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

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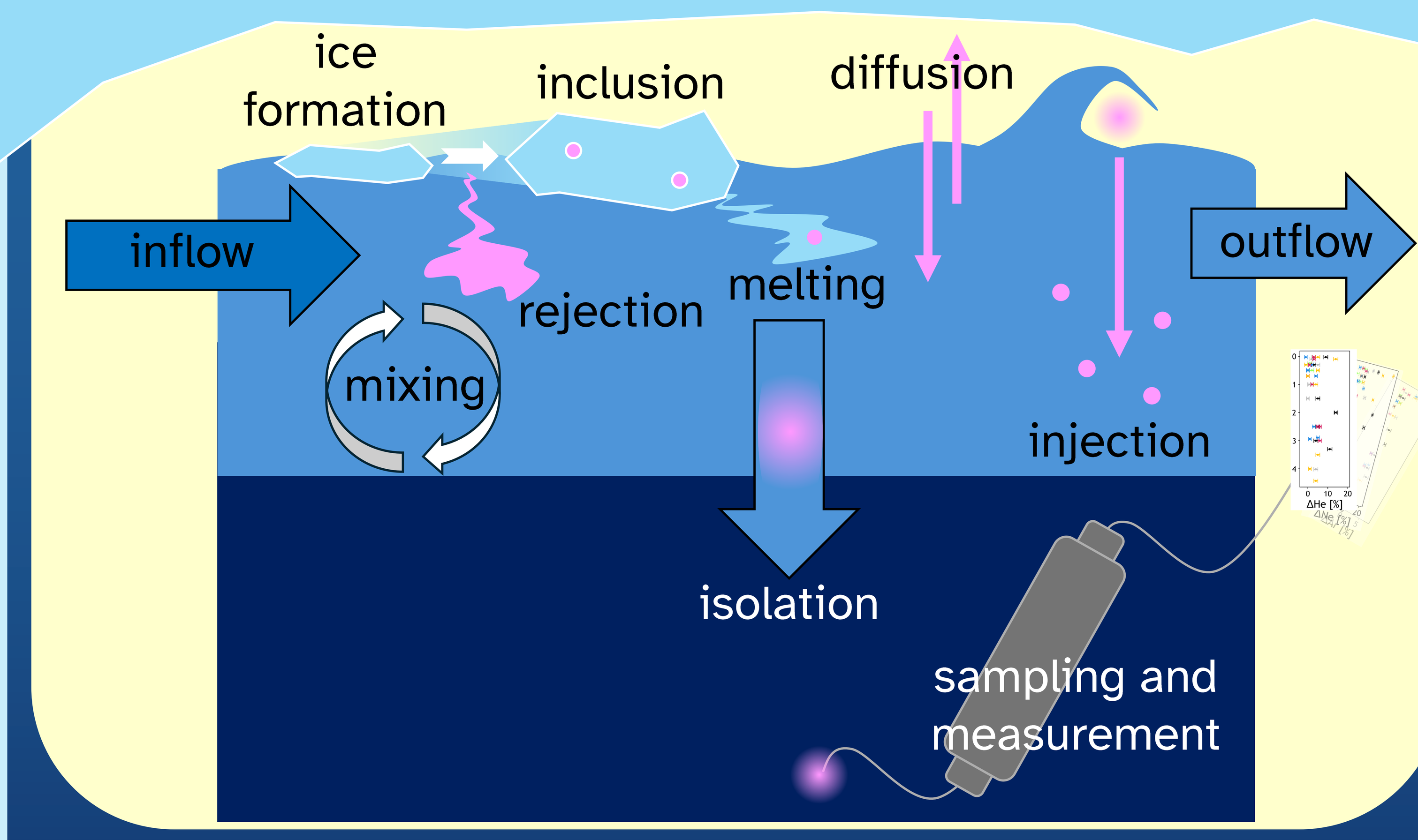
Background

