The physics behind Earth's latest ice ages

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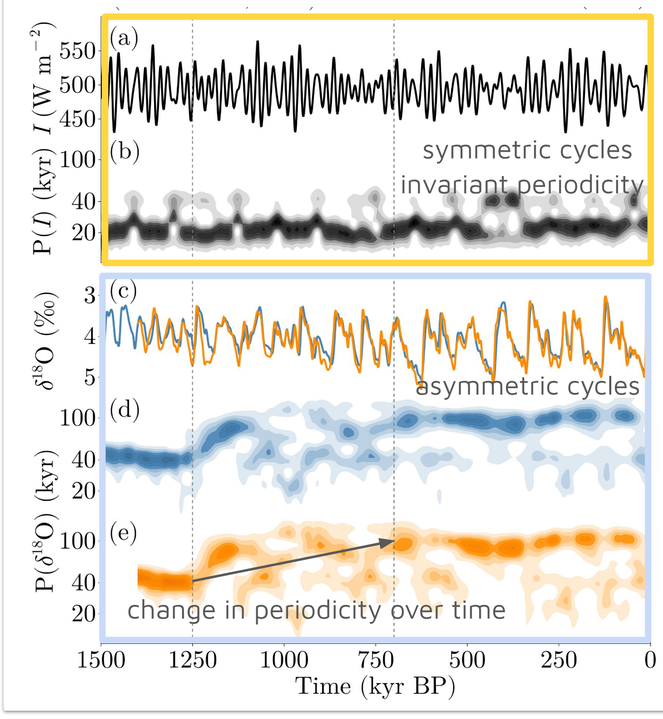
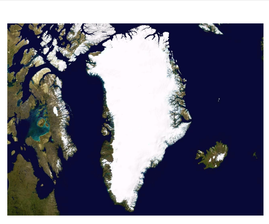
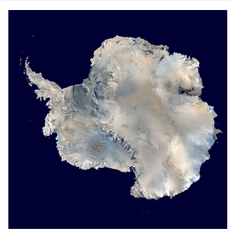
The **climate** variability of the **last 3 million years (Pleistocene)** have been long studied, however, **there are still uncertainties concerning the causes** of certain features in the paleoclimate records. These unknowns are believed to be due to intrinsic **nonlinearities in the climate system**. The longer timescales involved make it infeasible to use complex climate models because of the large computational cost involved. In this context, conceptual models are built to mimic complex processes in a simpler, computationally efficient way. Here we present the **Physical Adimensional Climate-Cryosphere mOdel (PACCO)** which represents the coupling between northern hemisphere ice sheets and climate employing state-of-the-art knowledge about climate and ice-sheet dynamics. In this way, PACCO is able to run several glacial cycles in seconds and produces results comparable to those of paleoclimatic proxies.

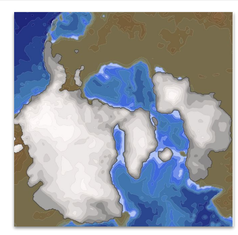
Glacial cycles are asymmetric (**100,000-yr paradox**) and their periodicity changes over time (**Mid-Pleistocene Transition**)

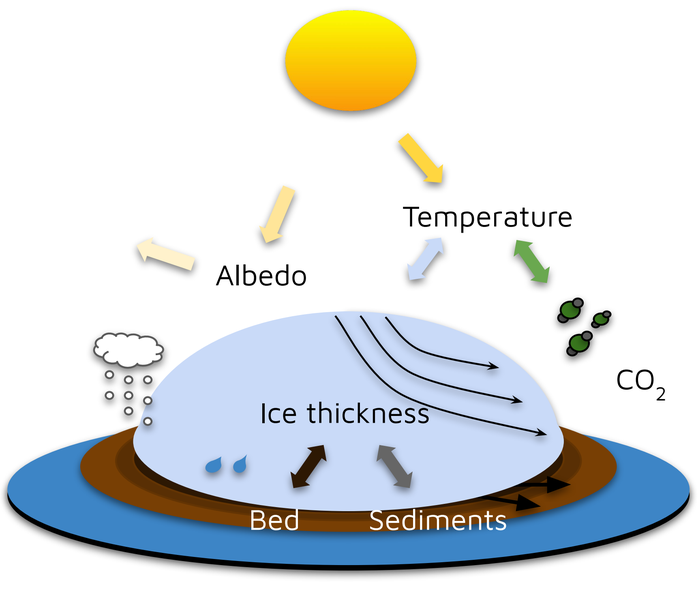






Ice sheets influence the climate because they are **big** (water storage, huge obstacle) **and white** (high reflectivity), and in the past covered vast areas of the continents





