Constraining Physical Gas Exchange Processes and Transient Tracer Saturations in the Arctic Ocean using Noble Gas

Stanley Scott[1], Yannis Arck[1], Edith Engelhardt[1], Lennart Gerke[1], Florian Freundt[1], Chiara Hubner[1], Sophie Negele[1], Toste Tanhua[1], and Werner Aeschbach[1]

[1]Affiliation not available

April 05, 2024

Abstract

The formation of sea ice in the Arctic Ocean, as well as other physical processes such as injection of air and rapid cooling, plays a crucial role in determining the physical and chemical properties of its waters, which in turn drive the circulation in the Arctic [1]. Such processes can be constrained by conservative tracers which are biologically and chemically nonreactive, such as the noble gases. The full suite of stable noble gases (He, Ne, Ar, Kr and Xe) have been measured for the first time in the Arctic Ocean—along with CFC-12, SF_6, and other transient tracers—during the Ventilation and Anthropogenic Carbon in the Arctic Ocean (VACAO) project of the wider Synoptic Arctic Survey 2021 (SAS21) [2]. The noble gas profiles indicate a water column strongly influenced by rapid cooling and excess air injection, with a surface signature characteristic of solute rejection by sea ice formation.

We have compared multiple Arctic Ocean gas exchange models (based on similar models used in the Antarctic by Loose et al. [3] and in the Labrador Sea by Hamme et al. [4]) to constrain the fractions of Arctic water composed of Pacific, Atlantic and sea ice melt-derived origin waters, as well as the amount of sea ice being formed and air being injected into the water via bubbles. These parameters are estimated using a χ^2-minimisation procedure, where the misfit between fitted parameters and data is minimised. Preliminary results indicate a non-negligible sea ice term in the equations describing gas saturation anomalies in the Arctic.

Another key goal of VACAO is to use transient tracers to study the ventilation timescales of the Arctic Ocean, with application towards the study of the efficacy of its CO_2 solubility pump/storage. CFC-12/SF_6 is one tracer pair with which this is attempted; water dating with this pair requires knowledge of the concentration history of the tracers in the surface water, for which there are no direct measurements. Thus, the physical gas exchange parameters modeled from the noble gas data can be used in conjunction with observed atmospheric histories to more accurately describe the surface water histories of CFC-12 and SF_6. This in turn can be used to better constrain the Transit Time Distribution parameters used when dating Arctic waters [5]. Comparisons with other VACAO age tracer data (^{39}Ar and ^{129}I/^{236}U) may act as validation tools to this "correction" to CFC-12/SF_6 dating.

References for Abstract

[1] Rudels, B., and Carmack, E. 2022. Arctic ocean water mass structure and circulation. *Oceanography*, 35(3–4), 52–65 pp.

[2] Snoeijs-Leijonmalm, P. and the SAS-Oden 2021 Scientific Party (2022). Expedition Report SWEDARCTIC Synoptic Arctic Survey 2021 with icebreaker Oden. Swedish Polar Research Secretariat. 300 pp.

[3] Loose, B., Stammerjohn, S., Sedwick, P., & Ackley, S. (2023). Sea ice formation, glacial melt and the solubility pump boundary conditions in the Ross Sea. *Journal of Geophysical Research: Oceans*, 128, e2022JC019322.

[4] Hamme, R. C., Emerson, S. R., Severinghaus, J. P., Long, M. C., & Yashayaev, I. (2017). Using noble gas measurements to derive air-sea process information and predict physical gas saturations. *Geophysical Research Letters*, 44, 9901–9909 pp.

[5] Jeansson, E., Tanhua, T., Olsen, A., Smethie, W. M., Rajasakaren, B., Ólafsdóttir, S. R., & Ólafsson, J. (2023). Decadal changes in ventilation and anthropogenic carbon in the Nordic Seas. *Journal of Geophysical Research: Oceans*, 128, e2022JC019318.

