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A computationally feasible assimilation of proxy data with comprehensive Earth system models for multi-decadal climate field reconstruction: experiments with the Community Earth System Model (CESM)

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Overall, the PalMod project goal is to provide the best answers to overarching questions as, for example, What are the processes that govern the built-up and termination of ice sheets, or What is the best methodology to optimize comprehensive Earth system models.

The data assimilation work in PalMod Working Group (WG) 3 “Proxy data synthesis” can be thought of as a direct contribution towards addressing (some of) the overarching questions, as it provides itself climate field reconstructions (CFRs) within its specific framework. But also, the methodologies being evaluated within WG3 can potentially be integrated within the model integrations conducted in PalMod WG1 “Physical system” and PalMod WG2 “Biogeochemical system”.

We have been focusing on evaluating relatively computationally efficient methods for studying the climate sensitivity to a subset of selected parameters (for example, in relation to ocean horizontal and vertical mixing and cloud formation) in the Community Earth System Model (CESM) as climate controls, and conducting the corresponding assimilation of the proxy observations for a climate field reconstruction (CFR). This is relevant as a major factor constraining the assimilation for comprehensive Earth system models is the computational requirements. For this reason our assimilation experiments are being evaluated at a coarser horizontal resolution (4º x 5° in the atmospheric component) than used for the same model in WG1 (2°), because a number of model integrations is needed to apply data assimilation techniques, which opposes the (normally) single integrations for studies with the same model at a higher resolution in WG1.

Here we first show results from a synthetic experiment with CESM and data following the sparse spatial distribution of the MARGO (“Multiproxy Approach for the Reconstruction of the Glacial Ocean surface”) project, which indicates that combining climate models with proxy data via data assimilation is a powerful means to obtain more reliable estimates of a past climate state and the model parameters. as well as of the uncertainties of both the state and the parameters. Specifically, careful data-model comparison and data assimilation for selected time slices or periods of the past is an efficient method to check comprehensive Earth system models against paleoclimate reconstructions, saving expensive computing time on long transient simulations.

How these results may be used to interface with the forward modeling strategies in WG1 and WG2 regarding the simulation of the last glacial cycle clearly depends on the computing requirements of each specific model. Some could possibly implement the relatively low-cost data assimilation schemes we now demonstrated in WG3, others (for example, CESM at higher resolution) would likely need to resort to a reduced-order approach, either by the use of a coarser resolution or alternative means within an incremental setup.

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Paleo-ice sheet reconstructions constrained by glacial isostatic adjustment and geological data

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Paleo-ice sheet reconstructions are complicated by large uncertainties, particularly since it is usually only possible to infer thickness from indirect means such as the response of glacial isostatic adjustment (GIA). Recently, there has been increased attention to refining the chronology of ice sheet margins of paleo-ice sheets, and changes in relative sea level in formerly glaciated regions. Using this information, it is possible to infer the configuration of the ice sheets through time. Using the program ICESHEET (Gowan et al 2016), we reconstruct past ice sheets using a simple, though glaciologically plausible ice sheet model. The ice sheet volume is reconstructed by adjusting the basal shear stress at discrete time intervals in the region of interest until the modelled sea level is consistent with the sea level indicators. We demonstrate this technique by applying it to the Innuitian Ice Sheet. We also show the utility of the models for use in paleo-geographic reconstructions, as well as usage in paleo-climate simulations.

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Simulated Eemian Greenland Surface Mass Balance shows strong sensitivity to SMB model choice

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Understanding how the Greenland Ice Sheet (GrIS) behaves in a warmer climate is of utmost importance in respect to improve future sea level rise projections. Many authors in the past did so by simulating the GrIS during the Eemian Interglacial, the most recent warmer-than-present period in Earth's history, approximately 125,000 years ago. The idea behind it is that future Arctic temperature may become similar to the past Eemian Arctic temperature. Furthermore, there is proxy data to constrain models results, in contrary to solely rely on future model projections. Although the Eemian warming was caused by orbital conditions rather than higher Greenhouse Gas concentration as today, much can be learned from the simulated response of the GrIS.

The various Eemian GrIS studies result in very different ice sheets and sea level rise contributions from Greenland. The key to simulate the GrIS extend correctly in an ice sheet model is to get the Surface Mass Balance (SMB) during this period right. In this study we use three different types of SMB models forced with a Global and a Regional Climate Model to calculate the SMB on Greenland during the Eemian Interglacial. A simple, empirical Positive Degree Day (PDD) model, as a legacy baseline, a full Surface Energy Balance (SEB) model, as a best-guess approach, and an intermediate model. We discuss how a single global climate simulation (and its dynamically downscaled realization) can result in very different SMBs. We evaluate the influence of the climate forcing resolution and the SMB model choice and review the approaches of earlier studies with a focus on their SMB calculation. We find that the differences in previous Eemian GrIS simulations is dominated by different SMB forcings.

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Global loess deposits – their distribution and estimates on changes of chemical weathering fluxes from Last Glacial Maximum to today

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Loess sediments, defined as aeolian silt deposits, cover today about 3.3% of global land surface and are globally widely distributed, although more abundant at higher latitudes (around 70°N-30°N, 25°S-40°S). Generally, loess deposits present high weathering fluxes because of their grain size distribution and mineralogical composition. Due to their significant area coverage and relatively high weatherability, loess deposits should therefore be considered for global calculations of land-to-ocean carbon fluxes. The loess distribution during LGM conditions is slightly larger than today, mainly because of additional loess areas on the exposed continental shelves (e.g. shelf of Patagonia), and can be reconstructed. In this study, we have found that loess weathering signature reflects observations found for carbonate sedimentary rocks, which is especially interesting since carbonate weathering contributes 34% to 50% to the global CO2 consumption at shorter time scales. Applying different carbonate weathering functions, we have compared loess-derived alkalinity fluxes for LGM, the Mid-Holocene and today.

References:

Börker, J., Hartmann, J., Amann, T., Romero-Mujalli, G., accepted. Terrestrial sediments of the Earth: Development of a Global Unconsolidated Sediments Map (GUM). G-Cubed.

Gaillardet, J., Dupré, B., Louvat, P., Allègre, C.J., 1999. Global silicate weathering and CO2 consumption rates deduced from the chemistry of large rivers. Chemical Geology, 159(1–4): 3-30.

Hartmann, J., Jansen, N., Dürr, H.H., Kempe, S., Köhler, P., 2009. Global CO2-consumption by chemical weathering: What is the contribution of highly active weathering regions?

