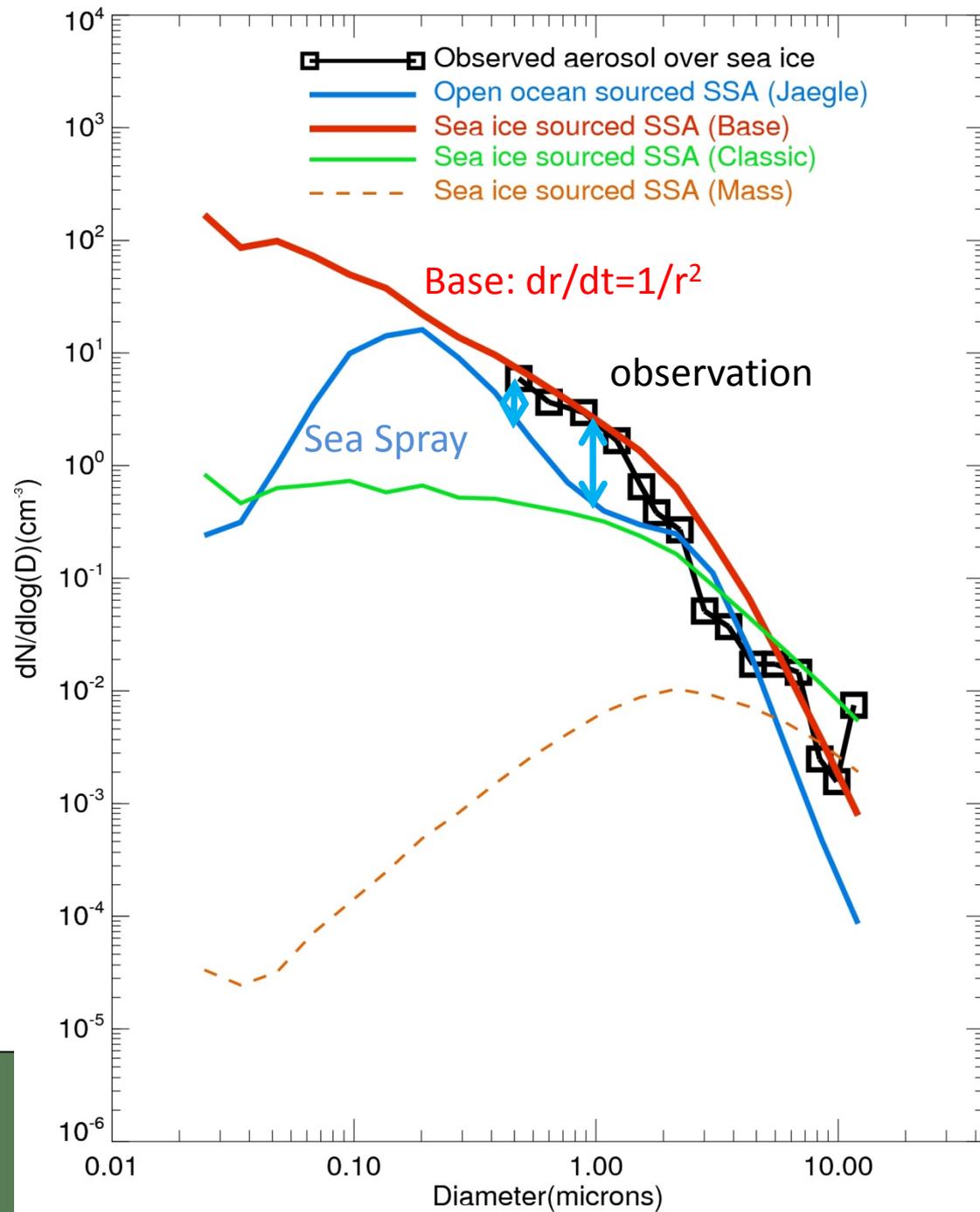
ii) sea spray is important at marginal-ice-zone.

iii) the observed enhancements of aerosol can be explained by blowing snow sourced SSA.



Averaged aerosol size spectra along the cruise track (between 13 June-26th July).

