Modelling of long-term future climate change with application to the problem of permanent nuclear waste storage in Germany

Christine Kaufhold, Dr. Andrey Ganopolski

Earth System Analysis Department
Potsdam Institute for Climate Impact Research

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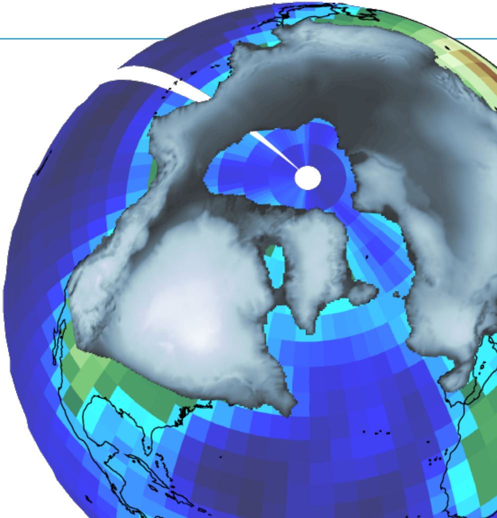
URS 2023 KLAUSURTAGUNG

Potsdam Institute for Climate Impact Research
PIK

GRS BGE Universität Potsdam



Our past climate...

- Climate has been changing for last Myr via Milankovitch cycles
- Connection between maximum summer insolation at 65°N and CO_2 for glacial inception

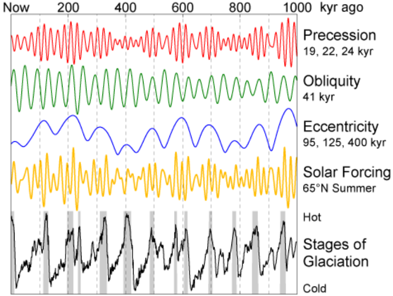


Figure 1: Data from Quinn et al. 1991/Liseki & Raymo 2005. Generated by Rohde 2006.

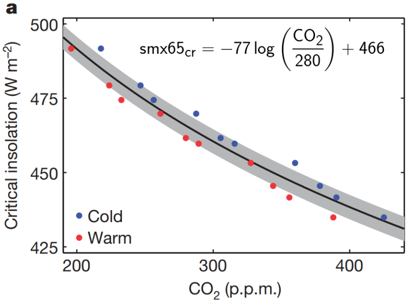


Figure 2: Critical CO2-insolation relation for glacial inception. From Ganopolski 2016, *Nature*.

Our future climate...

- Available fossil fuel carbon reserves have the capacity to impact the climate hundreds of thousands of years into the future
- Large uncertainties exist in long-term future climate evolution since we cannot accurately predict anthropogenic CO_2 emissions even during this century
  - RCP-SSP scenarios with extensions
- Anthropogenic CO_2 emissions can change future glacial cycles

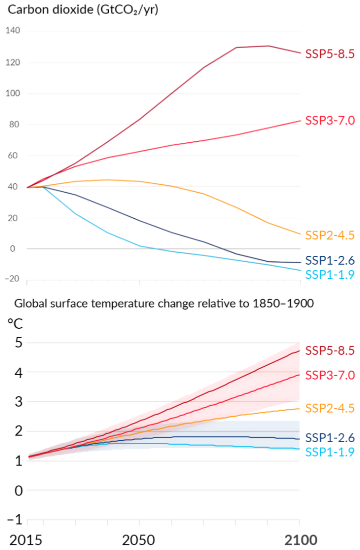


Figure 3: Taken from IPCC's AR6.

How does this affect the management of nuclear waste?