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The role of the Fennoscandian Ice Sheet in shaping European summer climate

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The deglaciation over the Euro-Atlantic region is characterized by rapid climate shifts between warm/cold (inter-)stadials. Proxy- and modelling-evidence suggest a consistent link between cold annual/winter climates with cold ocean states of the Northern Atlantic. However, it remains unclear whether and (if so) how these cold ocean states during stadials should lead to cold European summers in the presence of very high and further increasing summer insolation.
Here we present results from ongoing high resolution (~100 km) time slice simulations for the late deglaciation with the Community Earth System Model (CESM1). We study the link between cold/warm ocean states and changes in European summer temperatures under different solar and greenhouse gas forcing. In these simulations (Oldest Dryas, Bølling, Older Dryas, Allerød, Younger Dryas and Early Holocene), we use a realistic paleo-topography with ice sheets and low sea-level stands. Global SSTs and sea-ice concentrations for the different warm/cold states are prescribed from a previous coarse resolution (~375 km) fully coupled transient simulation with CCSM3 (TraCE).
Our simulations show that atmospheric/orographic blocking over the Fennoscandian Ice Sheet (FIS) is a dominant mechanism during the summer season. However, this is only found in simulations with a high model resolution (~100 km) while it is absent at the coarser model resolution of CCSM3. The presence/absence of atmospheric blocking over Europe leads to strong differences in mean summer temperatures as well as humidity. CESM1 simulations suggest that a very cold ocean state like during the Younger Dryas (YD, GS-1) leads to enhanced blocking and hence a slight summer warming rather than strong cooling across Europe. A cold-ocean-only sensitivity experiment confirms that the ocean state alone leads already to warmer summers in the presence of FIS. Increased solar forcing weakens blocking over central Europe but instead leads to stronger warming over continental Eurasia.
Warm (but shorter) summers during stadial conditions of the YD are confirmed by climate indicator plant species (macrofossils, aquatic pollen). In addition, there is geological evidence for (potentially very) dry conditions during stadials consistent with our CESM1 simulation. This suggests that very cold conditions in winter/spring and aridity during short warm summers may be a key driver behind lateglacial European summer conditions. CESM1 simulates a positive feedback of low soil moisture, late summer heating and atmospheric blocking in response to cold SSTs. This appears to be consistent with recent observations linking unusually cold North Atlantic SSTs with European heat waves.

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A new glacial ocean map of gridded climatological surface data (GLOMAP) for model forcing and model evaluation

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We present a new ocean climatology of the sea surface during the Last Glacial Maximum (LGM, 23,000–19,000 years before present) mapped on a global 1° × 1° grid (GLOMAP, glacial ocean map of gridded climatological surface data). This is an extension of the Glacial Atlantic Ocean Mapping (GLAMAP) sea-surface temperature (SST) reconstruction of the Atlantic SST, which is based on results of the Multiproxy Approach for the Reconstruction of the Glacial Ocean Surface (MARGO) project and some additional data.

Such a new ocean climatology of the SST during the LGM is urgently needed for forcing and evaluating numerical climate models. For example, it may serve as a boundary condition for atmospheric general circulation models (AGCMs) including water isotopes.

As for the GLAMAP SST reconstruction, a comparison of water-isotope distributions to ice-core data from Greenland and Antarctica and a speleothem dataset revealed a better agreement for an atmosphere-only than for a coupled atmosphere-ocean simulation of the LGM climate. The possible reason is a stronger gradient between mid- and high latitudes, but a closer analysis requires an updated and extended SST climatology for the LGM.

The gridding of the sparse SST reconstruction is done in an optimal way using the Data-Interpolating Variational Analysis (DIVA) software, which takes into account the uncertainty on the reconstruction and includes the calculation of an error field. In addition to the SST, we also deal with the reconstructed sea-ice boundaries in the northern and southern hemispheres and the sea-surface oxygen isotope ratio of seawater derived from fossil shells of planktonic foraminifera.

It is planned to use water isotopes as a tool to compare the performance of two different atmospheric models, using a simulated SST climatology as well as our new ocean gridded climatology as lower boundary conditions, thereby isolating the impact of the ocean feedback on the simulated distributions of water isotopes over land, ice and ocean.

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Assessment of models of global oceanic biogeochemistry

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Some values of parameters (constants) of global oceanic biogeochemical models are highly uncertain, yet their specification may affect simulation results on long time scales and / or under transient forcing. For example, the sinking speed of particulate organic matter and phytoplankton growth rate can determine the partitioning of nutrients, and hence oxygen and carbon dioxide, among different water masses of different origin and age. While it may seem straightforward to assess the model's outcome with root-mean-square errors of dissolved inorganic tracer concentrations, this kind of assessment can be extensively influenced by the model's representation of ocean physics. Small deficiencies in physics may render large errors in biogeochemical tracer distributions. Eventually, inter-model comparison of biogeochemistry become biased towards model physics. Furthermore, optimization against such a misfit function will attempt to compensate for physical offsets when calibrating biogeochemical model parameter values – a characteristic that is undesirable.

We here evaluate alternative misfit functions that compare nonparametric probability densities of the tracers' concentrations, such as the Hellinger Distance. We compare the output of Hellinger distances against more common descriptors of model fit, e.g., the global model RMSE or model biases of dissolved inorganic tracers, and discuss their respective merits with respect to long (millennial) simulations of global ocean biogeochemical models. Results of different metrics are presented for different biogeochemical model types and simulations.

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Northern Hemisphere (>40 □ N) biome reconstruction since 40 ka based on pollen data and modelling

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Pollen data from North America (1064 sites), Europe (1384 sites) and Siberia (402) were extracted from available data bases. Pollen names were homogenized and assigned to plant functional types and then to biomes respectively, following the standard biome reconstruction procedure. The mean value of pollen taxa from all available pollen assemblages within a time window is selected as the "pollen sample" for a given time-slice. Then the reconstructed biome datasets were mapped and compared to with biome distribution estimated via biomisation of palaeoclimate data derrived from Earth System Models. Via sensitivity studies the driving factors of biome changes since 40 ka were investigated at hemispheric scale

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Position and orientation of the Westerly jet determined Holocene rainfall patterns in China

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Proxy-based reconstructions and modelling of Holocene spatio-temporal precipitation patterns for China and Mongolia have hitherto yielded contradictory results, indicating that the basic mechanisms behind the East Asian Summer Monsoon and, in particular, its interaction with the westerly jet stream, remain poorly understood. Here we present quantitative reconstructions of Holocene precipitation derived from 101 fossil pollen records which show similar trends and anomalies as simulations of a minimal numerical model. We infer a south-westerly to north-easterly orientation for the westerly jet stream axis during the early Holocene, in contrast to its east-west orientation since the middle Holocene. Our results also suggest that the westerly jet stream axis shifted gradually southward since the middle Holocene. This re-orientation and shifting of the westerly jet stream was tracked by the main summer monsoon rain band, resulting in an early Holocene precipitation maximum over most of western China, a mid-Holocene maximum in north-central and north-eastern China, and a late Holocene maximum in south-eastern China. Our results indicate that, irrespective of the time-scale or the forcing mechanisms invoked, correct simulation of the orientation and position of the westerly jet stream is crucial to reliable prediction of precipitation patterns in China and Mongolia

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Sensitivity of Mineral Dust to Glacial Climate Boundary Conditions

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Mineral dust plays an important role in the Earth system both through direct and indirect effects, and changes in climate may also feed back onto the life cycle of mineral dust. Aerosol-cloud interactions and the role of aerosols in affecting the global biogeochemical and hydrological cycles are only partly understood, and additional challenges result from the ranges of spatial and temporal scales involved in mineral dust processes. These sources of uncertainty pose a major problem in the framework of future climate predictions, but also for the understanding and quantification of past climate dynamics. Terrestrial and marine archives provide evidence for pronounced dust variability in the past with substantially increased dust concentrations and deposition fluxes during glacial periods. Models of intermediate complexity have further suggested the importance of dust-related climate responses and feedbacks on multi-decadal to millennial time-scales and of mineral dust contributing to long-term variations of continental ice sheets through the dust-ice-albedo feedback. Further insight into the role of dust in paleo-climate is therefore expected from the transient simulations which are at the heart of the PalMod project and based on comprehensive earth-system models including mineral dust modules.