- i) Sea spray only (blue line) could not explain the observation (at size $>0.4 \mu\text{m}$)

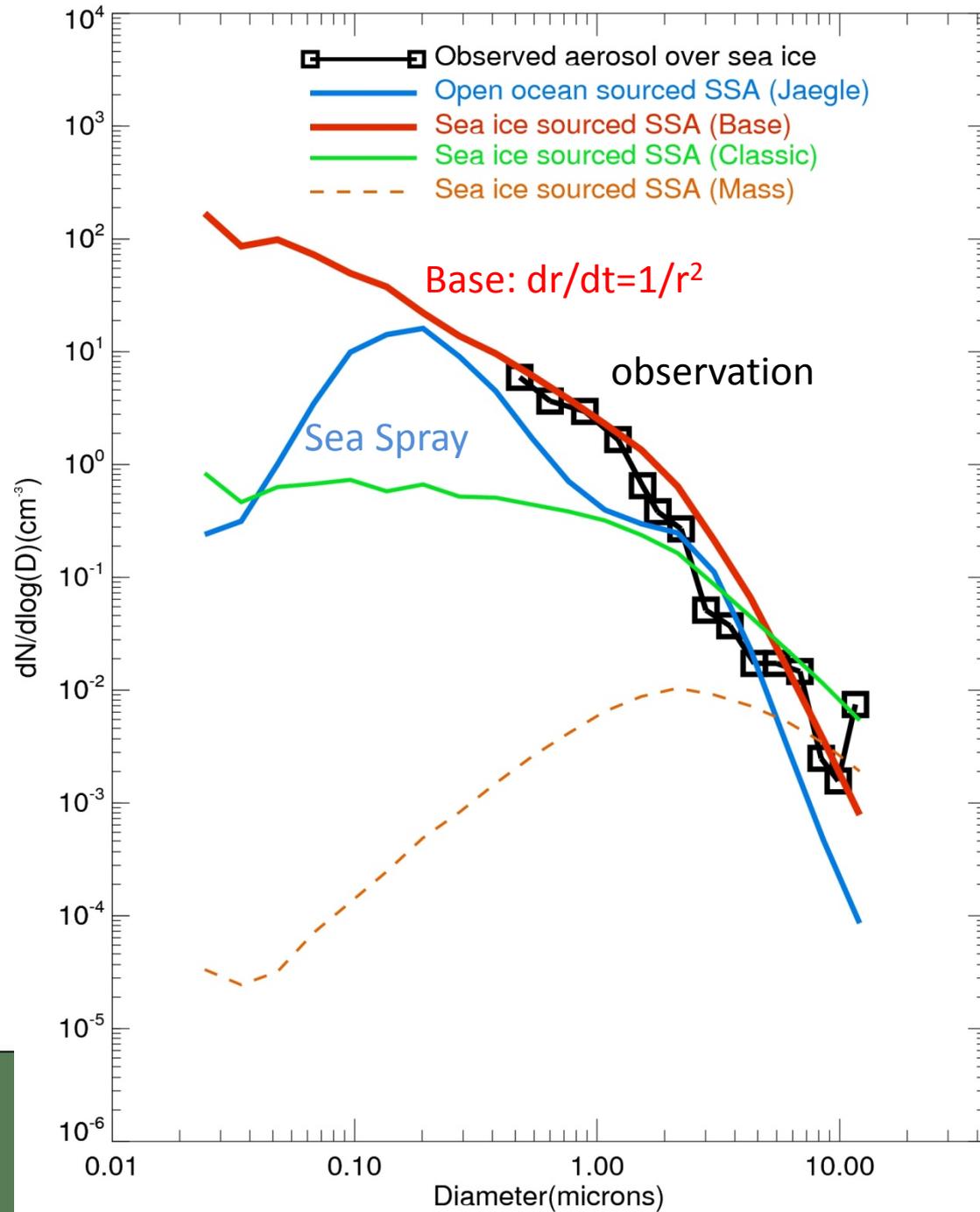


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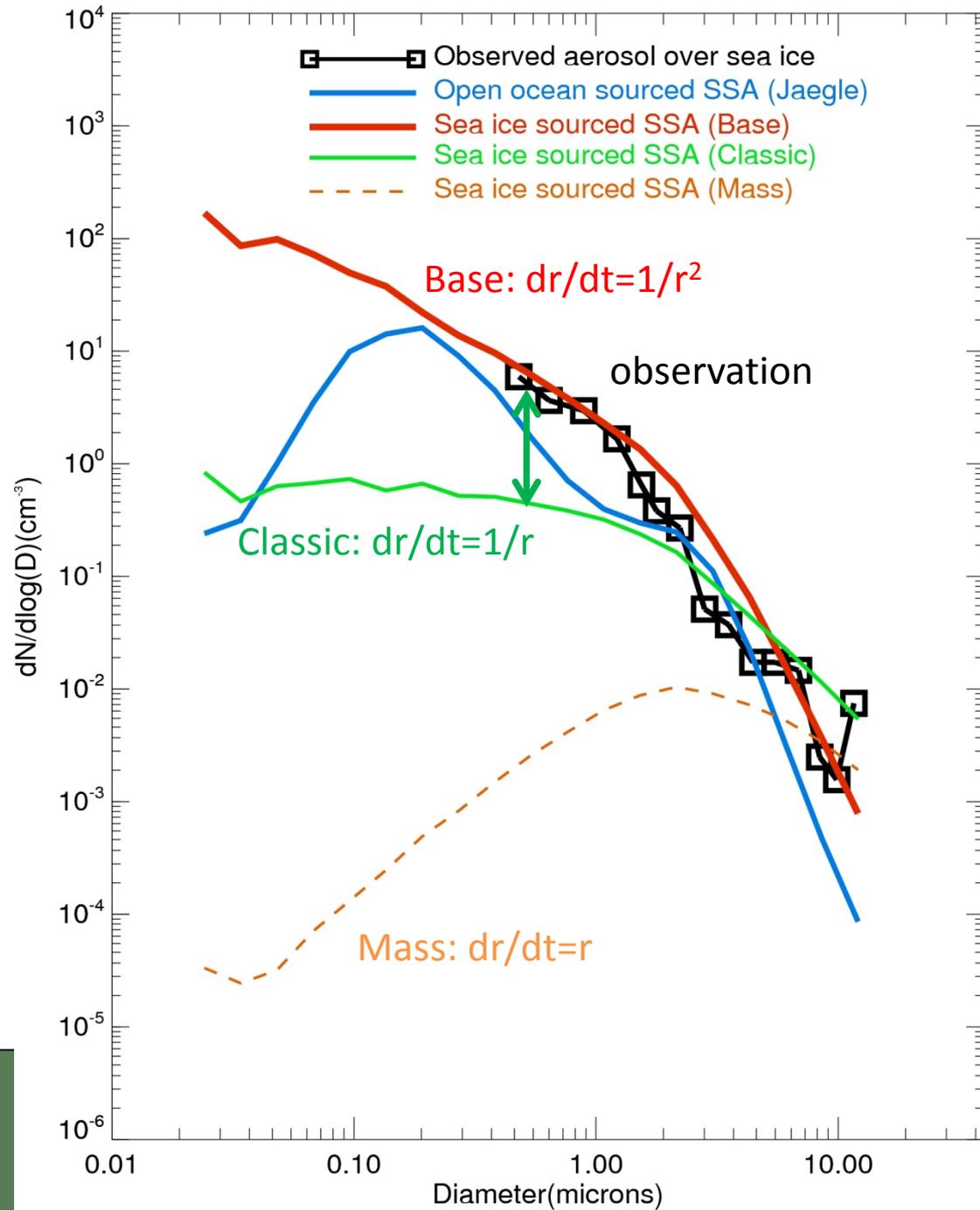
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- ii) Model with sea ice sourced SSA (red line) could well reproduce the observations.



