Comprehensive Earth System Models of the Last Glacial Cycle

Much of modern climate science fails to consider millennium-scale processes, many of which may prove to be important for predicting the climate trajectory in the shorter term.

The southern edge of the Greenland ice sheet near Kangerlussuaq, Greenland. What processes govern the advance and retreat of this and other ice sheets? The paleoclimate modeling initiative PalMod is working to find answers. Credit: Tim Brücher

By Mojib Latif, Martin Claussen, Michael Schulz, and Tim Brücher 23 September 2016

One of the grand challenges in climate system research is to understand the processes that determine the spectrum of climate variability on timescales that range from seasonal to multimillennial. Climatic processes are intimately coupled across these timescales. Understanding variability at any one timescale requires some understanding of the whole spectrum.

If we could successfully simulate the spectrum (https://eos.org/meeting-reports/characterizing-climate-fluctuations-over-wide-scale-ranges) of climate variability during the last glacial cycle, such a simulation might enable us to more reliably assess the future climate and to assess whether, for example, a regime shift in the variability could occur during the next centuries and millennia in response to global warming. Will the future climate be more or less variable, and what is the probability of rapid climate transitions? Could polar ice sheets collapse catastrophically? How quickly can sea level rise under present and future climate conditions?

The paleoclimate modeling initiative (PalMod) is specifically designed to better understand climate system dynamics and their variability on timescales up to the multimillennial.
The paleoclimate modeling initiative PalMod (https://www.palmod.de/) aims at filling gaps in knowledge about climate processes and climate modeling. The program, supported by the German Federal Ministry of Education and Research, is specifically designed to better understand climate system dynamics and their variability on timescales up to the multimillennial. The target is to simulate a full glacial cycle with comprehensive Earth system models (ESMs) incorporating a detailed description of interactions between the physical and biogeochemical components of the Earth system.

PalMod Goals

We aim to identify and quantify the relative contributions of the fundamental processes that determined the Earth's climate trajectory and variability during the last glacial cycle, spanning approximately the past 126,000 years. We are also working to simulate the climate with comprehensive ESMs from the peak of the last interglacial up to the present, including the changes in the spectrum of variability. A third goal of the program is to assess possible future climate trajectories beyond this century and into the next millennia with sophisticated ESMs tested in such a way.

The program started in late 2015, and we intend to conduct it over a period of 10 years. The research consortium includes a total of 17 institutions in Germany and will seek close collaborations with similar efforts at the international level.

Taking the Long View on Ice Sheet Variability

Glacial-interglacial transitions are one prominent example of processes that occur on multimillennial timescales. To simplify onerous computations involved, scientists have mostly used energy balance models and Earth system models of intermediate complexity (EMICs) to study such long-timescale variability.

EMICs can provide valuable guidance with regard to initialization of and selection of model parameters in comprehensive ESMs. However, these models do not capture the detailed interaction between processes at short timescales (e.g., weather development) and processes at long timescales (which occur in the ocean and ice sheets). A unified approach tackling the full range of climate variability up to multimillennial scales is lacking. PalMod scientists seek to fill this lack.

Capturing glacial variability is an intriguing challenge for PalMod scientists.
Comprehensive ESMs represent one unified approach, in principle. However, the current generation of comprehensive ESMs still lacks potentially important processes with regard to long-term climate variability. For example, the feedbacks between the continental ice sheets, sea level, and large-scale ocean circulation are not sufficiently captured by the ESMs. Hence, capturing glacial variability is an intriguing challenge for PalMod scientists who employ comprehensive ESMs.

Searching for the Causes of Climate Variability

The climate of the last glacial period has been extremely variable, with rapid and strong cold and warm events of global significance, but with differing amplitudes in the Arctic and Antarctic (Figure 1). PalMod scientists are seeking the origin of the cold events, termed Heinrich stadials (https://en.wikipedia.org/wiki/Heinrich_event).

Origin mechanisms are hotly debated, but both ice sheet instability and ocean dynamical processes are presumably critical to their development. Most mechanisms center on the variability of the Laurentide ice sheet (https://en.wikipedia.org/wiki/Laurentide_Ice_Sheet), which advances and retreats over Canada and the northern United States, but others suggest that the instability of the West Antarctic ice sheet may also have played a role.