Imperial College London

Contact
Stanley Scott
stanley.scott20@imperial.ac.uk

Constraining Physical Gas Exchange Processes and Transient Tracer Saturations in the Arctic Ocean using Noble Gases

S. Scott[1, 2], Y. Arck[1], E. Engelhardt[1], L. Gerke[3], F. Freundt[1], C. Hubner[1], S. Negele[1], T. Tanhua[3], W. Aeschbach[1]

[1]University of Heidelberg, Institute of Environmental Physics, D-69120 Heidelberg, Germany; [2]Imperial College London, Department of Physics, London SW7 2AZ, United Kingdom; [3]GEOMAR Helmholtz Centre for Ocean Research Kiel, D-24148 Kiel, Germany

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

INSTITUTE OF ENVIRONMENTAL PHYSICS

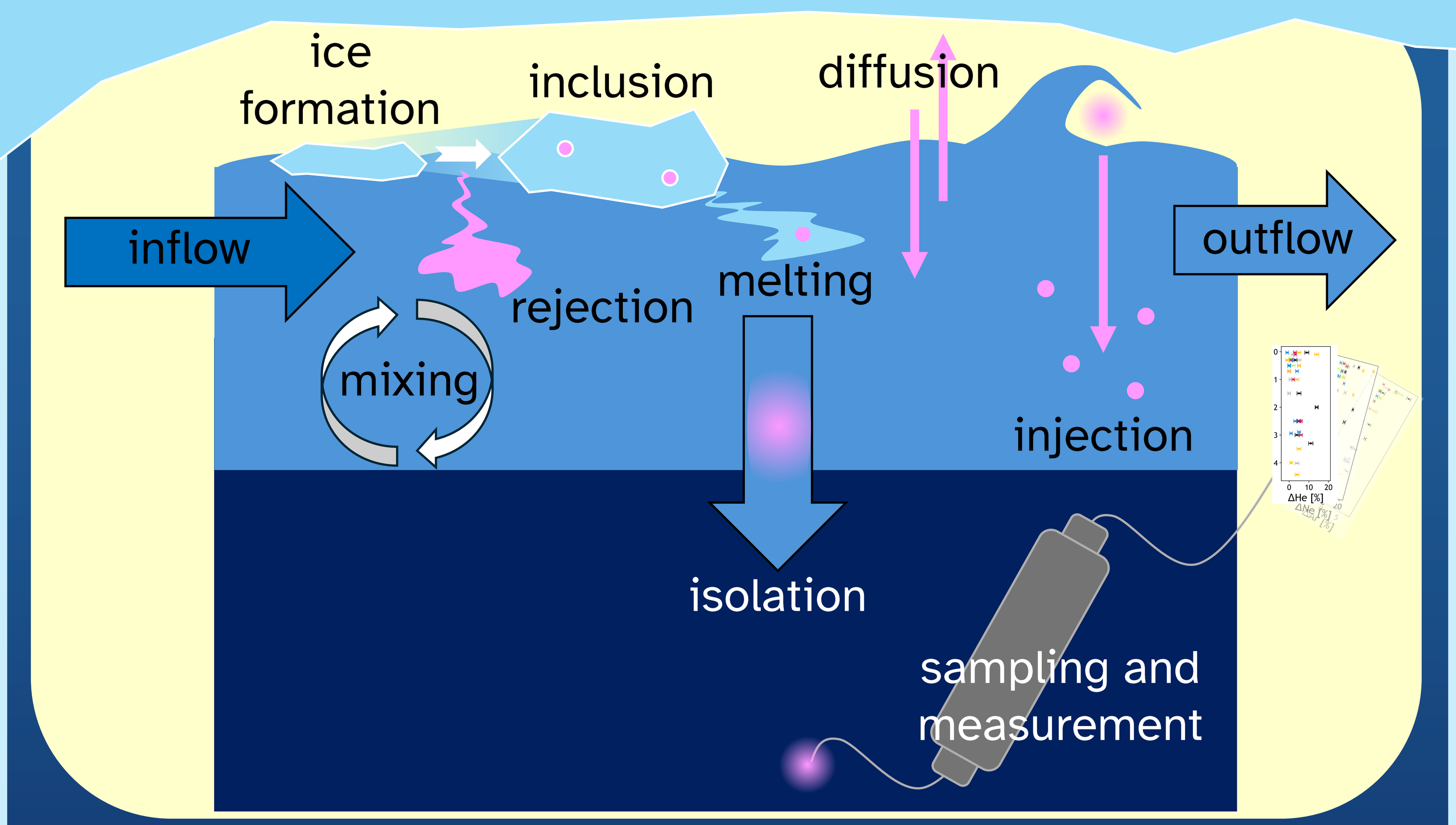
Background

- Project: Ventilation and Anthropogenic Carbon in the Arctic Ocean (VACAO), Synoptic Arctic Survey 2021 (SAS21) [1]
- Goals: understand timescales of ventilation and carbon uptake in the Arctic Ocean
- Physical processes at the surface control rates of gas uptake
- Noble gas concentration anomalies act as non-chemical tracers for physical gas exchange processes. [2]
