# Modelling of the deep future with CLIMBER-X
## Investigating uncertainties on very-long timescales

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BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

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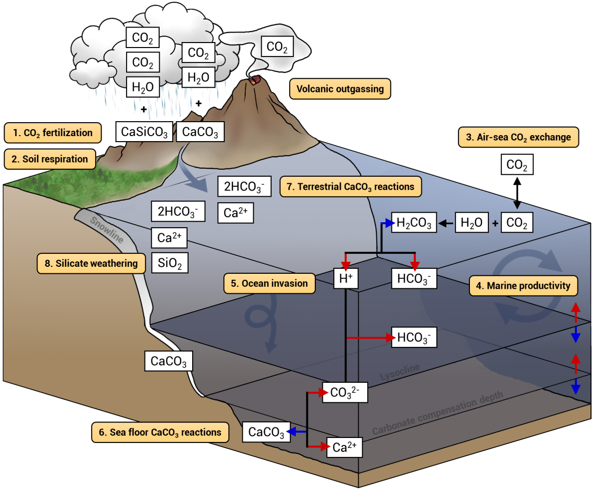


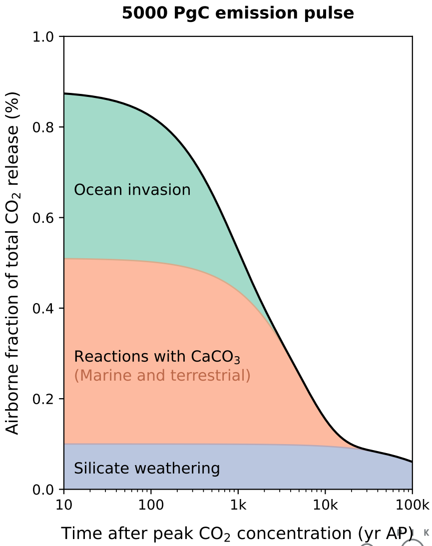
# Why study the deep future and general scope of this talk

- Climate change studies are often limited to ‘short’ timescales in consideration for governance and policy, but there is a growing societal need and no shortage of scientific inquiries for far future studies
- Most notably concerns site selection and post-closure safety assessments for nuclear waste disposal, as a number of environmental factors can compromise long-term safety
- Deep-future simulations have many uncertainties, but these can be partially addressed and explored
- This talk will focus on 2 investigations and their uncertainties, from long to very long timescales

# Part 1:
# Uncertainties beyond the first millennium and long-term uptake of anthropogenic $CO_2$

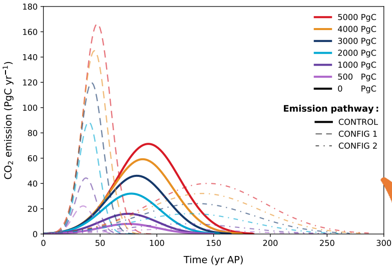
# Motivation

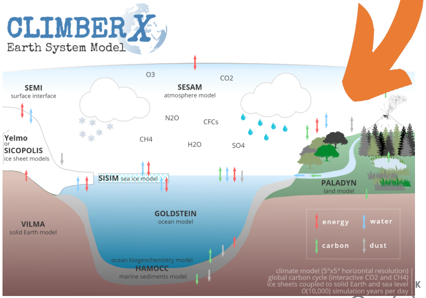
- Even without considering unpredictability of emissions pathway and magnitude, predictions for deep future $CO_2$ concentration show considerable diversity
- Largely due to poor constraints on the long-term carbon cycle
- Our study generally provides a new estimate on the atmospheric lifetime of $CO_2$ and attempts to quantify the role of other factors
- **Uncertainties:**
  - weathering feedback
  - climate sensitivity,
  - land carbon, methane cycle
  - climate-carbon interactions



# Experimental set-up

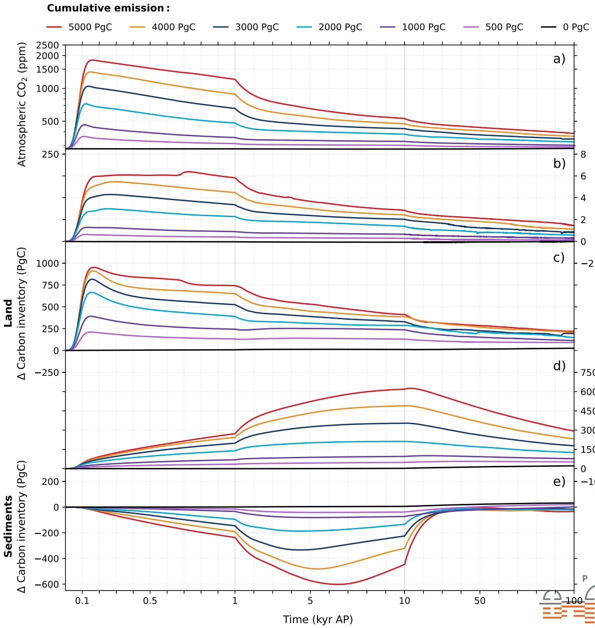
- Experiments start from a pre-industrial equilibrium state and run for 100,000 years
- Simulations forced by the cumulative emission scenarios of 0 PgC to 5000 PgC
- Interactive carbon cycle (interactive $CO_2$)
- All ice sheets prescribed by their present-day state (no interactive ice sheet model)
- Baseline experiment:
  - **CONTROL** emissions pathway
  - Present-day orbital configuration and methane
  - Climate relaxes back to pre-industrial conditions