In preparation of the millennial-scale transient simulations of the last deglaciation on which the current PalMod project phase focusses, we investigate the sensitivity of glacial mineral dust in a series of experiments using the CESM1.2 comprehensive climate model with a fully prognostic mineral dust module. The dust variations can be related to changes in source strength, deposition, but also to atmospheric transport patterns which are affected directly or indirectly by the glacial boundary conditions. By prescribing individual glacial forcing factors such as orbital parameters and greenhouse gas concentrations each at a time, the respective impact of each glacial boundary condition on the response of atmospheric dust concentrations as well as dust deposition fluxes is examined. Preliminary results will be shown from LGM time-slice experiments. Furthermore, we will present a new setup currently under development and aiming at more computational efficiency of transient simulations including a mineral dust module. The setup will allow to periodically couple computationally costly prognostic mineral dust only during short parts of the transient CESM1.2 simulations and to run extended parts of the simulations at reduced computational load by prescribing atmospheric dust concentrations and deposition fluxes derived from the previous fully prognostic model run interval. The setup takes into account both the atmospheric dust concentrations and the dust deposition fluxes. Sensitivities to the detailed technical realization of transitioning between segments will be discussed as well as dust responses and feedbacks in test simulations serving as a preparatory step for a CESM1.2 transient deglaciation run.

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Component Concurrency in Atmospheric Simulation

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The scalability of the atmospheric model ECHAM6 at low resolution as used in paleo climate simulations suffers from the limited number of gridpoints. As a consequence, the potential of current HPC architectures cannot be used at full scale for such experiments, particularly within the available domain-decomposition approach. Therefore, we propose to extend concurrency further by running the radiation component in parallel with the rest of the atmospheric model, while at the same time applying data parallelism inside the component.

In a similar attempt, Balaji et al. applied component concurrency to the radiative transfer in GFDL FMS. They argued that the multiphysics character of Earth system models (ESM) allow for extending the existing parallelism among a few components (e.g. atmosphere, ocean) to more coarse-grained component concurrency. The radiation component, as Balaji showed, can be a successful candidate to apply component concurrency in a typical ESM. Experiments reveal that this component is also one of the most expensive computational parts in ECHAM6, at least for paleo climate simulations. Currently, as a compromise, the radiation is computed only at a larger timestep in order to reduce computational costs.

Since the radiation physics is calculated entirely columnwise, individual columns have no cross-dependency. This property allows for a much more flexible and finer data decomposition than the one used for the rest of the atmospheric model - potentially leading to a higher scalability. In contrast to the OpenMP approach used by Balaji et al., we choose MPI to fully exploit the potential of higher concurrency. In addition, different independent executables realize the idea of separation of concerns. Therefore, the radiation implementation can be optimized independently from the model allowing for higher throughput, which is essential for the ambitious long-term simulations of the PalMod project.

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Quantifying Glacial Ocean Carbon Cycling

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Glacial-interglacial variations in atmospheric CO_2 remain one of the great challenges in paleoclimate research. Improved understanding requires a quantification of the glacial ocean's carbon cycle. Here we present a decomposition of the modern and glacial ocean's carbon cycle using data-constrained models. Offline calculations using the Transport Matrix Method (TMM) are used to accurately quantify ocean carbon storage due to the solubility and biological pumps and disequilibrium (Cdis) effects due to slow air-sea gas exchange. Contrary to previous suggestions we show that the the efficiency of the biological pump expressed as the amount of respired organic carbon (Corg) or the amount or respired phosphate was lower in our glacial simulations compared with the pre-industrial. We demonstrate that often used approximations such as Corg ~ AOU (Apparent Oxygen Utilization) have large errors and cannot not be used to quantify glacial-interglacial changes. A large number of sensitivity experiments with the TMM allow investigation of individual variables such as temperature, sea ice, circulation, and iron fertilization on ocean carbon storage. These experiments suggest that temperature and iron fertilization are the dominant drivers of glacial atmospheric CO_2 draw-down into the ocean. They increase disequilibrium carbon storage and contribute both to a decrease of atmospheric CO_2 by about 80 ppm. Conversely and contrary to previous suggestions, sea ice and circulation changes have only minor impacts on CO_2 due to opposing effects on Cdis, which they increase, and Corg, which they decrease.

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Assessing LGM changes of the Antarctic and Greenland ice sheets by explicit water isotope diagnostics

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During the past two decades, several atmospheric and oceanic general circulation models (GCMs) have been enhanced by the capability to explicitly simulate the hydrological cycle of the two stable water isotopes H218O and HDO. They have provided a wealth of understanding regarding changes of the water isotope signals in various archives under different past climate conditions. Fully coupled atmosphere-ocean GCMs with explicit water isotope diagnostics are required for a more comprehensive simulation of both past climates as well as related isotope changes in the Earth's hydrological cycle. Atmosphere-only simulations with high spatial resolution can also improve a process-oriented understanding and interpretation of observed past isotope changes.

In this study, we investigate the linkage between the isotope signal in precipitation and potential changes of the Greenland and Antarctic ice sheet during the LGM. During the last years, several distinct Antarctic and Greenland LGM ice sheet reconstructions have been suggested within the framework of the PMIP2, PMIP3, and PMIP4 paleoclimate model inter-comparison projects. These data sets show some large differences in the reconstructed LGM ice sheet, e.g. for the region of West Antarctica.

We have run a set of identical high-resolution ECHAM isotope simulations with identical LGM boundary conditions, except for the prescribed ice sheet height and extent. Our modelled LGM delta O-18 changes in precipitation are compared to ice core data from both Greenland and Antarctica. First analyses of our simulations indicate that the lowered West Antarctic ice sheet, as suggested by the latest ice sheet reconstruction within PMIP4, leads to an improved model-data fit for this region. However, compared to the simulation results using the older PMIP3 LGM ice sheet reconstruction, the model-data agreement of delta O-18 changes with East Antarctic ice core data becomes worse. The difference in these isotope results can be directly linked to glacial temperature changes and prescribed ice sheet elevations and demonstrate, how isotope simulations may be used for assessing ice sheet reconstructions within the PalMod initiative.