- Previous glaciation events reached Germany
  - many short-term and long-term consequences
  - precipitation, temperature, subterranean stress, surface denudation, and permafrost/taliks
- High emissions scenarios present sea level rise
- Why does this matter for repository health?
  - some radioisotopes have long half lives
  - waste must be stored for a period of 1 million years (EndSiAnfV § 3)
  - **we must consider future climate for deep geological repositories**

The REDUKLIM project

Research Field 4:
Preliminary safety investigation

Research Cluster:
Uncertainties and Robustness with regard to the Safety of a repository for high-level radioactive waste (URS)

Topic 4:
Physics-based scenario modelling and impact models

Project:
Reduction of scenario uncertainties through Climate models (REDUKLIM)

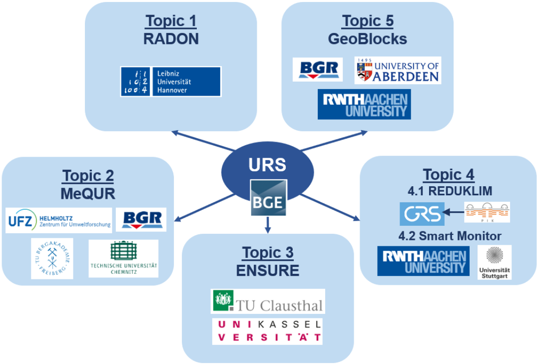


Figure 4: Structure of the URS cluster from BGE

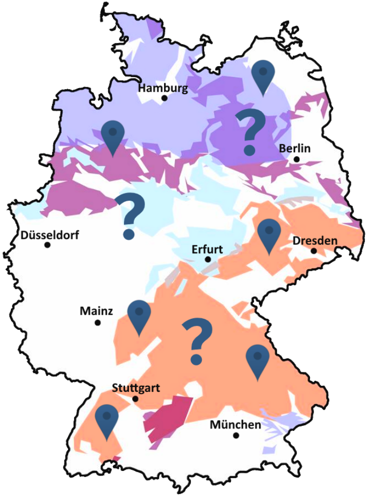
The goals of REDUKLIM

The task:

- assess future climate for next 100 kyr and 1 Myr
- link climate development to groundwater processes (GRS)
- identify and quantify uncertainties via our projections
- **provide additional confidence in site selection**

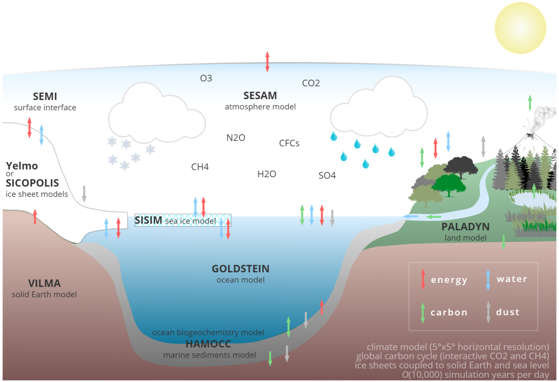
Our tools at hand:

1. distributed density-driven flow model d³f++ (GRS)
2. Earth system model of intermediate complexity CLIMBER-X
3. reduced complexity model by Talento & Ganopolski 2021



CLIMBER-X
Earth System Model

- Fully coupled EMIC
- Climate components have comparable complexity and grid ($5^\circ \times 5^\circ$)
- More options for the ice sheet model
  - e.g., variable domain
- Best suited for long timescales
  - does not resolve weather, inter-annual variability, diurnal cycle, etc.
  - we will use until $\sim$100 kyr AP
- Model validation in Willeit et al. 2022



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A reduced complexity model

3 coupled, nonlinear equations concerning mechanisms relevant for the climate–icesheet–carbon cycle system on very long timescales (> 10 kyr)

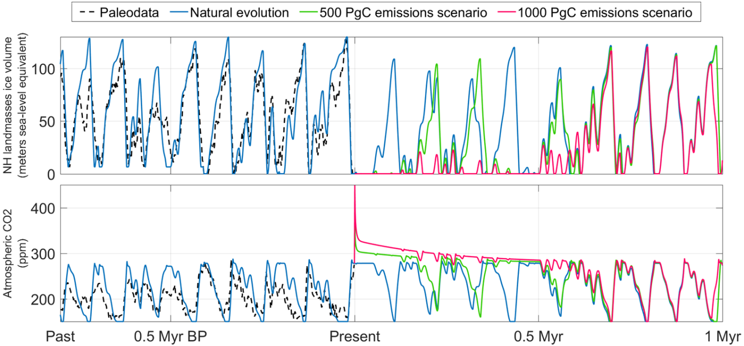
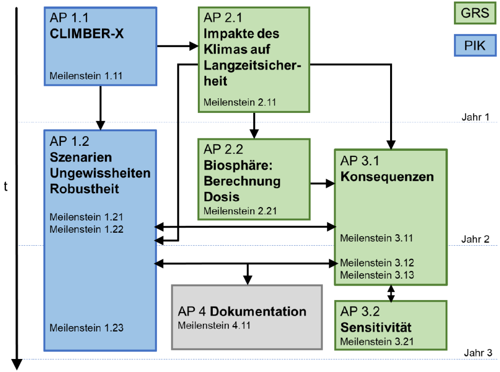