- 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

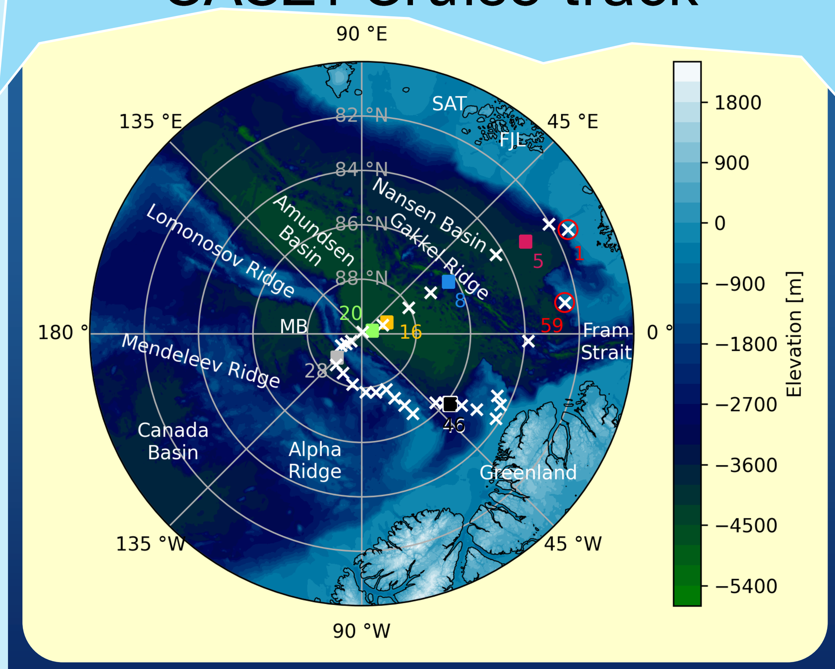
- Five stable noble gases: He, Ne, Ar, Kr, Xe
- (Bio-)Chemically inert and have constant atmospheric histories
- Practically no degradation in subducted waters: effectively conservative
- Concentrations only dependent on *physical* exchange parameters
- Atmospheric concentrations, solubilities, solubility-temperature 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