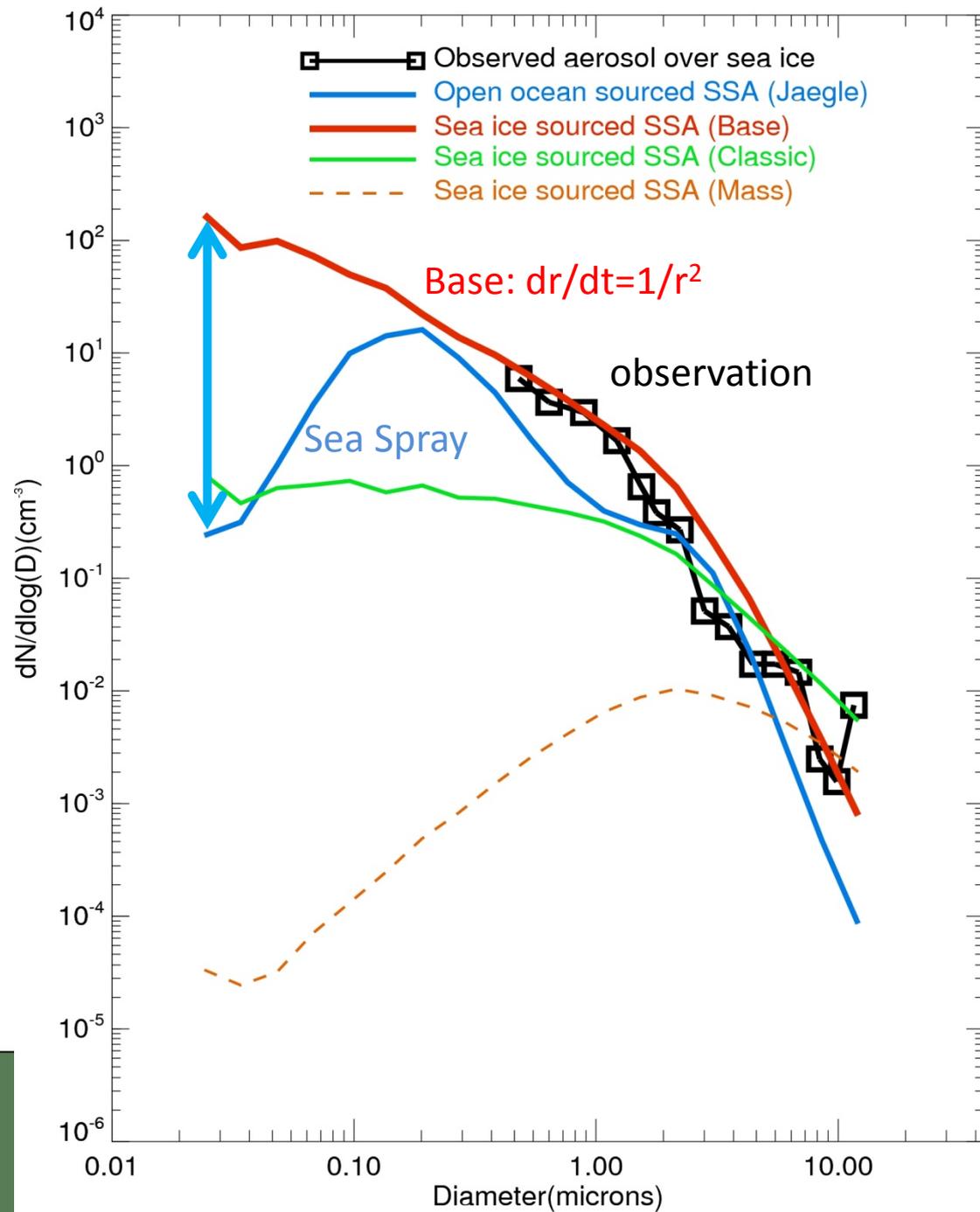
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- iii) Model with evaporation rate following a function of $dr/dt=1/r$ (diffusion effect) could not reproduce the observations \rightarrow indicating blown particles must suffer an accelerated evaporation rate, e.g. due to curvature effect and/or air ventilation effect (Thorpe and Mason 1967).