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Early interglacial legacy of deglacial climate instability

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Throughout the last glacial cycle natural millennial scale variations in atmospheric CO2 have occurred in response to abrupt changes in deep ocean circulation, which themselves are reflected by observable changes in surface conditions across the North Atlantic region; CO2 tends to increase while the surface North Atlantic is anomalously cold and covered in rafted ice (conditions typically associated with Heinrich events) and decrease when conditions are anomalously warm and relatively ice free. We use continuous proxy records of NE Atlantic surface temperature and ice rafting to demonstrate that an equivalent relationship has held over the last 800kyr i.e. since before the appearance of Hudson Strait-type Heinrich events. Our results show that glacial terminations (deglaciations) are characterised not only by an interval of intense ice rafting, but also by a subsequent and abrupt shift to anomalously warm surface conditions, which we interpret to reflect an abrupt recovery of deep ocean circulation in the Atlantic. According to our analysis, this is followed by a period of enhanced overturning lasting thousands of years until equilibrium interglacial conditions are attained and during which atmospheric CO2 is likely to decrease (following an interval of rising CO2 associated with deglacial ice rafting). Our results therefore demonstrate that deglacial oscillations in ocean circulation can have a lasting influence on early interglacial climate and highlight the transient nature of atmospheric CO2 overshoots associated with the onset of some previous interglacials. Accordingly we suggest that these intervals should be considered as a part of (or at least affected by) the deglacial process. This has implications for studies concerned with the evolution of atmospheric CO2 during past interglacials as well as the Holocene.

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A New TraCE Simulation - Now with Water Isotopes and Other Geotracers

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The TraCE-21000 Project, a collaboration among the National Center for Atmospheric Research, the University of Wisconsin, and Oregon State University, explored the transient evolution of the climate system, especially the time-evolving nature of the atmosphere, ocean, sea ice, and land surface and their interactions, from 22,000 years before present to today. The transient simulations with the Community Climate System Model (CCSM3) were made possible by the increase in computing power, the development and coupling of improved model components of the climate system, and the availability of improved chronologies of changes in the important forcings and responses. The TraCE-21000 project allowed better understanding of the mechanisms and feedbacks responsible for explaining the temporal nature of the records - leads and lags, abrupt changes - with researchers combining analyses of the TraCE-21000 simulations and data together.

The second phase of the project, iTraCE, has started, taking advantage of an improved and higher resolution version of the Community Earth System Model (CESM) that now includes direct simulation of water isotopes in the coupled model and other geotracers in the ocean. First results illustrate more nuanced interpretations of isotopic records from tropical Pacific marine cores, cave speleothems in Brazil, and the Greenland ice cores.

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Modelling The Last Glacial Cycle

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Performing a fully transient simulation of the last glacial cycle and particularly the last deglaciation is a phenomenal challenge for our understanding and ability to model climate change. As a precursor for such an endeavour, we present results from a large series of "snapshot" simulations. Implicit within such simulations is the assumption that climate is in equilibrium with its forcing. We will review the lessons learnt from such simulations, in terms of the feedbacks operating during these time periods. In addition, we will discuss the challenges involved in setting up these simulations in terms of the boundary conditions and other aspects of climate model forcing. Finally we will show some preliminary results for the deglaciation, contrasting the "snapshot" simulations with fully transient simulations.

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Part 1. Taming ice sheets in coupled ice sheet-climate simulations: Towards realistic spin-up of the coupled system

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The appropriateness of a deglacial simulation with a fully coupled ice sheet-climate model critically depends on the Last Glacial Maximum (LGM) state from which it is initialized. However, as the dynamics of ice sheet complexes operate over long time-scales (many thousands of years), obtaining such a state requires a computationally efficient spin-up strategy. Such a strategy has to carefully balance computational efficiency and the complexity of the coupled ice sheet-climate system. To this end, we present a three-phase initialization strategy and show that interactions between ice sheets on different continents are crucial, as the buildup of an ice sheet in one place can inhibit ice-sheet growth somewhere else and vice versa.
In the first phase, we use a stand-alone global ice-sheet model (10 km resolution) to simulate an ensemble of ice-sheet evolutions from the Last Interglacial to the LGM following a glacial-index method and testing a range of setups for the ice-sheet model and its interfaces with the atmosphere and ocean. This ensemble is run towards the LGM to compare the resulting ice masses with geomorphological evidence and sea-level reconstructions. The resulting subset of ice-sheet evolutions is used to provide the starting point to phase two of the initialization strategy at the end of Marine Isotope State 3 (30 ka ago). In phase two we use different 30-ka ice-sheet geometries from phase one to force 30-ka climate model simulations with CESM1.2 (2° and 1° resolution in atmosphere and ocean respectively) which are in turn again used to force the ice sheet model. The resulting ice-sheet-climate configurations that matches best with geomorphological evidence and sea-level reconstructions is the starting point of phase three of the initialization strategy, an asynchronously coupled transient ice-sheet-climate simulation from 30-ka to the LGM, detailed on the poster by Rogozhina et al.
We find that the different 30-ka climates reveal large differences and exemplify the crucial importance and benefit of this three-phase initialization strategy. The initial height of the North American ice sheet complex has a large impact on the surface climate over Arctic Siberia, and therewith, determines whether or not temperatures in that area become sufficiently low to start the build-up of a large Siberian ice sheet, which would be inconsistent with existing geomorphological evidence. Once the buildup of an undocumented ice sheet is triggered, its impacts on the regional climate through increasing topography and albedo will enhance its further growth and expansion towards the LGM. Taking the interaction between ice sheets and climate into account is key in initializing a reasonable LGM state of the coupled ice-sheet-climate system.

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Changing topography and land-sea mask in transient simulations of the last deglaciation using CESM

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Sea level changes may have an important effect on climate. In Earth-system models the land-sea mask is usually fixed. The time-dependent ocean boundaries and bottom topography need to be considered for simulations of the last deglaciation, where the global sea level increased by about 120m. The aim of this project is to make the ocean component POP (Parallel Ocean Program) of the CESM (Community Earth System Model) capable of dealing automatically with those changes. Before the algorithm was developed and tested, manual checks were performed regarding the control of key straits, modification of through-flow depths at important sills, connections of ocean basins and determination of closed basins. The algorithm applies changes in the land-sea mask whenever sea level change crosses a z-level of the vertical grid. The land-sea changes take place upon a restart of the model, which requires a modification of restart files. New ocean cells are initialized with nearest neighbor values. We performed experiments with the CESM1.2 at coarse horizontal resolution (~3° in POP) to investigate how those changes in ocean boundaries and bottom topography influence the ocean circulation and ocean dynamical processes, which in turn affect the atmospheric circulation. We find significant changes not only near narrowing straits or widening shelves, but also in the resulting flow path of the North Atlantic Current and the strength of the Atlantic Meridional Overturning Circulation.