# Climate/carbon cycle response

- Various processes function to remove anthropogenic $CO_2$ emissions
- **Land:**
  - Uptake from enhanced productivity
  - Partially or totally offset by soil respiration
- **Ocean/Sediments:**
  - Air-sea $CO_2$ exchange, dissolution $\sim O(10^{0-1})$
  - Ocean acidification, marine productivity
  - Ocean invasion, mixing $\sim O(10^2)$
  - Sea floor carbonate reactions, lysocline response $\sim O(10^3)$
- **Weathering:**
  - Carbonate weathering $\sim O(10^{3-4})$
  - Silicate weathering $\sim O(10^{5-6})$



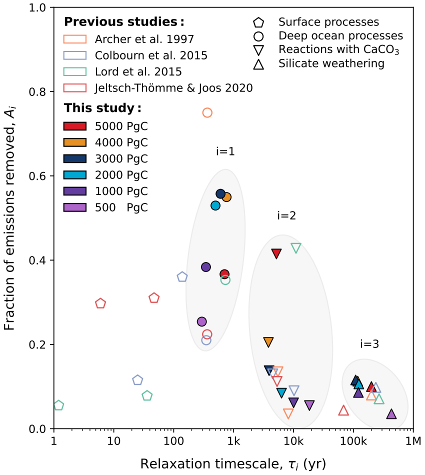
# Multi-exponential timescale analysis

- By fitting our $CO_2$ concentrations to the following function using a least-squares fit

$$C_{atm}(t) = 280 + C_{max} \sum_{i=1}^{n} A_i \cdot \exp\left(-\frac{t}{\tau_i}\right)$$

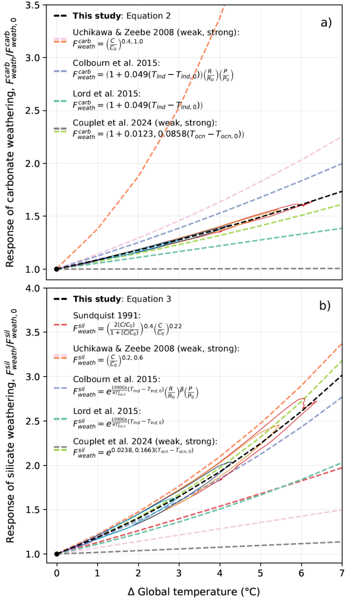
we find mean relaxation timescales of approximately 540, 8000, and 184,000 years

- Magnitude and behaviour of ocean invasion and $CaCO_3$ reactions with increasing emissions match literature
- Silicate weathering has a shorter timescale than in literature and exhibits nonlinear behaviour