Figure 5: Talento & Ganopolski 2021

Package milestone #1

Working Package 1.1:
Construction and evaluation of climate models

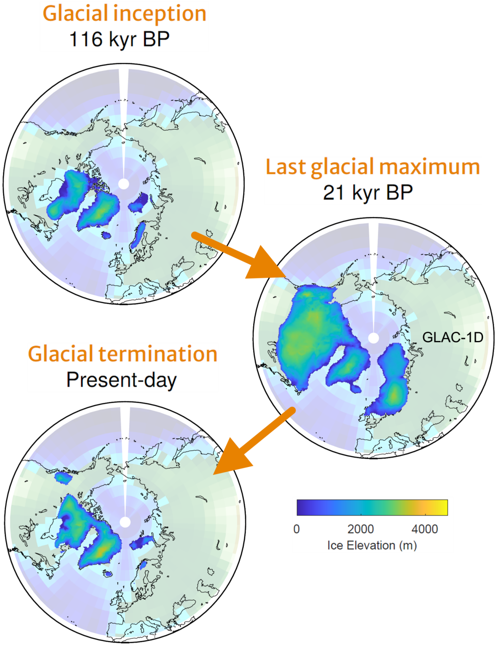
1. simulate the last glacial cycle
2. simulate the next 100,000 yrs for different scenarios
3. for 100,000 yrs and beyond, the reduced complexity model is used
4. scenarios developed for the next million years in northern Germany/Alpine region



Milestone 1.11 (month 12):
Evaluation of future climate scenarios for Germany based on results of CLIMBER-X

Paper 1: Glacial cycles

- **To simulate future glacial cycles, we must be able to simulate the last one!**
  - glacial inception, LGM, and deglaciation
- Major objective as model performance can be tested against paleodata
  - sediment core, ice core, planktonic data
  - reconstructions (GLAC-1D, ICE-6G_C)
  - sea level reconstructions
  - PMIP4 model ensemble results
- Currently status:
  - model tuning
  - identifying model biases
  - drafting paper (e.g., introduction, methods)

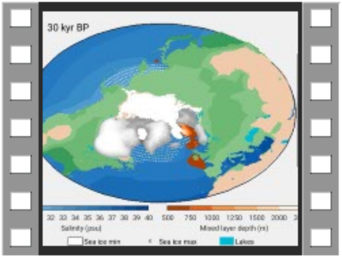


Paper 1: Transient simulation

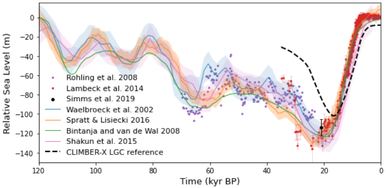
"a serious impediment... is that no modern model of the coupled climate system has ever been shown to naturally produce such oscillatory behavior under glacial climate conditions"
- Peltier 2014, Geophysical Research Letters

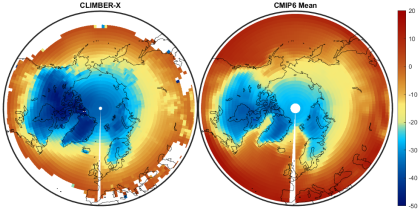
"this deficiency is related to both the computational expense which prevents models from being run for the longer time periods..."
- Malmierca-Vallet 2022, EGUsphere