- Formation/melting of sea ice, injection of air and rapid cooling can be modelled and constrained using noble gas data.
- Results are used to quantify the primary surface exchange processes and to correct age-tracer data which assumes diffusion as the only form of gas exchange

The noble gases as exchange process tracers

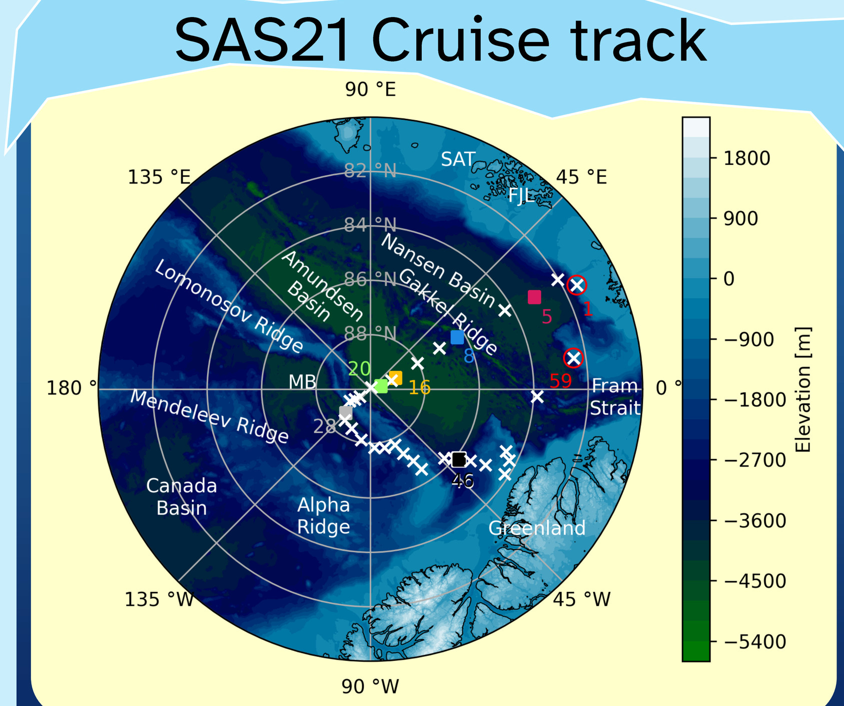
- Five stable noble gases: He, Ne, Ar, Kr, Xe
- (Bio-)Chemically inert and have constant atmospheric histories
- Practically no degradation in subducted waters: effectively conservative
- Concentrations only dependent on *physical* exchange parameters
- Atmospheric concentrations, solubilities, solubility-temperature gradients and behaviour in ice varies greatly from species to species of noble gas
- These properties make them excellent environmental tracers for surface gas exchange parameters
- Concentration/Anomaly profiles can be used with an appropriate model and fitting algorithm to parameterise surface gas exchange [2]