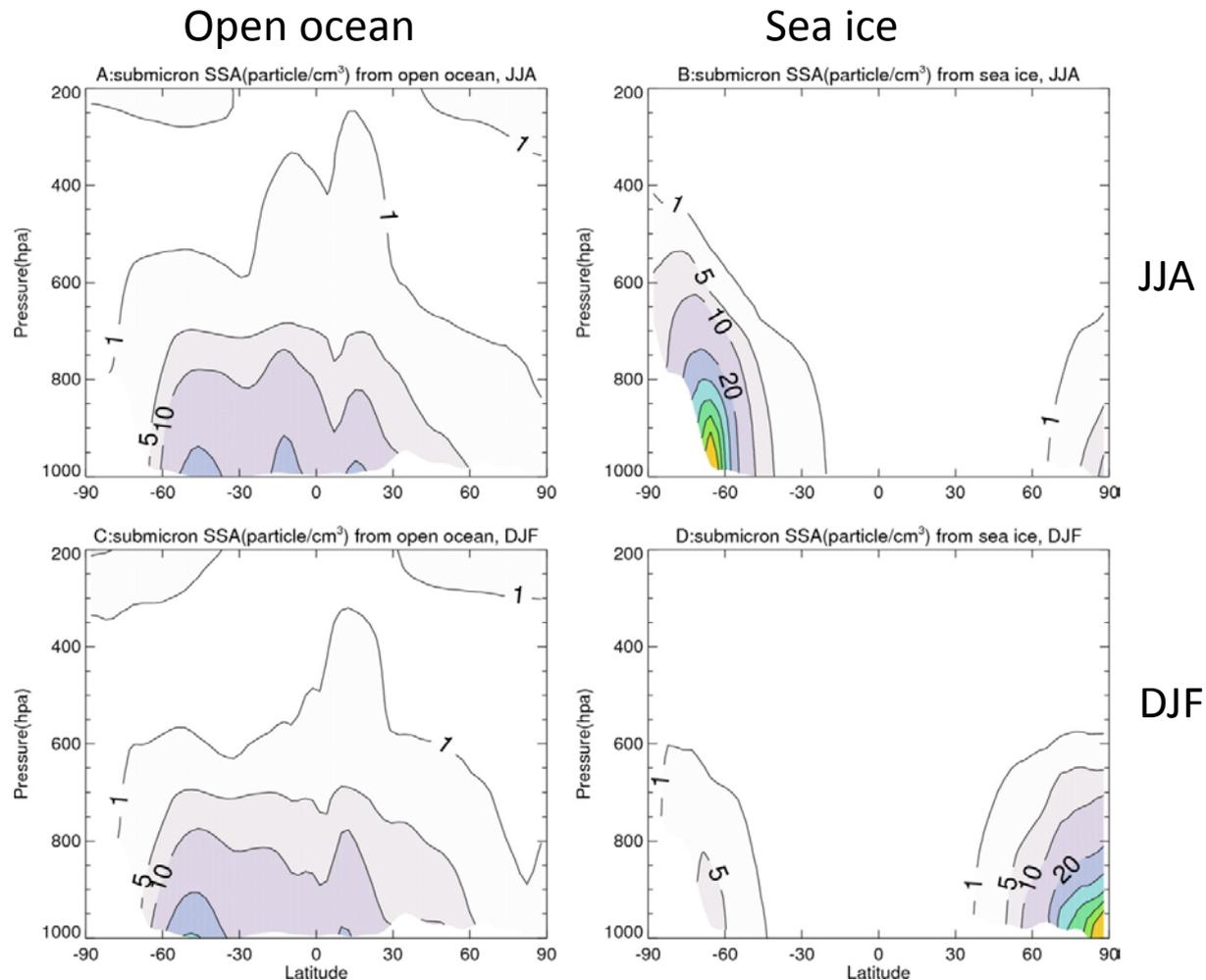


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- i) Sea spray only (blue line) could not explain the observation (at size $>0.4 \mu\text{m}$).
- ii) Model with sea ice sourced SSA (red line) could well reproduce the observations.
- iii) Model with evaporation rate following a function of $dr/dt=1/r$ (diffusion controlled) could not reproduce the observations \rightarrow indicating blown particles suffer an enhanced water evaporation rate, due to, e.g. curvature effect and/or air ventilation effect (Thorpe and Mason 1967).
- iv) Base run also predicts a much larger SSA production (at size $< 0.1 \mu\text{m}$) than that from sea spray (by orders!)