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Investigating wetland expansion and methane emission dynamics since the LGM using a dynamical global vegetation model

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Although methane is an important greenhouse gas, the CH4 budget and the attribution of relative emissions to specific sources is still poorly constrained. Emissions from wetlands contribute most to natural CH4 emissions and to its uncertainty. In bottom up model estimates, that prescribe wetlands using various wetland mapping datasets, uncertainties result mostly from the uncertain spatial distribution and global extent of wetlands, which ranges from 5.3 to 10.2 Mkm2 (Zhang 2017). Reconstructions of past variability in CH4 from ice cores and of peatland extent from pollen data provide the opportunity to evaluate and independently test bottom up models. Such an investigation may not only help to clarify open questions about the underlying drivers of reconstructed past variability, but also help to further constrain bottom up models to give improved estimates for the present and the future.

Our goal is to reproduce and investigate the variability in terrestrial methane emissions and wetland extent since the Last Glacial Maximum using the LPX-Bern Dynamic Global Vegetation Model. LPX-Bern includes formulations for dynamic wetland expansion using a TOPMODEL approach (Stocker 2014) and an integrated methane module (Spahni 2011). Here we present results of a first preparatory transient simulation over the past 22,000 years. In the simulation, the wetland extent decreased slightly over the deglaciation by about -0.4 Mkm2, which is the result of a decrease in the mid and low latitudes (-1.9 Mkm2), in part following flooding of continental shelves, and an increase in high latitudes (+1.6 Mkm2), following the retreat of the ice shield. The present day total wetland area of 8.9 Mkm2 lies well within the wetland dataset spread. Modelled latitudinal distribution is shifted more towards higher latitudes with 2.6 Mkm2 in boreal regions compared to estimates ranging between 1.1-2.1 Mkm2. Although the resulting wetland methane emissions (154.3 TgCH4) and the global soil sink (26.4 TgCH4) for present day are comparable to bottom-up and top-down estimates (Kirschke 2013), and the variability in methane emissions shows features measured in ice-cores, such as high emissions during the Bølling/Allerød event, the overall trend of an approximately doubling of the CH4 concentration from the LGM to the early Holocene could not be reproduced with the current simulation setup. More rigorous evaluation of the model against available data and the implementation of necessary adjustments in the model setup will be the next steps in the ongoing investigation.

Zhang et al. "Methane emissions from global wetlands: An assessment of the uncertainty associated with various wetland extent data sets." Atmospheric Environment 165 (2017): 310-321.

Spahni et al. "Constraining global methane emissions and uptake by ecosystems." Biogeosciences 8.6 (2011): 1643-1665.

Stocker et al. “DYPTOP: a cost-efficient TOPMODEL implementation to simulate sub-grid spatio-temporal dynamics of global wetlands and peatlands.” GMD, 7(6) (2014): 3089-3110.

Kirschke et al. "Three decades of global methane sources and sinks." Nat. Geosci. 6.10 (2013): 813-823.

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Self-sustained AMOC transitions driven by salt-oscillations and interactions with the North Atlantic subpolar gyre in a coupled climate model

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We present a set of simulations with the coupled climate model MPI-ESM, in which the Atlantic Meridional Overturning Circulation (AMOC) oscillates between a weak and a strong state on multi-centennial to millennial timescales. In each simulation, all respective forcings are held constant. The oscillations occur under medium to low CO2 concentrations (pCO2) of approximately 207 to 190 ppm in combination with prescribed preindustrial ice sheets. At a pCO2 above 207 ppm, the AMOC remains in a strong state; at a pCO2 below 190 ppm, the AMOC remains in a weak state. The strong AMOC state is characterised by a warm and salty North Atlantic, a weak subpolar gyre, and partially ice free Nordic Seas with active deep convection. The weak AMOC state is characterised by a cold and fresh North Atlantic, a strong subpolar gyre, and extensive sea-ice cover. The transition between the two states is driven by a redistribution of salt between the tropical and the subpolar North Atlantic and interactions between the North Atlantic subpolar gyre and deep convection in the Nordic Seas and eastern North Atlantic. Changes in the temporal AMOC variability suggest that the AMOC transitions are the result of oscillations between two weakly unstable states. The timescales of the oscillations of 700 to 1500 years are comparable with the timescales of reconstructed Dansgaard-Oeschger (DO) events. Even though the simulated oscillations occur with prescribed preindustrial ice sheets, they support the hypothesis that DO-events could occur as a result of unforced abrupt changes in the ocean circulation.

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Interactive ocean bathymetry and coastlines for simulating the last deglaciation with the Max Planck Institute Earth System Model (MPI-ESM)

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As ice sheets melt or grow, the flux of freshwater into the ocean changes and the bedrock adjusts due to isostatic adjustments, leading to variations in the bottom topography and the oceanic boundaries. For long-term integrations with large changes in the ice volume, it is therefore necessary to consider transient ocean bathymetry and coastlines. However, in most standard ESMs they are fixed throughout the simulations because the generation of a new ocean model bathymetry implies several levels of manual corrections. Hence, it is one of the main challenges in adequately simulating a complete glacial cycle with ESMs.

We present for the first time, a tool to allow for an automatic computation of bathymetry and land-sea mask changes during long-term climate simulations. It is applied within the Max Planck Institute ESM (MPI-ESM). The procedure includes the generation of the bathymetry file and the modification of the restart file to run the ocean component of MPI-ESM. Our approach guarantees the conservation of mass and tracers at global and regional scales.

We investigate the performance in simulating the ocean circulation when the interactive bathymetry and land-sea mask are implemented. Therefore, we compare two simulations of the last deglaciation with MPI-ESM. In the first run, the bathymetry and coastlines are automatically changed every 10 years. The ICE-6G reconstructions of ice thickness and topography are prescribed to compute both, the changes in the ocean floor and the freshwater fluxes into the ocean. In the second run, the bathymetry and land-sea mask are fixed to the Last Glacial Maximum condition (21kyrs BP). Both simulations are externally forced with solar insolation and greenhouse gas concentrations.

The presented modules constitute a powerful tool and a step forward towards a realistic simulation of the last deglaciation. We are currently continuing our efforts to combine single components into a fully coupled ice sheet-solid earth-climate model with interactive coastlines and topography, forced with only solar insolation and greenhouse gas concentrations.

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Surface mass balance variability during the last deglaciation

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Studying glacial climate variability with complex Earth System Models (ESMs) remains a major challenge. Large part of the long-term variability throughout the glacial cycles is caused by interactions between the ice sheets and the climate (e.g. Heinrich Events starting in Dansgaard-Oeschger stadials). Modeling these interactions requires the coupling of interactive ice sheets into the model systems. To allow for adequately fast integration times, ESMs need to be run in coarse resolution. The surface mass balance (SMB), however, exhibits large gradients at the margins of the ice sheets. Hence, a downscaling of the SMB from the coarse resolution atmospheric grid onto high resolution ice sheet topographies, that resolve the margins, is required.

We present a sophisticated energy balance model (EBM) to calculate and downscale the SMB for multi-millennial simulations. It accounts for changes in the snow albedo (due to varying snow properties such as snow age, depth, melting and refreezing of water), cloud cover, and key physical processes like percolation and refreezing of melt water. The SMB is calculated on the atmospheric grid on different elevation classes, which results in a 3-D SMB data set. This allows for an interpolation on different ice sheet topographies.