Physical gas exchange processes



- Both models we present here consider only the interaction between the atmosphere and elements in the Polar Mixed Layer (PML)
- PML is assumed well-mixed and coupled to the atmosphere
  - Diffusive exchange: acts to push gas concentrations toward equilibrium
  - Excess air injection: wave breaking forces bubbles into the water which release gases – diffusivities and abundances of gases control how much their concentrations are affected
  - Ice formation: all noble gases (except He) are squeezed out of the ice matrix upon freezing, causing fractionation [3]
  - Ice melting: gases trapped in ice are released into the PML
- Water below the PML is considered isolated and noble gases conserved

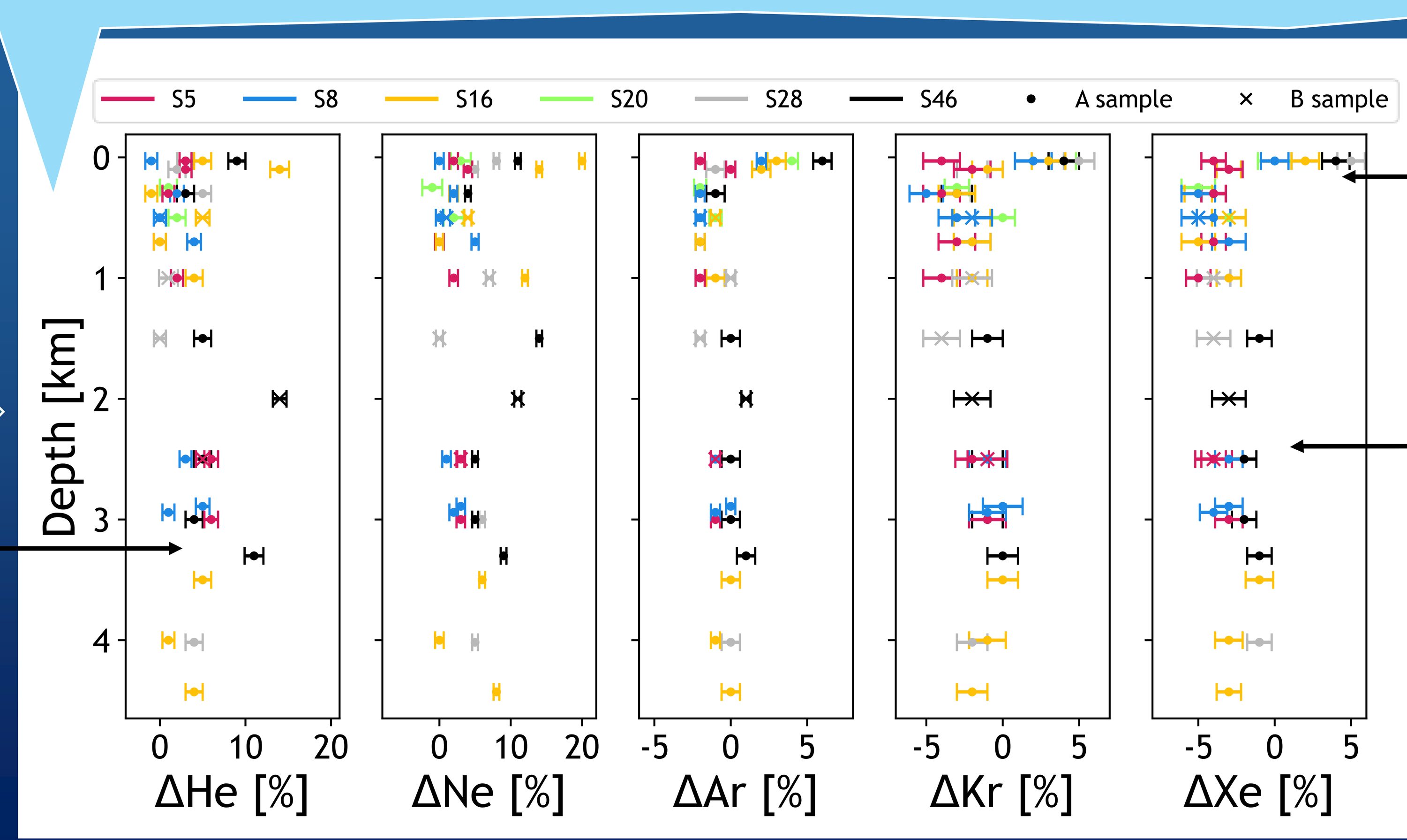
SAS21 Cruise track



Vertical gas concentration profiles taken at each station shown [1, 4]

NOBLE GAS LAB ANALYSIS

Noble gas anomaly profiles



Oversaturated light gases: bubble injection?

Surface oversaturation of all gases: ice formation?

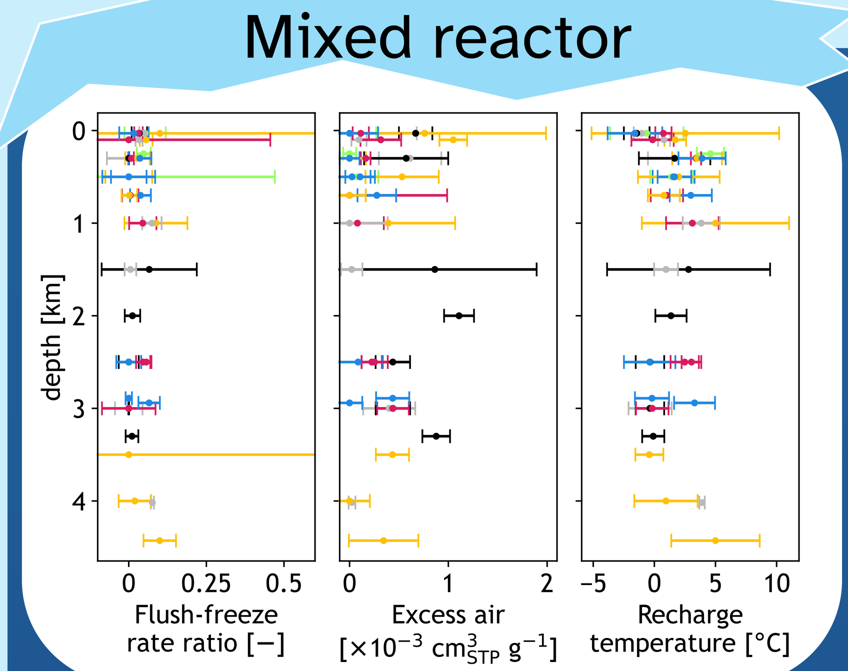
Undersaturated heavy gases: rapid cooling?