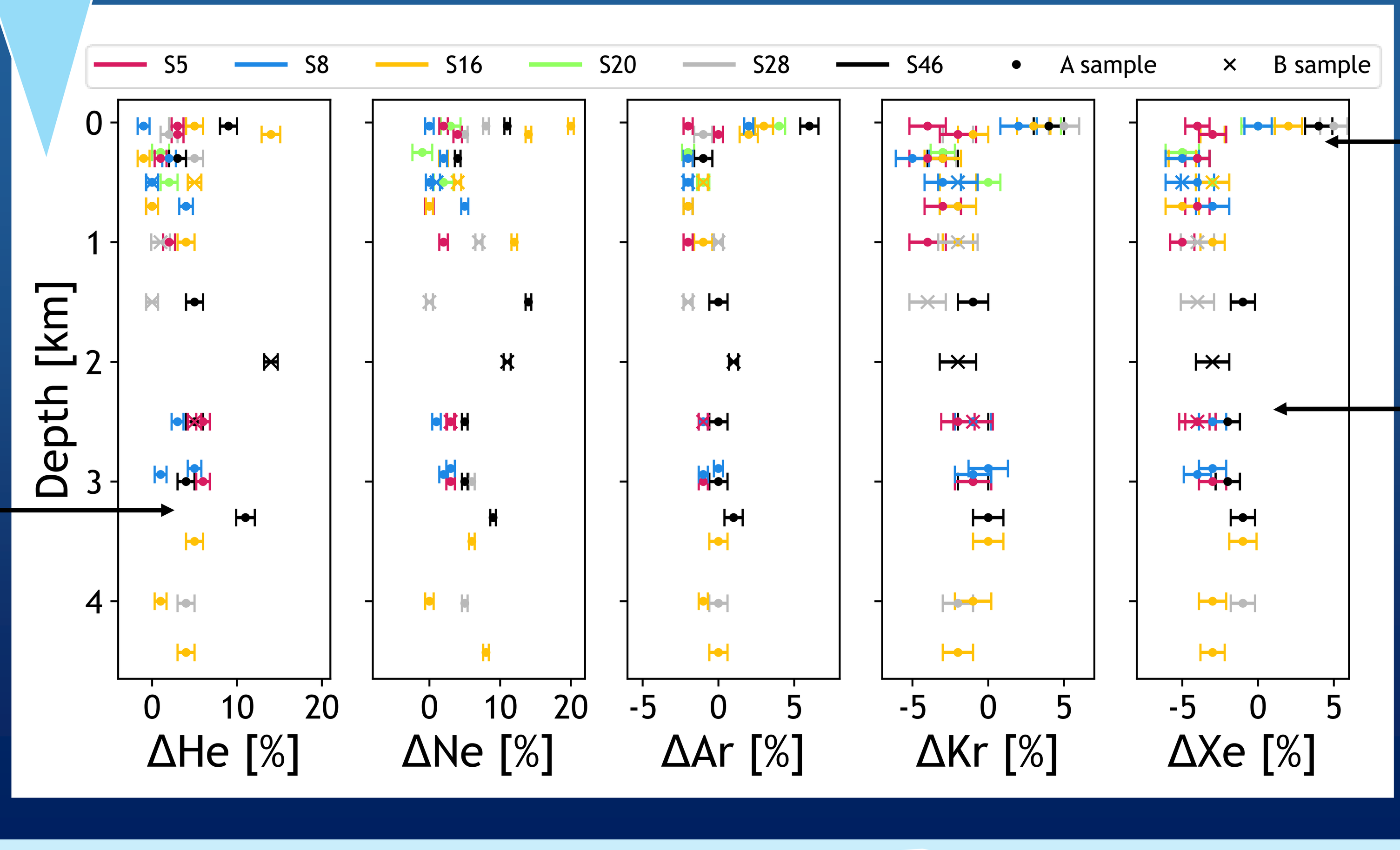
SAS21 Cruise track



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

NOBLE GAS LAB ANALYSIS

Noble gas anomaly profiles



Surface oversaturation of all gases: ice formation?

Oversaturated light gases: bubble injection?

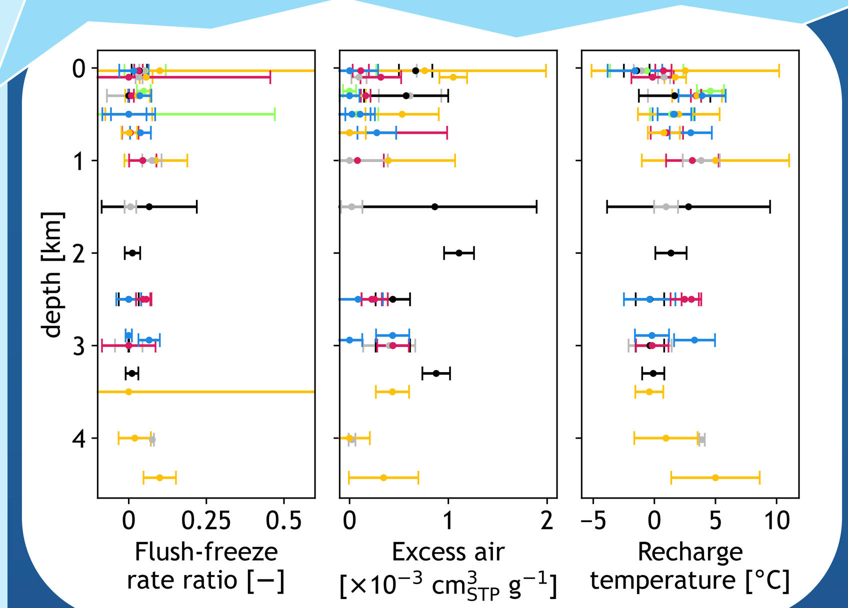
Undersaturated heavy gases: rapid cooling?