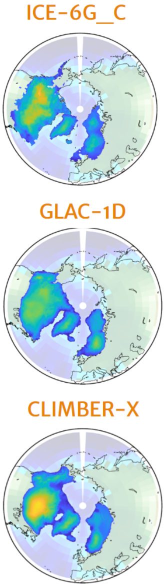
"a full transient glacial cycle is currently computationally unfeasible as it requires a too-large amount of computation time"
- Scherrenberg 2023, Climate of the Past

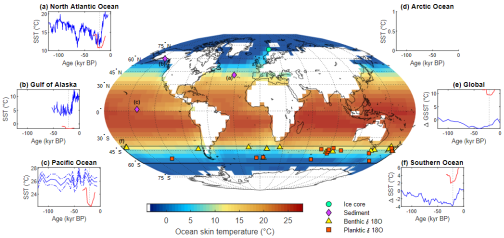


Paper 1: Preliminary results









Transient simulations and model-data comparison of the last glacial cycle using a coupled climate-ice sheet model

Christine Kaufhold[1,2], Matteo Willeit[1], and Andrey Ganopolski[1]
[1]Earth System Analysis, Potsdam Institute for Climate Impact Research, Potsdam, Germany
[2]Institute of Physics and Astronomy, University of Potsdam, Potsdam, Germany
Correspondence: Christine Kaufhold (kaufhold@pik-potsdam.de)

Abstract. TEXT

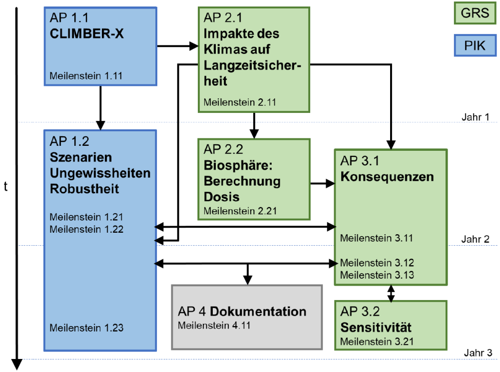
1 Introduction

The last few million years in Earth's history saw generated a large variability in our climate (Lisiecki and Raymo, 2005). As a result, there are still many unknowns as global proxy data on seasonal to millennial timescales from sources ranging from ice cores to marine sediments has provided poor constraints on paleoclimatic conditions. Yet one such exception is the last glacial maximum (LGM) of the Pleistocene epoch, which is generally suggested to have occurred sometime between 24.5 to 17 kyr BP (Clark et al., 2009). Ice sheets at this time are generally well constrained by present-day observations in addition to terrestrial (tree rings, sediments), ice (e.g., stacked $\delta^{18}O$ data in cores) and marine indicators (e.g., lake sediments, ice-rafted debris). LGM can be distinctly recognized in paleoclimate records by a large volume of Northern Hemisphere (NH) ice sheets and correspondingly low global eustatic sea level (Fairbanks, 1989; Yokoyama et al., 2000; Waelbroeck et al., 2002; Peltier

Package milestone #2

Working Package 1.2:
Scenarios, uncertainties, robustness

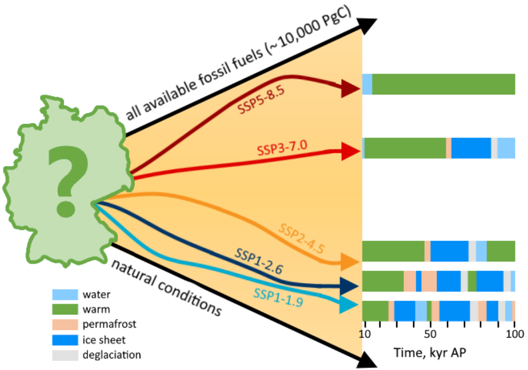
1. examine uncertainty/consequences of a wide range of cumulative CO_2 scenarios
2. examine how glacial inception depends on parameters of the carbon component
3. explore uncertainties in climate sensitivity and ice sheet parameterization