Gas anomaly

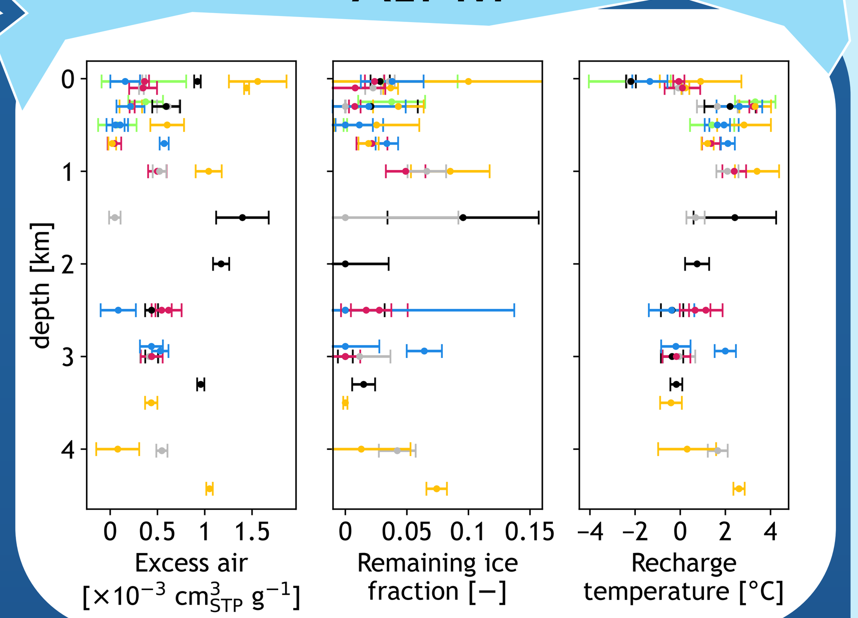
$$\Delta\mathrm{Gas} = \left(\frac{C^{\mathrm{meas}}_{\mathrm{Gas}}}{C^{\mathrm{eq}}_{\mathrm{Gas}}} - 1\right) \times 100\%$$

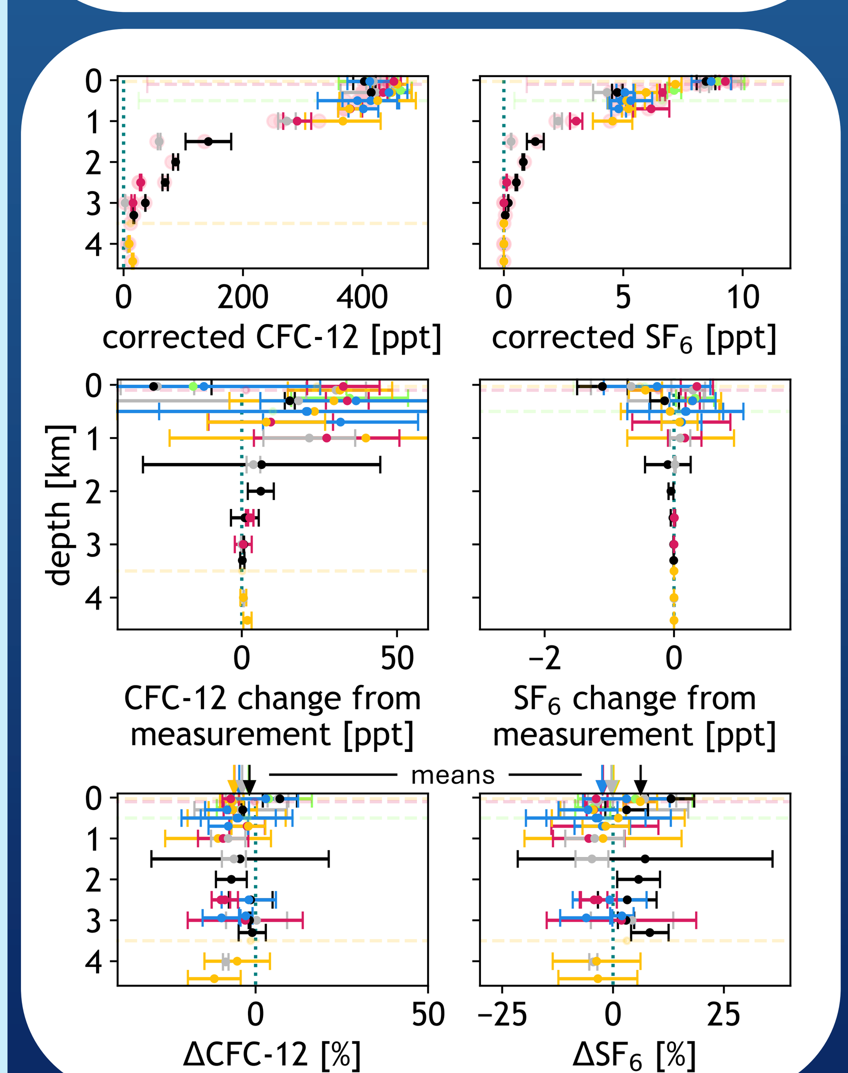
$\Delta\mathrm{Gas} = 0\% \Rightarrow$ equilibrium/saturation