Here, the EBM is evaluated for a historical simulation with the Max Planck Earth System Model (MPI-ESM) and shows good agreement with reconstructions from regional climate modeling. To explore the SMB variability on glacial time scales, we additionally force the EBM with a transient simulation of the deglaciation. For the latter, MPI-ESM is run with prescribed ice sheets and topography and accounts for changes in river directions, ocean bathymetry and land sea mask due to the retreating ice sheets and isostatic adjustments. In the near future, we plan to introduce this 3-D SMB data set to the ice sheet modeling community for future investigations of ice sheet variability throughout the last deglaciation.

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Implementation of An Optimality-Based Ecosystem Model in the UVic-ESCM

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We have implemented an optimality-based NPZD model with Nutrients (nitrogen, phosphorus), ordinary Phytoplankton and diazotrophs, Zooplankton, and Detritus into the UVic Earth System Climate Model. The new model decouples C, N and P in the optimality-based plankton compartments, which allows phytoplankton to utilize ambient nutrients in different N:P ratios and thus allows for dynamic stoichiometry of nitrogen and phosphorus in phytoplankton, diazotrophs, and detritus. Preliminary results show some ability in reproducing global patterns in the N:P ratios of marine particles, as well as the distribution of global nitrogen fixation. Due to the increase in computing cost and number of tracers in our model, we have also adapted our optimality-based ecosystem model for the transport matrix method for fast spin-ups and are currently incorporating an automatic parameter optimization method with a search distribution algorithm (Covariance Matrix Adaptation Evolution Strategy, CMAES) for model calibration.

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Analyzing climate variability in Antarctica over the past millennia using data assimilation.

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Climate variations at decadal to centennial timescales are not well understood in the Southern Ocean and Antarctica because of the lack of data and the systematic biases of climate models. Nevertheless, by combining both sources of information using data assimilation, we can reduce the uncertainties during some periods, test hypotheses about the mechanisms ruling past changes and highlight some fundamental incompatibilities between reconstructions and model results. This is illustrated here using two examples. First, we discuss the incompatibility between models and data on the twentieth century warming over Antarctica. This warming is much larger in models, even after data assimilation of the reconstructed continental signal, while states of the climate system compatible with the forcing estimates, the reconstructions and the model physics can be obtained over the past millennium for all other continental regions when the uncertainties are taken into account. This incompatibility can be related to a too strong response of the models to greenhouse gas forcing or to the uncertainties in the reconstruction of temperatures based on isotopic records. Nevertheless, assimilating directly the isotopes does not improve significantly the results over East Antarctica. The second example is devoted to the atmospheric and oceanic cooling from 10 to 8 ka BP in the high latitudes of the Southern Hemisphere shown in paleoclimate records. Models are generally not able to simulate this cooling, suggesting an incompatibility. By performing simulations with data assimilation, the model results and observations can be reconciled and the cooling can be explained by the combination of a modified atmospheric circulation and an enhanced freshwater flux in the Southern Ocean.

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A transient simulation of the last deglaciation

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We present the latest results from a fully transient simulation of the early last deglaciation (21-15 ka) using the Hadley Centre Climate model, HadCM3. In line with the Palaeoclimate Model Intercomparison Project Phase 4 (PMIP4) core experiment design, this simulation uses the ICE-6G_C ice sheet reconstruction with the land-sea mask and bathymetry updating every 500 years, and the height of the ice sheet evolving smoothly through the simulation. We have performed a pair of simulations starting from 23 ka, with and without additional routed fresh water fluxes from the melting of the ice sheets to investigate the impact on Atlantic Meridional Overturning Circulation (AMOC) and climate, and to evaluate the role of freshwater in preconditioning the glacial ocean. Thus, we are able to highlight the contrasting importance of the evolution of the ice sheets and meltwater. Furthermore, we identify that AMOC is sensitive to the evolution of Eurasian river routing, which affects the strength of Atlantic overturning by more than 15% in the early deglaciation.

In addition, we have investigated the impact of performing "snapshot" simulations of the Last Glacial Maximum (LGM) by running two equilibrium type simulations: one that is a typical PMIP 21 ka equilibrium simulation (adhering to the PMIP4-CMIP6 protocol), and one that freezes the boundary conditions of our transient simulation at 21 ka, running it out to equilibrium. The results show that the traditional PMIP assumption of the LGM being in equilibrium with the forcing is reasonable for surface climates and overturning circulation. At 21 ka, the transient simulations compare very well with the equilibrium runs.

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A comparison of the climate impacts of volcanic eruptions at the Last Glacial Maximum and the Preindustrial period

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The paleoclimate record allows to establish the role of natural forcing in generating climate variability in states that are very different from today, such as at the last Glacial Maximum 21 000 years ago.
Here we present the results from an ensemble of idealized 1000-year-long simulations for the Last Glacial Maximum (n=5) and the Preindustrial (n=5), performed with the isotope-enabled version of the Hadley Center Coupled Model Version 3.
All 'forced' ensemble members were initialized separately from the spin-up, but forced with the same volcanic and solar forcing. We perform a superimposed epoch analysis to identify the short-term (1-2 year) and medium-term (3-5 year) effects of eruptions in the different states for large eruptions. We find that, globally averaged, the modeled temperature and precipitation change is similar for an eruption at the LGM, compared to an eruption in the preindustrial.
However, focusing on spatial patterns, there are significant differences. The change is more uniform across the globe, and between the years after the eruption for the LGM, whereas for the preindustrial strong signals are identified in the North Atlantic and the Southern Ocean which vary between the years after the eruption. We discuss the relative importance of sea ice feedbacks, and the Atlantic Meridional Overturning Circulation in sustaining temperature anomalies, and in creating long-term climate variability in the different climate states, and evaluate, to what extent volcanism could have contributed to a larger climate variability in the Glacial climate.

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Searching for the deglaciation: sampling spatio-temporal climate uncertainty for simulating ice sheet evolution

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Ice sheet models fail to reproduce reconstructed patterns of Northern Hemisphere ice sheet retreat through the last deglaciation (21,000-6,000 years ago) without tuning of the climate input. This is the main barrier to understanding the role of ice sheets in past abrupt climate and sea level changes. The primary reason for this failure is the large climatic uncertainty. We developed a statistical method to systematically explore the uncertainty in the temporal and spatial evolution of climate (temperature and precipitation) through this period, by combining output from transient General Circulation Model (GCM) simulations of the last 21,000 years (from the FAMOUS and CCSM3 climate models) with proxy records of surface temperature changes.

The method consists of decomposing the pattern of variability through time and space in an ensemble of transient climate simulations. Bayesian statistical methods were used to combine these patterns of variability to generate 500 time-evolving climate fields that match reconstructed temperatures within their uncertainty. With this, we ran 500 simulations of the North American ice sheet evolution from 21,000 to 6,000 years ago with the Glimmer-CISM ice sheet model, where climate and ice sheet parameters were simultaneously varied. We designed a metric to assess how well our results match the reconstructed evolution of ice sheet extent (Dyke, 2004). In the first wave of simulations, a systematic cold bias in the interior of the continent lead to a delay in the deglaciation of Alberta. The input climate was updated to optimise the simulated ice extent and the process was repeated for two further waves of simulations which produced improved results.