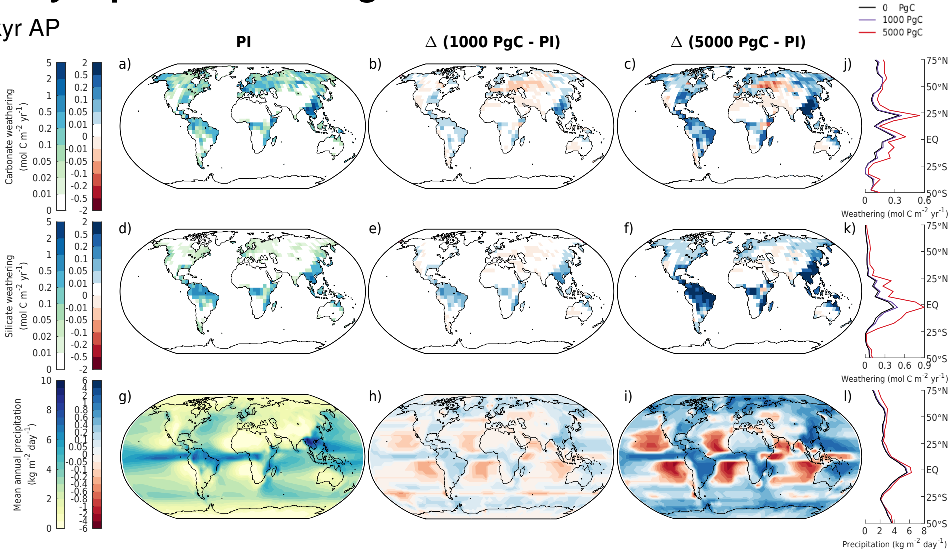
# Response of weathering feedbacks

- Two types of terrestrial weathering
- Silicate weathering is an important negative feedback which determines the timescale of the long-term response to a perturbation in the carbon cycle (i.e., $CO_2$ emissions)
- Present-day weathering rates are not accurately known; temperature dependence is poorly constrained
- We use the most advanced weathering model available as it is based on the most high-resolution lithological map (GLiM, Hartmann et al. 2009)
- Response of silicate weathering to temperature in CLIMBER-X stronger than in some previous studies



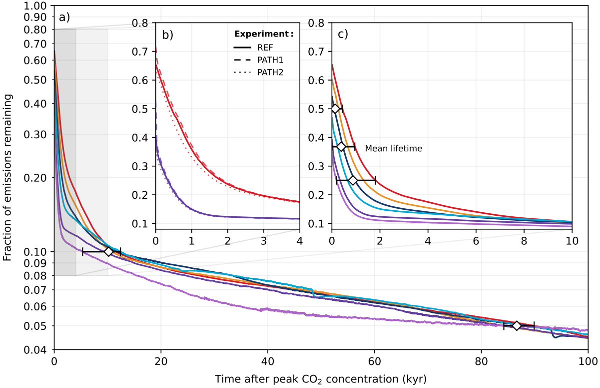
# Spatially explicit weathering

At 1 kyr AP



# Atmospheric lifetime of anthropogenic $CO_2$

- Using the IRF, we determine a mean lifetime of 900 years across the different emission scenarios
- 10% of emissions persist for longer than 10 kyr, while 5% longer than 85 kyr



# Part 2:

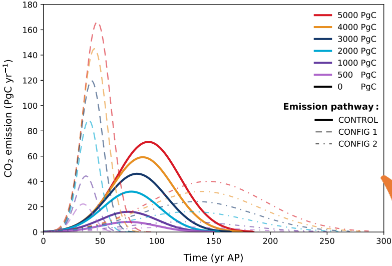
# Timing of the next glacial cycle

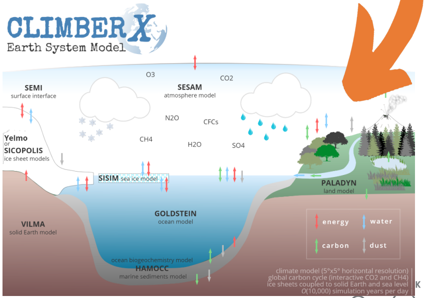
# The next glacial cycle

- Orbital parameters (therefore solar insolation) is known for the next ∼20 Myr
- Fundamental relationship between maximum summer insolation at 65°N and $CO_2$ concentration which can diagnose glacial inception

$$smx65_{cr} = -75 \log\left(\frac{CO_2}{280}\right) + 465$$

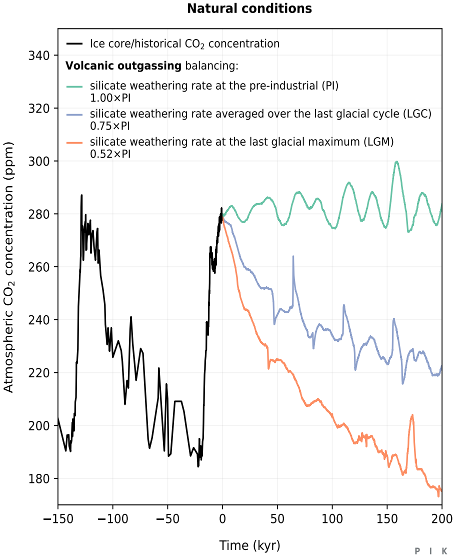
- Run similar experiments as before, but now with:
  - orbital parameters
  - different volcanic outgassings
  - without/with interactive ice sheets
- **Uncertainties:**
  - climate-carbon-ice sheet interactions