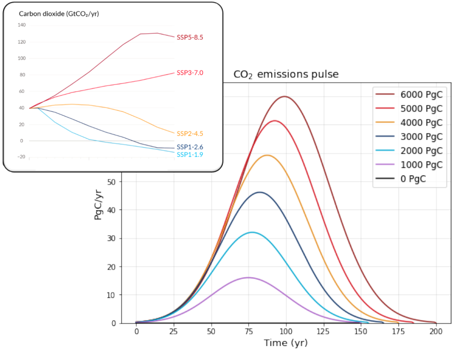
Milestone 1.21 (month 24):
Assessment of the robustness and uncertainties of future climate scenarios for Germany

Paper 2: Future scenarios

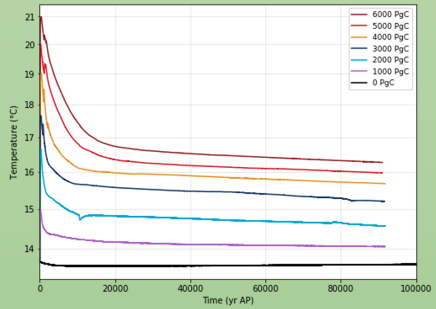
- Climate scenarios offer a spectrum of possible model outcomes
- Simulate long-term scenarios for a broad range of cumulative CO_2 emissions
- **How do cumulative CO_2 emissions affect timing of the onset of next glaciation?**
- Prescribe CO2:
    - interactive open carbon cycle
    - reduced complexity model
    - Lord et al. 2016
- range of possible climates over Europe (temperature, precipitation, sea level, etc.)

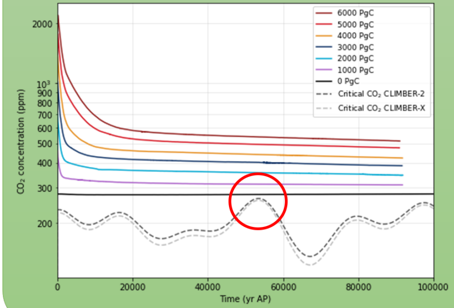


Paper 2: Preliminary results



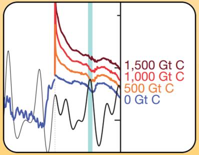
CLIMBER-X
Earth System Model





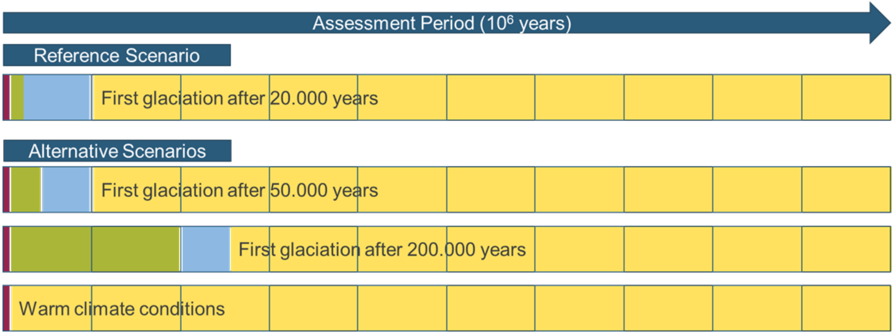
Ganopolski 2016
Critical CO_2 CLIMBER-2:

$$\mathrm{smx65_{cr}} = -77 \log\left(\frac{CO_2}{280}\right) + 466$$



Climate development benchmark

- Successful climate workshop held by BGE in Feburary
- Common scenario benchmark was developed for our climate reports



Strategy & outlook

- Learnt CLIMBER-X over the course of the last months and made good progress
- Clear aim in terms of what must be done & the general timeline
- Few ideas to navigate bumps and prepare for success
- **We are open to collaborations and can provide climate variables to those interested**

Funded by:

GRS BGE BUNDESGESELLSCHAFT FÜR ENDLAGERUNG

Project Information:
Ungewissheiten und Robustheit mit Blick auf die Sicherheit eines Endlagers für hochradioaktive Abfälle (bge.de)

Contact:
kaufhold@pik-potsdam.de