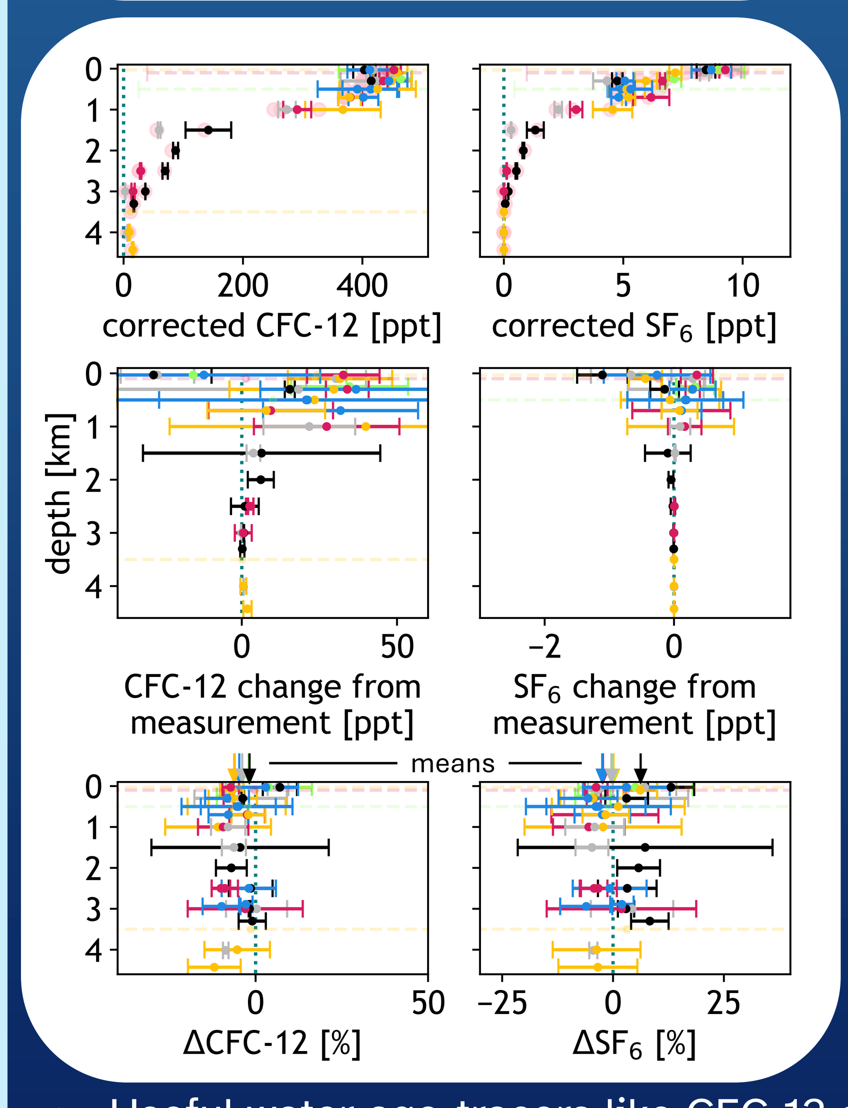
Gas anomaly

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

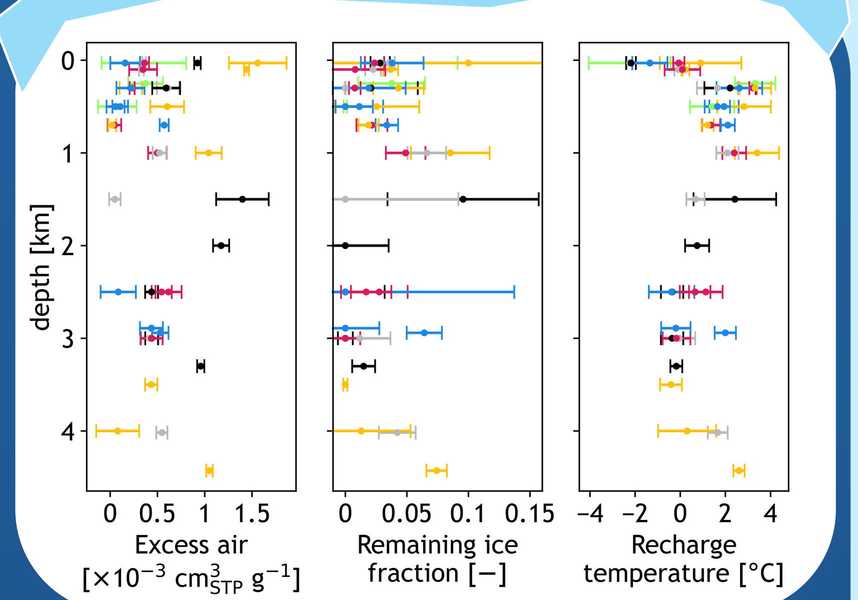
$\Delta\text{Gas} = 0\% \Rightarrow$ equilibrium/saturation