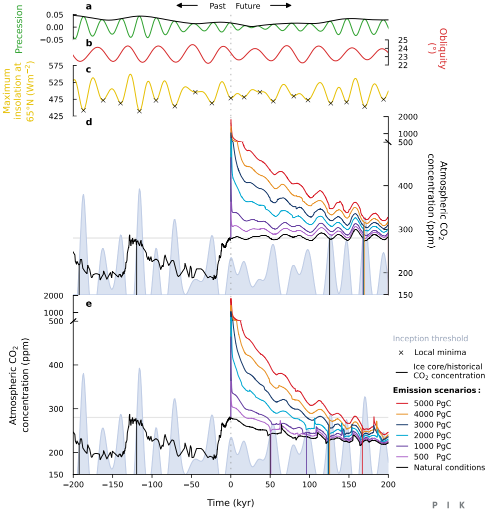
# Effect of the initial carbon state

- Volcanic outgassing is a tuneable parameter
- For initial conditions in the model spin-up, we need an assumption about the relationship between weathering rate and volcanic outgassing
- Balancing outgassing with LGC weathering rate leads to a steady decrease in $CO_2$ over the next 100 kyr
- Balacing outgassing with minimum weathering rate (LGM) leads to more than a 80 ppm difference in $CO_2$ over 100 kyr
- Important with interactive ice sheets as it will determine the timing of the next glacial cycle



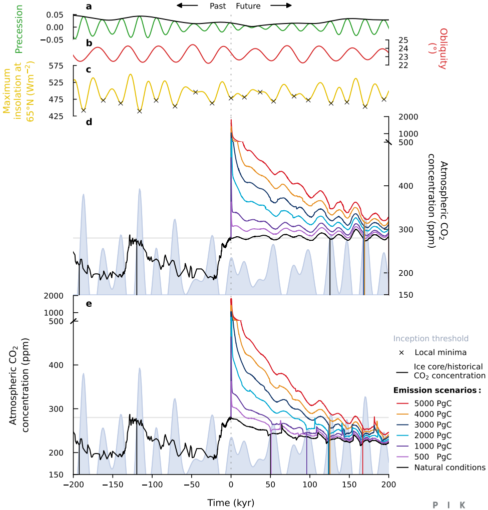
# Natural length of the current interglacial

- An imminent glacial inception could only occur at the next local minima in insolation (∼500 yr AP) for $CO_2$ values lower than approximately 225 ppm
- A decrease of over 50 ppm would have to have occurred before 2500 CE for a Holocene glacial inception
- The estimated timing of the next glacial cycle under natural conditions could change from ∼125 kyr AP to ∼50 kyr AP depending on volcanic outgassing
- **This latter value more accurately matches previous projections**, meaning that an LGC volcanic outgassing is appropriate



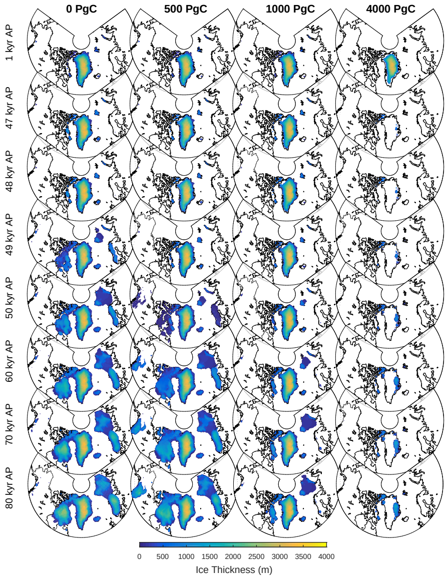
# Global warming and the next glacial cycle

- Glacial inception in the experiment with LGC outgassing would occur around ∼50 kyr AP under present-day anthropogenic emissions (∼500 PgC)
- Glacial inception under almost all emission scenarios occurs before 200 kyr irregardless of the chosen volcanic outgassing
- **These results contest previous studies**
- The reason for this is related to the strong silicate weathering feedback, significantly reducing the atmospheric lifetime of $CO_2$



# Confirmation of our diagnosis

- **We additionally run a set of experiments with the LGC volcanic outgassing which have the ice sheet model enabled for ∼100 kyr**; this would confirm our diagnosis and show ice sheet extent at the next glaciation
- Glacial inception, where ice volume grows larger than ∼15 m sle, is only seen for the 0 and 500 PgC scenario (as expected)
- For emission scenarios over 1000 PgC, a rapid expansion of the ice sheet in the Canadian Arctic is not seen, and glacial inception is evaded



# Conclusion

# Summary & outlook

- Deep-future simulations have many uncertainties, but these can be partially addressed and explored
- CLIMBER-X is a powerful Earth system model which can be used to perform investigations that cannot be easily done with other state-of-the-art Earth system models, like
  1. Life time of anthropogenic $CO_2$ and sensitivity of the long-term carbon cycle response
  2. Future glacial cycles and the possible ice sheet extent and volume
  3. Speculative studies such as the plausibility of a hothouse Earth, and multi-millennial "worst-case" scenarios (not shown today)

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