**Zonal mean SSA
number density from
both open ocean and sea
ice (based on a 3-year-
integration)**

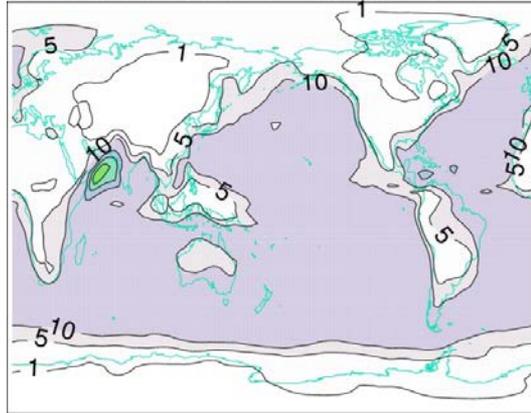


Zonal mean number concentration of submicron SSA (dry radius of 0.01-0.5 μm) from open ocean (left) and sea ice (right) during months of June-July-August (JJA) (upper panel) and December-January- February (DJF) (lower panel).

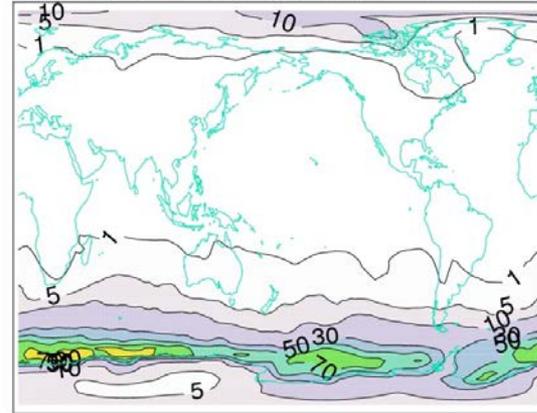
Open ocean

Sea ice

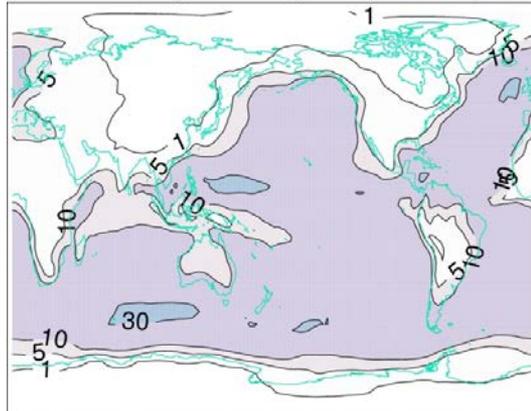
A: Surface SSA (particle/cm³) from open ocean, JJA



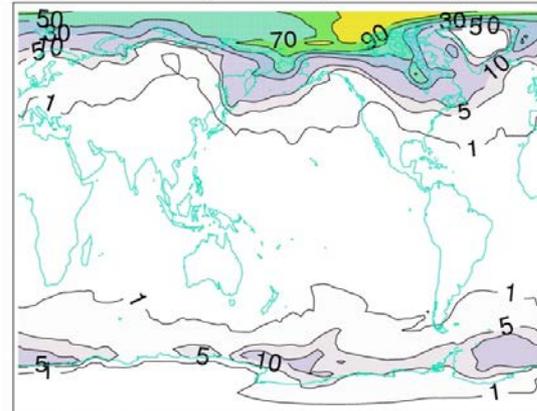
B: Surface SSA (particle/cm³) from sea ice, JJA