This approach of running ensembles of simulations is crucial for understanding the response of ice sheets to past climate changes and the potential triggering of ice sheet instabilities, which lead to rapid sea level changes.

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Dynamical controls on the depth of the boundary between bottom and deep waters in the Last Glacial Maximum Atlantic

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Proxy measurements of ocean tracers at the Last Glacial Maximum (LGM, ca. 23-19 ka) suggest that the western Atlantic Ocean was filled dominantly by Antarctic Bottom Water (AABW), with a lesser role for North Atlantic Deep Water (NADW) relative to the modern. Proposed explanations for a shoaled NADW-AABW boundary (NAB) include changes in the strength and/or structure of the Atlantic meridional overturning circulation (AMOC), possibly driven by some combination of changes in surface buoyancy forcing, wind stress, and abyssal mixing. Given the complexity of the AMOC – which is incompletely understood in the modern ocean, let alone in the geologic past – it remains unclear which (if any) process is most important for setting NAB depth in the glacial Atlantic. Improving our knowledge of these dynamics is important for our understanding of the climate system, including possible abrupt climate changes, as changes in AABW volume could explain deglacial variations in carbon dioxide.

This work uses the adjoint capability of the MITgcm ocean model to infer how changes in wind stress, surface air temperature, and precipitation contribute to shoaling the equilibrium NAB position (defined as the depth of the 50% isopleth of a tracer released south of 60S) by 500 m in the western Atlantic Ocean between 45 S and 45 N. Integrating the model forward under inferred patterns of wind and buoyancy forcing changes illustrates dynamical pathways and time scales by which NAB position can be adjusted. We find that equatorial wind stress changes suggestive of a migration in the intertropical convergence zone lead to a reduction in deep western boundary current transport that in turn reduces the export of NADW and decreases the presence of associated water properties in the Atlantic basin. We also report on ongoing experiments investigating NAB sensitivity to changes at high northern and southern latitudes, including mediating effects from a fully coupled sea ice model.

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Portable OpenCL-based framework for climate model couplers using accelerators (GPUs and FPGAs)

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Couplers for large-scale simulations of climate systems have to satisfy a number of very stringent requirements in terms of flexibility (support of different grids/discretizations in each sub-model), accuracy (produce possibly few interpolation artifacts and guarantee the conservation of critical physical properties), and performance (be as light-weight as possible on shared and distributed memory computing systems).

In this work, we present our efforts towards porting OASIS3 to existing and emerging classes of compute accelerators (GPUs and FPGAs). To make our work as portable as possible, our implementation is based on the OpenCL framework, which allows the same code to run on multi-core CPUs, GPUs, FPGAs, and DSPs. The three main stages of our project include:

1) (Completed): several kernels were implemented and tested on GPUs and FPGAs emulating the compute-intensive interpolations between different model grids. These synthetic tests were performed in order to gain experience with the high-level synthesis (OpenCL-to-VHDL) tools for the FPGAs, and also to understand the optimization strategies applicable to the target architectures.
2) (Ongoing): the actual sparse matrix-vector multiplication kernels in the OASIS3 are being ported to OpenCL. The latest version of OASIS3 relies on the powerful MCT library, which was specifically designed for scalability in large MPI-jobs in mind. To port this code to the high-throughput hardware architectures found in compute-accelerators, we are currently investigating two possible strategies:
(a) replacing the operations on the SparseMatrix data-structure at each node with corresponding OpenCL kernels,
(b) replacing the entire MCT library with an OpenCL-based implementation of the interpolation step. We discuss the trade-offs corresponding to each approach, as well as the current results of the porting task.
3) (planning stage) running full MPI-ESM simulation on accelerated OASIS3 coupler.

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Development of a CESM-MEDUSA coupled model to simulate the impact of sediment diagenesis on climate

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A simulation of the history of the atmospheric carbon dioxide concentration (pCO2) during the last glacial cycle is one of the crucial tasks of the PalMod project. Since the marine carbon cycle plays a key role for the pCO2 variations at the glacial-interglacial time scale, we aim at coupling a sediment diagenesis model, which treats the dissolution/preservation of particulate matter formed by marine biogeochemical processes, with an ocean model. Consequently, the budget of calcium carbonate (CaCO3) in the ocean, thereby the chemical conditions (e.g., pH) of the entire ocean, can be modeled in a more realistic way. Besides that, the sediment model will act as a "bridge" between the ocean model and paleoceanographic data enabling direct comparison between them.

For the ocean model, we employ the Parallel Ocean Program version 2 (POP2), which is the ocean component of the Community Earth System Model (CESM), while for the sediment model, we use the Model of Early Diagenesis in the Upper Sediment A (MEDUSA). POP2 is configured to include marine biogeochemical processes (BEC; e.g., Lindsay et al. 2014) and a carbon isotope package (Jahn et al. 2015). Oxic and suboxic remineralization of organic matter as well as parameterized CaCO3 and opal dissolution in the upper sediments are modeled in MEDUSA.

Here we present results of our development and test runs with the POP2-MEDUSA coupled model. We evaluate the performance of the coupled model as follows: First, we compare the modeled physical/chemical ocean tracer fields with observations and with optimized model-ocean states (e.g., Kurahashi-Nakamura et al. 2017). Second, we can compare the sediment model results directly with data taken from upper sediments, such as global maps of weight fraction of calcium carbonate, organic matter and opal. It turns out that the sediment component provides another good measure of model performance.

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Deciphering climatic signals from lake sediments of the last glacial cycle

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The reconstruction of reliable paleo-climatic signals from terrestrial records is crucial for robust model-data comparisons of past climates on the continents. Lake sediments are ideal archives of continuous paleoclimatic information, due to their wide geographical distribution and good chronological control. However, lake sediments enclose paleoenvironmental information that originates from multiple lake external and internal forcing. The variety of environmental forcing factors can complicate direct identification of single mechanisms like climatic change from proxy records. Here, we present the joint effort of the PalMod "Paleodata compilation and synthesis" working group to generate a comprehensive data synthesis of lacustrine proxy-records of the last glacial cycle. Based on international metadata standards, we generated a relational data-base for paleolimnological information (PALIM) from existing proxy records. Due to the application of identical age-depth modelling routines, the data-base provides harmonized records with full quantification of chronological uncertainty.

A key to reconstruct reliable climate signals from lake sediments are response models of landscapes to climate change. Physical experiments and forward models of erosion and transport laws predict transient responses of sedimentary processes to changes in climatic boundary conditions. However, their influence on proxy records of terrestrial archives remains poorly understood. We developed an inverse modelling approach to identify transient landscape dynamics in diverging proxy-records from lakes in similar environmental conditions. The approach consists of sedimentary process identification via multivariate statistics of high-resolution geochemical data and the identification of generic dynamical system models under the assumption of common climatic forcing functions. We present successful applications in regional comparisons and discuss implications for the reconstruction of paleoclimatic signals from the continental sediment record.