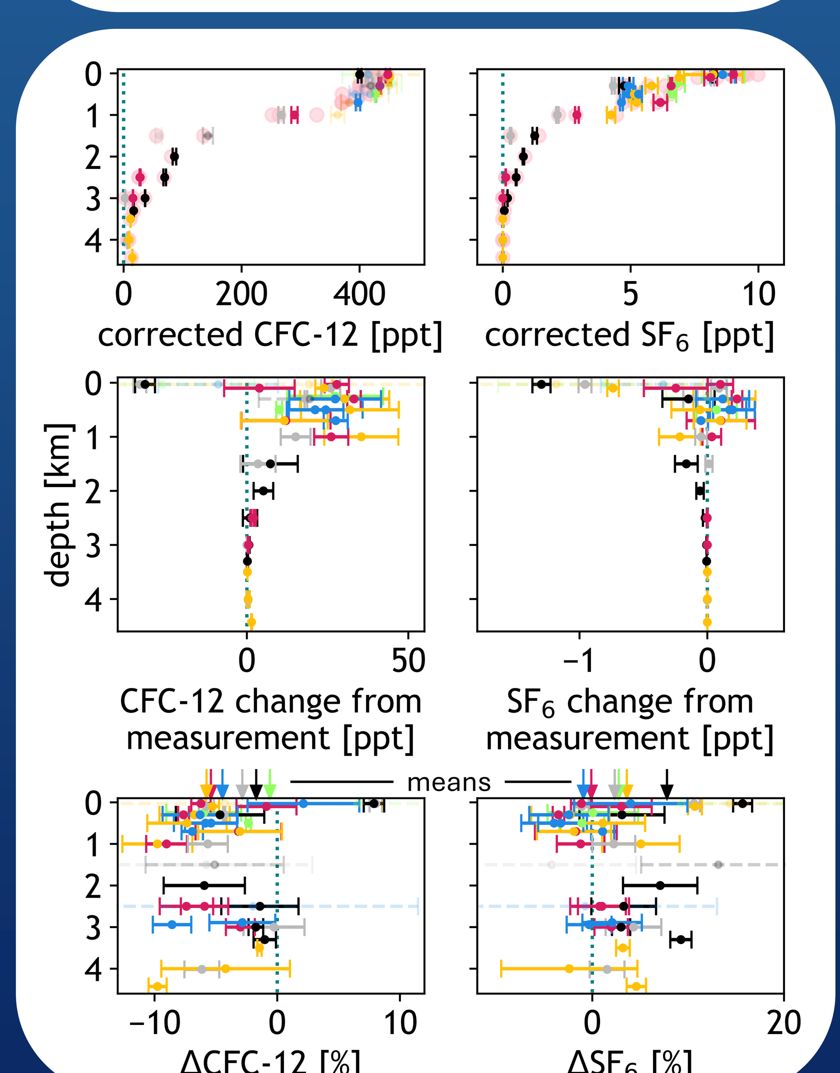
Mixed reactor



AIFM







- Useful water age-tracers like CFC-12 and SF_6 are also affected by physical gas exchange
- Modelled anomalies can be used to "correct" their measured concentrations: $C^{\mathrm{corr}} = C^{\mathrm{meas}} \div \left(1 + \Delta^{\mathrm{model}}\right)$ [6]
- CFC12 undersaturated in both models, SF6 differs between the two