C: Surface SSA (particle/cm³) from open ocean, DJF



D: Surface SSA (particle/cm³) from sea ice, DJF



Surface layer SSA number density

JJA

DJF

Submicron sized SSA density (particle/cm³) in model surface layer. Open ocean sourced in the left column and sea ice sourced SSA in the right. The averages are for months JJA (June-July-August) in the upper panel and DJF (December-January- February) in the lower panel.

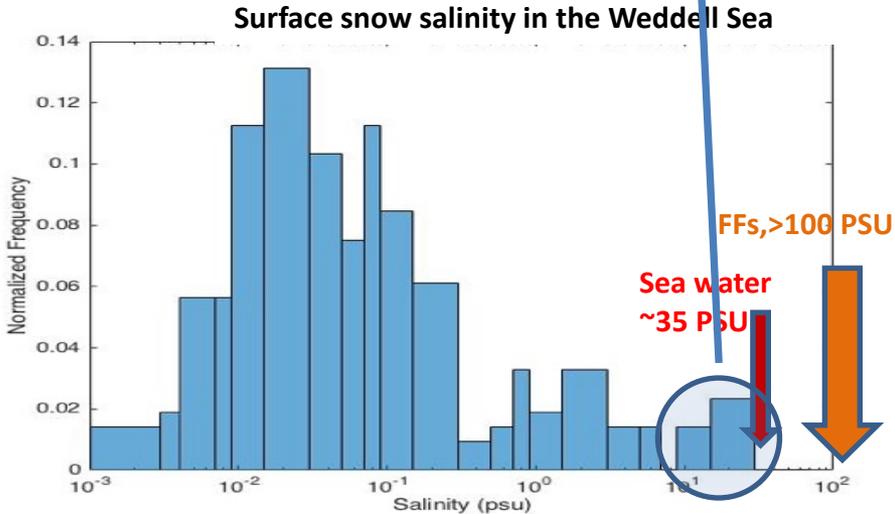
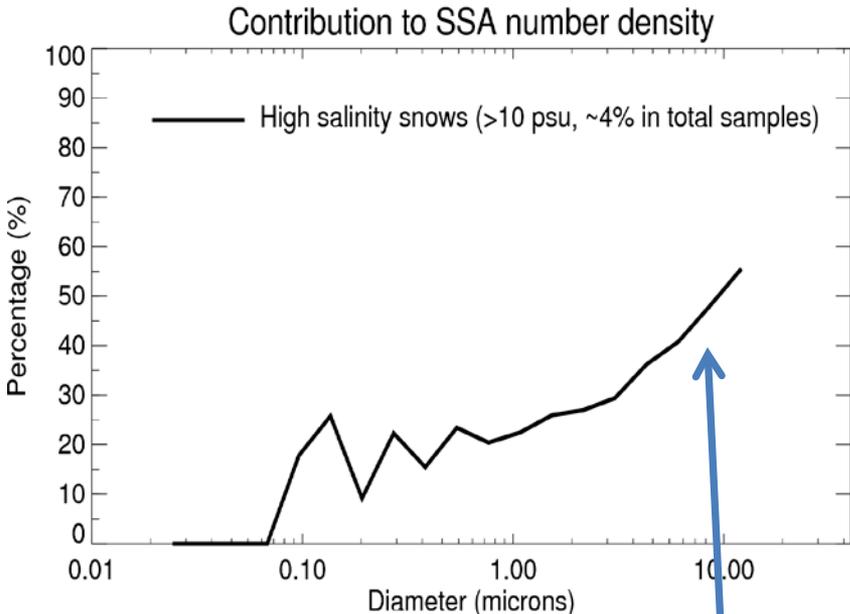