Our model, PACCO:
Physical **A**dimensional **C**limate **C**ryosphere m**O**del

Solar insolation

Input forcing (boundary condition)

Earth system processes
- Air temperature
- Carbon cycle
- Ice sheet evolution
- Albedo darkening
- Sediments erosion
- Lithospheric response

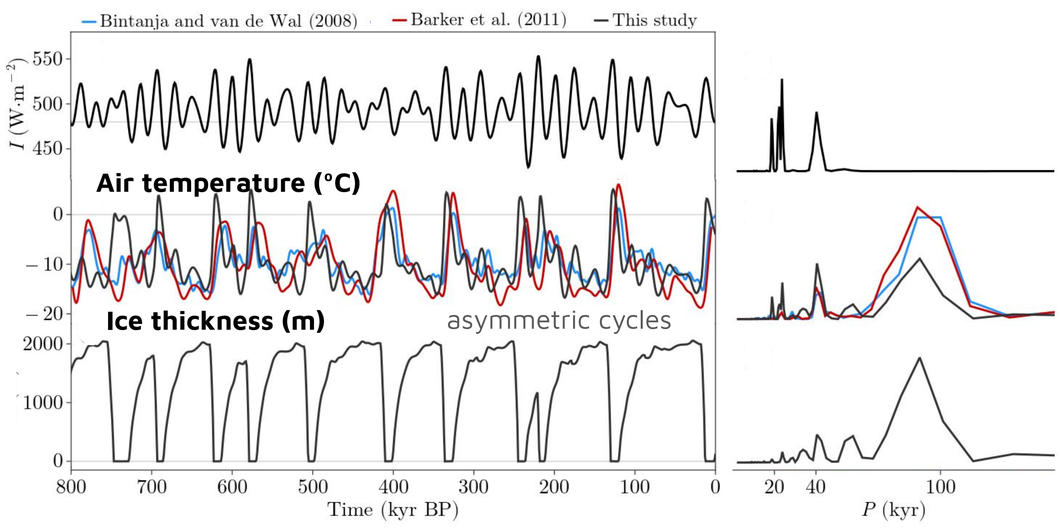
6 physical processes (5 coupled ODE's)

The figure above shows the evolution of (a) solar insolation (I, black) and (c) oxygen-18 isotope (δ^{18}O, Lisiecki and Raymo, 2005 in blue and Hodell et al., 2023 in orange). (b, d, e) Wavelet transforms of (a) and (c). These maps show the dominant periodicity as a function of time.

The satellite images above are from *Wikimedia* and show the current state of the Greenland and Antarctic ice sheets. The boreal map shows the distribution of ice sheets during the last glacial maximum (about 21,000 years ago). The diagram shows how different climate processes interact with each other and how the model PACCO operates.

What is the minimal physics that ...

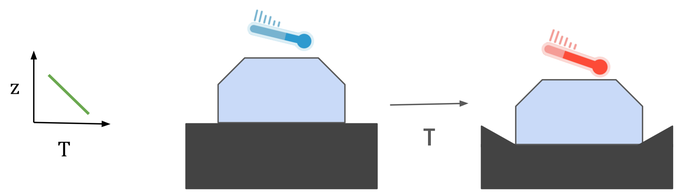
The 100,000-yr paradox
... produces the non-linear response to the forcing?



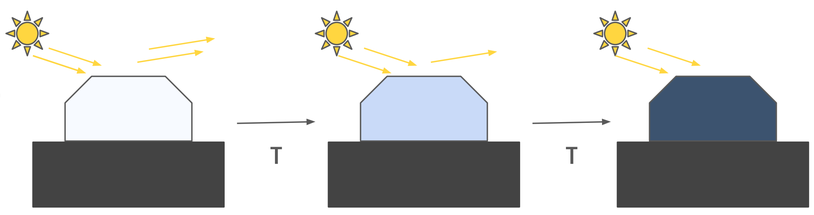
A **combination** of ice dynamics, interaction with the lithosphere, and ice absorption **slows down glaciations and accelerates deglaciations**!!