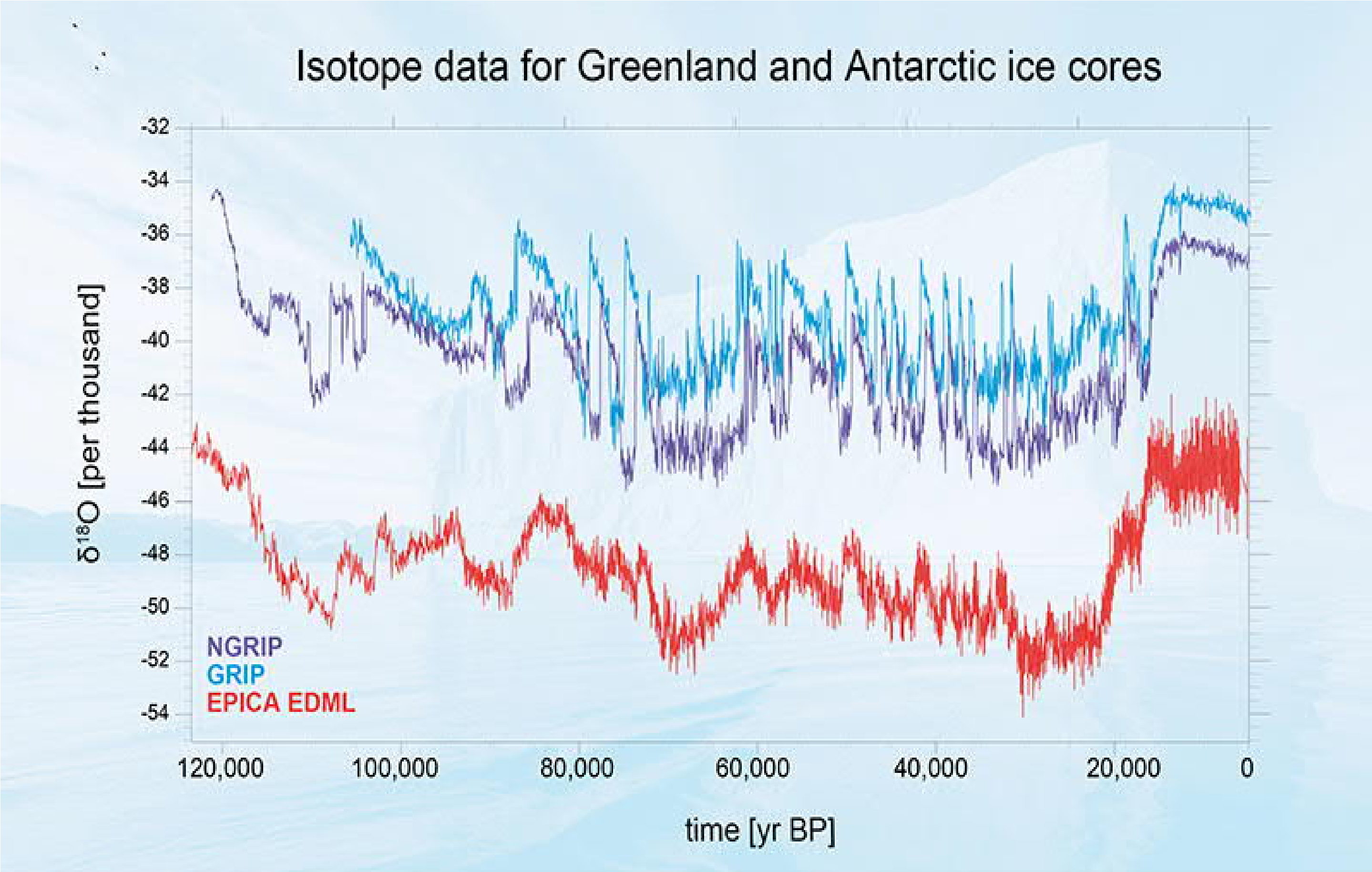

Fig. 1. Time series of measured $\delta^{18}O$ (the relative proportion of the stable oxygen isotopes ^{18}O and ^{16}O) for Greenland (GRIP = Greenland Ice Core Project; NGRIP = North GRIP) and Antarctica (EPICA = European Project for Ice Coring in Antarctica; EDML = EPICA Dronning Maud Land) as a proxy for local temperature, covering the past 1.2 millennia (BP is "before present"). The time series clearly show temporal variability on different timescales, as well as synchronous and asynchronous trends in both hemispheres. Credit: PalMod

Greenland and Antarctic temperature reconstructions also give evidence of several strong, rapid warming events followed by slow cooling. These are known as Dansgaard-Oeschger (http://www.ncdc.noaa.gov/paleo/abrupt/data3.html) (DO) events. PalMod scientists are searching for the origins of these rapid events, which again remain controversial.