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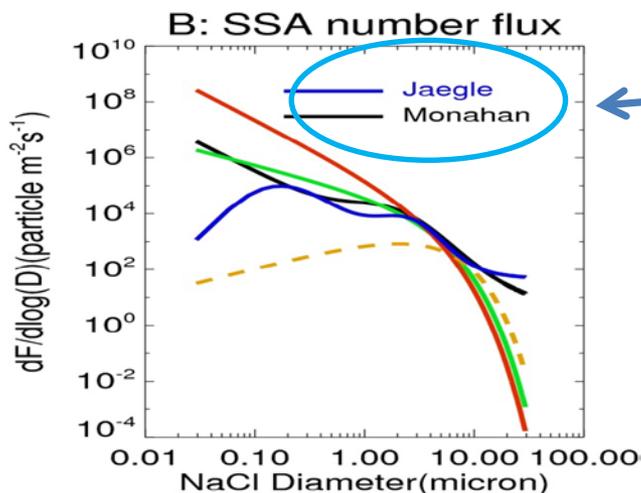
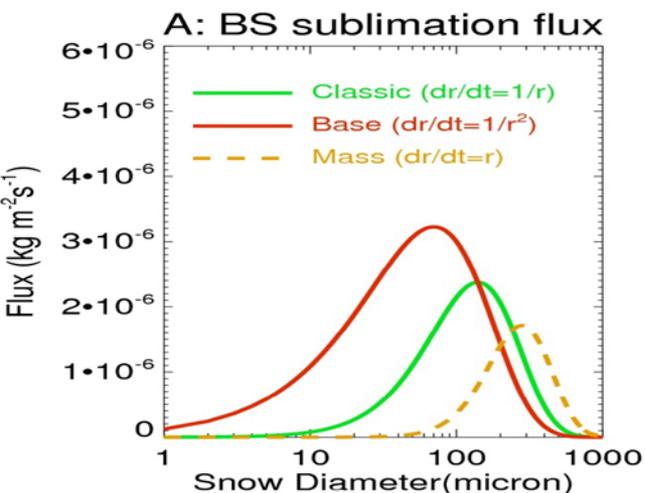
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The role of high saline crystals:

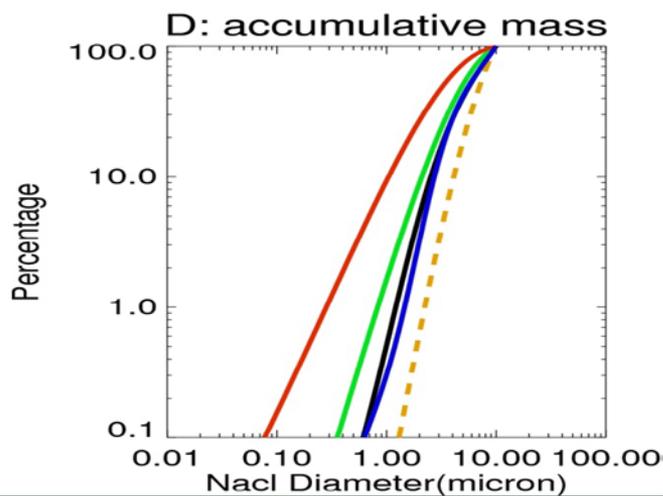
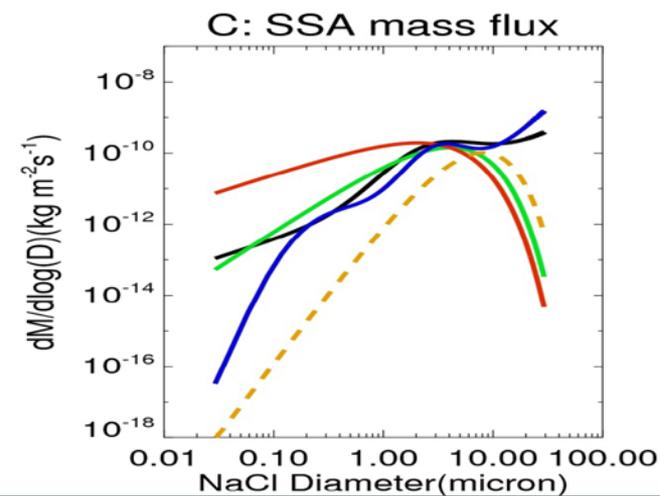


Comparison to sea spray (under wind speed=12m/s; for BS, at T=-10°C, RH=80% and median salinity of 0.06 PSU):



Two open ocean sea spray production schemes

Finger prints:
BS tends to form finer SSA at dry size < a few microns (e.g. ~3 μm here); while open ocean is preferential in producing larger ones.



thus, sea ice dominates number density, while open ocean dominates mass.