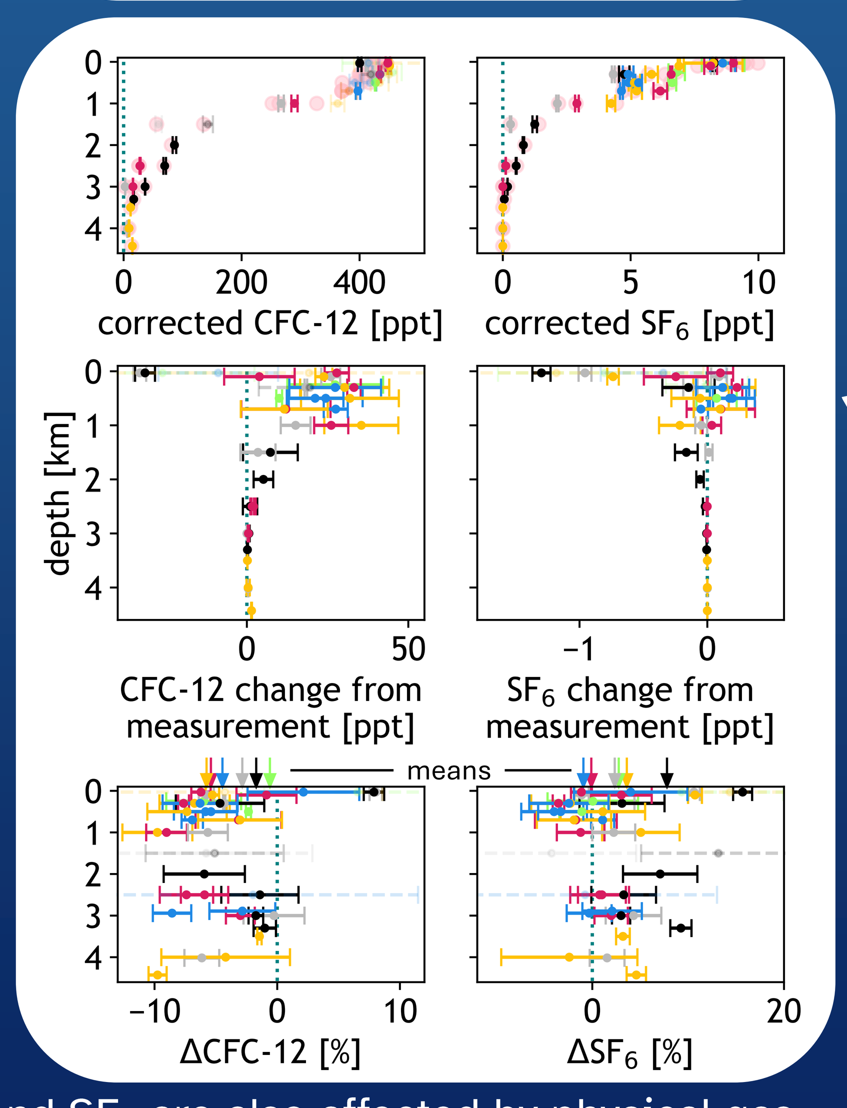
Mixed reactor





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: $C^{\text{corr}} = C^{\text{meas}} \div (1 + \Delta^{\text{model}})$ [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:

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

- **Mixed reactor model:**

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

  - 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):**

$$C_{\text{Gas}}^{\text{meas}} = \left(C_{\text{Gas}}^{\text{eq}} + A \cdot z_{\text{Gas}}\right) \cdot \left(1 + \left(1 - \kappa_{\text{Gas}}^2\right) \cdot f_{\text{ri}}\right)$$

  - 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

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