Model details and fitting

- Model parameters are constrained in a least-squares sense [2] using Levenberg-Marquardt nonlinear minimisation of:

$$\chi^2 = \sum_{\substack{\mathrm{Gas}\,\in \\ \{\mathrm{He},\,\dots,\,\mathrm{Xe}\}}} \left(\frac{C^{\mathrm{meas}}_{\mathrm{Gas}} - C^{\mathrm{model}}_{\mathrm{Gas}}(\text{fitted parameters})}{\sigma_{C^{\mathrm{meas}}_{\mathrm{Gas}}}}\right)^2$$

- **Mixed reactor model:**

$$C^{\mathrm{meas}}_{\mathrm{Gas}} = (1 + (2 - \kappa_{\mathrm{Gas}}) \cdot R_{\mathrm{ff}}) \cdot C^{\mathrm{eq}}_{\mathrm{Gas}} + A \cdot z_{\mathrm{Gas}}$$

  - κ = ice fractionation coefficient, z = atmospheric abundance, A = excess air, R_{ff} = flush-freeze rate ratio
  - Steady-state mixed reactor where fluxes due to ice formation balance those due to flushing rate of PML
  - Excess air added *after* as transient term, melting ignored
- **Air injection, freezing and melt model (AIFM):**

$$C^{\mathrm{meas}}_{\mathrm{Gas}} = \left(C^{\mathrm{eq}}_{\mathrm{Gas}} + A \cdot z_{\mathrm{Gas}}\right) \cdot \left(1 + \left(1 - \kappa^2_{\mathrm{Gas}}\right) \cdot f_{\mathrm{ri}}\right)$$

  - f_{ri} = remaining proportion of ice as a fraction of PML after melting
  - Excess air injected *before* freezing occurs
  - Freezing modelled as a single Rayleigh-fractionation process [5], melting as a single rapid event

Questions? Ask me here or email me!

Conclusions and outlook

- Decision still must be made as to if a model should over- or under-saturate SF_6
- Excess air should be divided into diffusive and non-diffusive regimes
- Glacial meltwater contribution could be modelled with a water-fraction model [7]
- Corrected profiles should be smoothed and used with transit time distributions of SF_6/CFC-12 tracer pairs to better constrain timescales of Arctic water circulation
- Application to the novel tracer ^{39}Ar is also a possibility

References and acknowledgements

[1] Snoeijs-Leijonmalm, P., *Expedition Report SWEDARCTIC Synoptic Arctic Survey 2021 with icebreaker Oden*. Luleå: Swedish Polar Research Secretariat, 2022.

[2] Jung, M. and Aeschbach, W., "A new software tool for the analysis of noble gas data sets from (ground)water," *Environmental Modelling & Software*, vol. 103, pp. 120–130, 2018.

[3] Top, Z., Martin, S. and Becker, P., "A laboratory study of dissolved noble gas anomaly due to ice formation," *Geophysical Research Letters*, vol. 15, no. 8, pp. 796–799, 1988.

[4] GEBCO Bathymetric Compilation Group, "The GEBCO_2022 Grid - a continuous terrain model of the global oceans and land," 2022.

[5] Kluge, T., Marx, T., Aeschbach, W., Spötl, C. and Richter, D. K., "Noble gas concentrations in fluid inclusions as tracer for the origin of coarse-crystalline cryogenic cave carbonates," Chem. Geol., vol. 368, pp. 54–62, 2014.

[6] Hamme, R. C., Emerson, S. R., Severinghaus, J. P., Long, M. C. and Yashayaev, I., "Using noble gas measurements to derive air-sea process information and predict physical gas saturations," *Geophys. Res. Lett.*, vol. 44, no. 19, pp. 9901–9909, 2017.

[7] Loose, B., Jenkins, W. J., Moriarty, R., Brown, P., Jullion, L., Garabato, A. C. N., Valdes, S. T., Hoppema, M., Ballentine, C. J. and Meredith, M. P., "Estimating the recharge properties of the deep ocean using noble gases and helium isotopes," *Journal of Geophysical Research: Oceans*, vol. 121, pp. 5959–5979, 2016.

This research was carried out with the generous support of the German Research Foundation (DFG) – project number 456675218