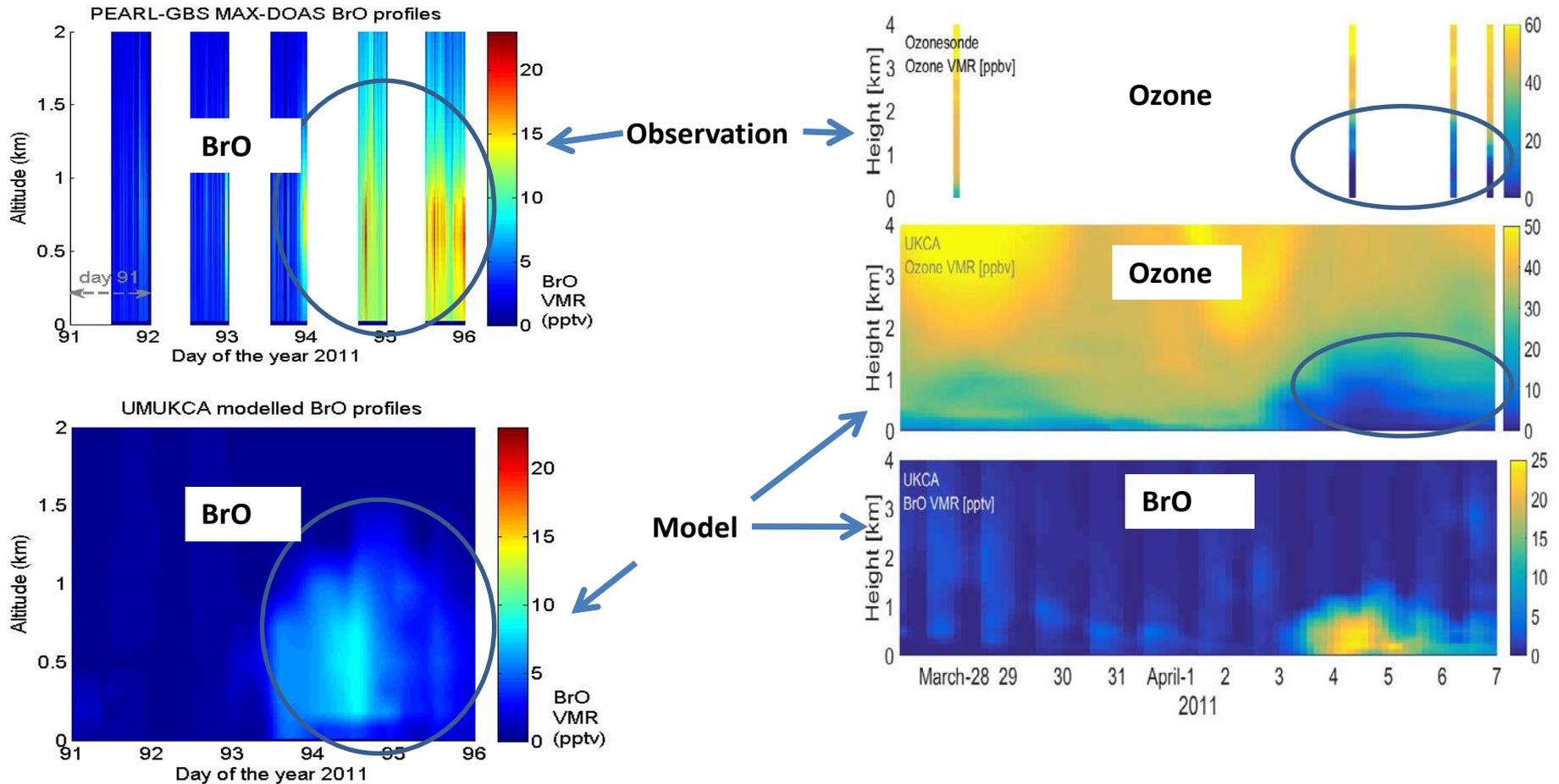


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Impacts on polar atmospheric chemistry, e.g. the bromine explosion' (left) and 'ozone depletion' (right) events.



✓ Left: profiles of MAX-DOAS BrO (top) and UKCA modelled BrO (bottom) at Eureka, Canada (Zhao et al., 2016).

✓ Right: profiles of ozonesonde ozone (top) and UKCA modelled ozone (middle) and BrO (bottom) at Eureka, Canada .

Conclusions:

- Model with SSA production from blowing snow included could (1) well explain the winter SSA peaks observed in polar regions and (2) reproduce the enhancement of aerosol number density observed in the Weddell Sea.
- The proposed SSA production mechanism (Yang et al. 2008) assumed an accelerated evaporation rate for snow particles in a turbulent air. For instance, the evaporate should follow a function of $dr/dt=1/r^2$ (rather than $1/r$ in a still air), which is likely related to air ventilation effect (Thorpe and Mason 1967), or the curvature effect, or even both. → a process is not fully understood
- Model predicts that sea ice surface is a large source of fine SSA ($<0.1\mu\text{m}$); for example, larger than that from open ocean by orders → which has not been evaluated



Outlook

- (1) The predicted large SSA production at size $<0.4 \mu\text{m}$ has not been evaluated till now; its impact on climate via serving as CCN or IN in high latitudes is not yet known.
- (2) The role of sodium (Na^+) recorded in ice cores could potentially act as a sea ice extent proxy.
- (3) The impacts on high latitude atmospheric oxidation capacity (e.g. via releasing bromine) →



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Thank you for your attention!