Although the effects of the DO events are most visibly expressed around the North Atlantic Ocean, ample evidence suggests that DO events had a global imprint. The so-called bipolar seesaw, a time lag between temperature change effects in one hemisphere and the appearance of these effects in the other hemisphere, is one possibility to explain the coherence between variations in the Northern and Southern Hemispheres. DO events occurred every few thousand years and possibly involved major reorganizations of the global ocean circulation (http://oceanservice.noaa.gov/education/tutorial_currents

/05conveyor1.html), specifically the Atlantic Meridional Overturning Circulation (AMOC).

Building a Better Carbon Cycle Model

Current ESMs also lack potentially important interactions, involving the global carbon cycle, sea level, and ice sheets, which may, for example, explain fast and asynchronous changes in atmospheric carbon dioxide (CO_2) and methane during abrupt climate changes. Also, ESMs do not yet adequately incorporate the effects of carbon and methane stored in permafrost on land and as gas hydrates in marine sediments in amplifying climate variations triggered by Earth's orbit and rotation axis changes.

PalMod scientists intend to fill these gaps. Climate reconstructions on multimillennial timescales show a high correlation between globally averaged surface air temperature and atmospheric CO_2 levels. This correlation suggests a tight coupling between the physical climate system and the carbon cycle, such that perturbations in either component will be reinforced by the other.

The sea surface temperature is one factor that influences oceanic carbon uptake because the solubility of CO_2 in water varies inversely with temperature. Sea surface temperature is largely governed by the strength of the greenhouse effect, which in turn depends on atmospheric CO_2 levels, so PalMod scientists are working to better incorporate proxies of past sea surface temperatures into their models.

PalMod scientists are working to better understand soil and vegetation feedbacks and the timescale at which weathering, the chemical breakdown of rocks at the Earth's surface, becomes important.
The scientists face several challenges, however. Oceanic carbon uptake also depends on biological processes, but little is known about how they vary with the physical and chemical ocean state and with timescale. The terrestrial component also contributes to unresolved issues in the global carbon cycle.

Specifically, PalMod scientists are working to better understand soil and vegetation feedbacks and the timescale at which weathering, the chemical breakdown of rocks at the Earth's surface, becomes important. They are also attempting to decipher feedback mechanisms arising from interactions among various biogeochemical cycles. For example, living organisms need nitrogen and carbon for their metabolic processes; thus, the cycles of nitrogen and carbon are strongly coupled with each other. The exact nature of this coupling is a topic of interest to PalMod scientists.

Projections of the future climate on a multicentury timescale obviously require a thorough understanding of the biogeochemical cycles, in particular the global carbon cycle. The simulation of the last glacial cycle, with its large excursions in both physical and biogeochemical parameters, offers a unique opportunity for PalMod scientists to test and improve our ESMs.

Stimulus and Response

PalMod scientists are also approaching questions about climate variability from a more holistic stance. Analysis of paleodata reveals the existence of two separate scaling regimes above and below centennial periods. These regimes suggest the presence of distinct controls on climate variability. First, the climate system has memory, for example, associated with the oceans and continental ice sheets, which causes variability on short timescales to accumulate into progressively larger and longer-period variations (producing the so-called continuum). Second, a long-term climate response driven by Milankovitch cycles (long-term cyclic patterns in the Earth's motion) drives short-term variability, on timescales of a few thousand years and shorter. It is possible that this response involves fast processes arising from nonlinear ice sheet dynamics.

This type of influence could possibly hold for the response to anthropogenic forcing as well. The climate responses to such short- and long-term forcing appear to be of nearly equal magnitude at centennial timescales, at which the long-term effects of global warming become prominent. Because PalMod scientists wish to skillfully project the climate out to the next centuries and beyond, they seek to understand the processes that lead to climate variability over a wide range of timescales.

Modeling the Past to Assess Future Climate Change

PalMod scientists work to improve comprehensive ESMs to be capable of simulating the climate evolution and the variability characteristics during the last glacial cycle and perform multimillennial climate projections (at relatively coarse model resolution). This capability will allow us to address key questions of climate research.

The question of the "true" climate system sensitivity, or Earth system sensitivity, remains unanswered.
One such challenge is determining the likelihood that unchecked growth in greenhouse gas emissions could drive changes within this century or the next few centuries that normally occur only on the very long multimillennial timescales, as suggested by some state-of-the-art climate models.

So far, most model studies have attempted to estimate equilibrium climate sensitivity—the globally averaged equilibrium surface air temperature change in response to a doubling of the preindustrial CO_2 concentration. However, the response of the very slow components of the Earth system, including ice sheets and weathering, is not yet represented in the models. Thus, the question of the "true" climate system sensitivity, or Earth system sensitivity, remains unanswered.

PalMod as a long-term project offers the unique opportunity to address such fundamental questions.

Persons interested in finding out more can contact the project office at mail@palmod.de.

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