Ice dynamics induce non linearities in mass balance
in agreement with Verbitsky et al. (2018)

Isostasy (bedrock sinking) accelerates melting
in agreement with Abe-Ouchi et al. (2013)

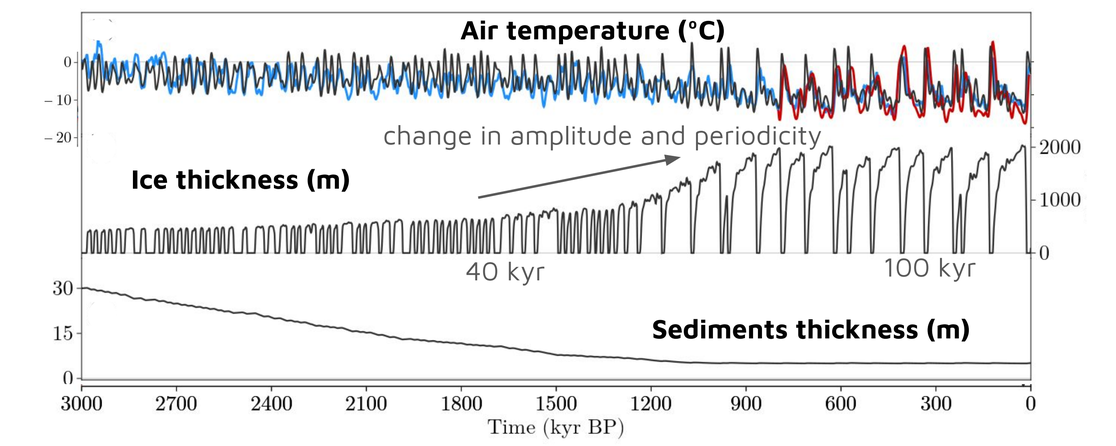


Ice darkening increases melting
in agreement with Ganopolski and Calov (2011) and Willeit et al. (2019)

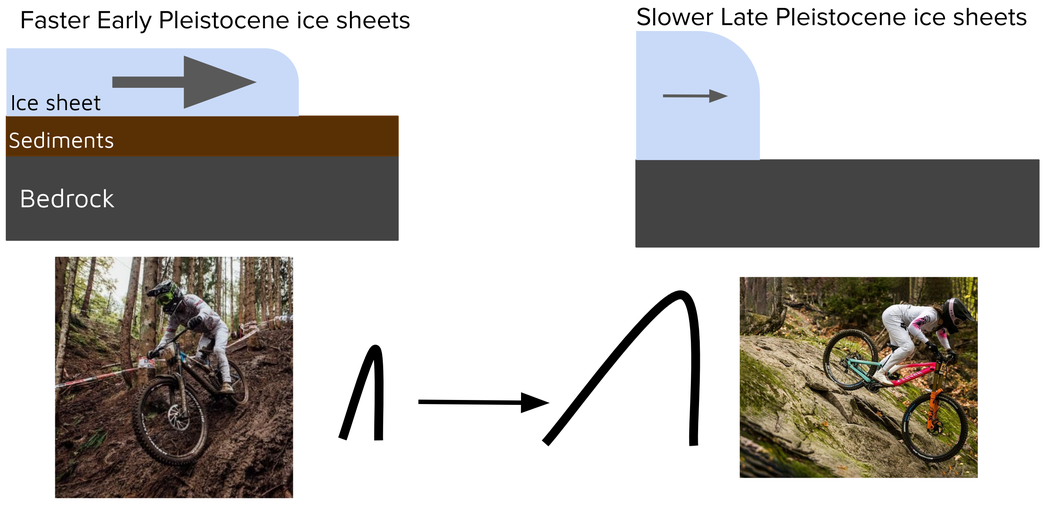


The Mid-Pleistocene Transition
... triggers a change in the behaviour of the Earth System under an invariant forcing?

Pliocene (warmer and wetter, extensive erosion, lots of sediment!) → Pleistocene (cooler, ice erodes sediments) → Holocene (present day)



The **speed** of ice depends on basal friction, basal friction **depends on sediments**, and faster ice sheets **melt easily**!!



The plots show PACCO results for (left) the 100,000-yr paradox and (right) the Mid-Pleistocene Transition. The diagrams show the different physical mechanisms underlying these features. The top images are from *Red Bull* and mimic the ease with which the ice sheet slides during the early and late Pleistocene.

All references in this poster can be found in the related articles:
Pérez-Montero, S., Alvarez-Solas, J., Swierczek-Jereczek, J., Moreno-Parada, D., Robinson, A., & Montoya, M. (2025). A simple physical model for glacial cycles. Earth System Dynamics, 16(3), 915-937.
Pérez-Montero, S., Alvarez-Solas, J., Swierczek-Jereczek, J., Moreno-Parada, D., Robinson, A., & Montoya, M. (2025, preprint). Understanding the Mid-Pleistocene transition with a simple physical model. EGUsphere, 2025, 1-30.