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Addressing glacial cycle uncertainty of the Greenland Ice Sheet: model, constraints, initial results towards full Bayesian calibration

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Paleo ice sheet reconstructions without confident uncertainty bounds have limited value. For approaches based on glaciological models, such bounds require a model that adequately probes uncertainties in both climate and ice processes along with a methodology for using paleo-observations to constrain this probe. To date, paleo glaciological models of the Greenland ice sheet (GrIS) either do not specify uncertainty bounds or have low confidence in their derived bounds. This is due in good part to limited probing of model uncertainties and sole reliance on climate forcings based on glacial indices derived from GRIP or GISPII ice core records.

We describe the constraint data set (and welcome new data), error model for the data, and model setup in working towards a full Bayesian inversion of the last glacial cycle Greenland Ice Sheet Chronology. We use the 3D Glacial Systems Model with asynchronously coupled glacial isostatic adjustment (including a first order gravitational correction). The climate component is distinguished by a weighting of diverse climate representations, including a fully coupled "climate generator" that has no dependence on Greenland ice core records. Calibrated model parameters also account for uncertainties in ice calving and submarine melt, basal drag, deep geothermal heat flux, and earth viscosity structure.

The ongoing calibration is currently against relative sea level observations, constraints on ice extent from cosmogenic dates, and borehole temperature records from the Greenland ice core sites. Initial calibration results will be presented for the last glacial cycle with a focus max/min bounds.

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CLIMBER-X: a new Earth system model to explore climate-cryosphere-carbon cycle interactions

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We present CLIMBER-X, a newly developed comprehensive Earth System model of intermediate complexity designed to explore and understand climate-cryosphere-carbon cycle interactions on temporal scales ranging from centuries to glacial-interglacial cycles.
CLIMBER-X includes a frictional-geostrophic 3D ocean model (GOLDSTEIN), a sea ice model, a semi-empirical statistical-dynamical atmosphere model (SESAM), an ocean biogeochemistry model including sediments (HAMOCC), a land carbon cycle and dynamic vegetation model (PALADYN) which also comprises a dust emission model and a weathering model. All components are run on a horizontal resolution of 5x5°, except the atmosphere which runs on a 10x10° grid. The land-ocean mask is allowed to vary with changing sea level. CLIMBER-X also includes the thermomechanical ice sheet model SICOPOLIS, which is coupled via a physically based surface energy and mass balance interface (SEMI). An erosion and sediment transport module will be implemented in the model in the near future together with the 3D-viscoelastic lithosphere and mantle model VILMA.
CLIMBER-X is a cost-efficient model and allows to integrate ~10,000 years in one day using OpenMP parallelization with 16 CPUs.

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Individual Influence of Climate-Cryosphere Feedbacks on Northern Hemisphere Ice Sheet Mass Balance during the Last Deglaciation

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Feedbacks between the cryosphere and the overall climate system are the strongest internal regulating mechanisms of Earth's climate during the last deglaciation. In order to evaluate the relative influence of bi-directional feedbacks between the cryosphere and the climate, we employ a coupled ice-sheet climate simulation of a limited time period within the last deglaciation. By isolating each feedback component between the cryosphere and the climate system, namely radiation and energy fluxes linked to albedo due to retreating ice coverage, changes in the mass balance of the ocean due to freshwater release from the melting ice sheet, and changes in the atmospheric dynamics due to modifications of the ice sheet height, we aim to uncover the feedback to the ice sheet mass balance. We compare our results to a traditional climate simulation with prescribed ice sheets and freshwater fluxes, and additionally evaluate the differences due to the selected ice sheet mass balance scheme, where melting is either solved via a positive-degree-day method, or alternatively with a full surface mass balance simulation.

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The PALMOD marine paleoclimate data synthesis

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Paleoclimate data provide a unique opportunity investigate climate dynamics on time scales beyond decadal. Despite the wealth of paleoclimate data that has been collected over the past decades, paleoclimate data is often archived in a fragmented and non-standardised way, hampering making full use of the data. To address this, we are building a multi-proxy marine paleoclimate data synthesis based on sediment records spanning the last 130,000 years. To enable rigorous uncertainty analysis of the data we archive raw/measured data and rich metadata in a standardised format. Using a transparent, semi-automated workflow we compiled stable oxygen isotope data from benthic foraminifera, which serve as the stratigraphic backbone of our synthesis. In addition, when available, we compiled benthic foraminifera δ13C, radiocarbon, planktonic foraminifera stable isotopes, temperature proxies, and the major sediment constituents organic carbon, calcium carbonate and biogenic silica from the same sediment cores. The dataset presently contains approximately 350 sites and >1,200 unique time series that are fully standardised and searchable. More sites are being added.
Age models of the time series are based on radiocarbon and/or synchronisation of benthic δ18O time series to a common reference curve. Whereas radiocarbon dating provides a way to obtain absolute age models, uncertainties in reservoir ages remain. To better constrain these, we use simulated radiocarbon reservoir age from a comprehensive ocean circulation model and assess the effect of temporally and spatially varying reservoir ages on the timing and uncertainty of transient oceanic changes during Termination 1.
The PALMOD marine paleoclimate data synthesis will set new data standards in paleoclimate data archiving, serve to validate climate and biogeochemical model output and provide a valuable source of information to address questions that cannot be answered by analysing data in isolation.

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Recent trends in extreme weather: A model study

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We investigate the frequency and intensity of extreme weather events such as heavy precipitation or heat waves in a global atmosphere model run from 1982 to 2016 with observed surface conditions.
Results from the simulations allow us to study how extreme weather events have changed due to recent decadal warming.
We use a suite of model experiments with varying horizontal resolutions, which also allow us to determine how horizontal resolution impacts extreme events and their trends in atmosphere models.
Our main focus is on European extreme weather events, and in particular heavy precipitation events.

Our predictions of future climates largely rely on results from global climate models.
However, state-of-the-art climate models in the CMIP5 archive are unable to resolve the mesoscale (10-100 km) and will thus not capture e.g. tropical storms or intense precipitation events.
Studies suggest that most types of extreme weather events, e.g. heat waves, heavy precipitation, or Atlantic hurricanes, will become more intense during the 21st century due to surface warming.
Furthermore, the amplified surface warming in the Arctic can slow propagation of midlatitude Rossby waves and lead to more persistent extreme weather events over Europe.
It is thus imperative that we understand how extreme weather events are represented in atmosphere models and what errors arise from insufficient horizontal resolution.
We therefore run simulations with the global atmosphere model OpenIFS from ECMWF from 1982 to 2016 using observed sea surface temperatures and sea ice extent. We compare extreme weather events in simulations with spectral truncation of T255, T511 or T1023, which corresponds to 80 km, 40 km and 20 km horizontal resolution respectively. The vertical resolution is fixed with 91 levels.

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A stand-alone software toolbox for the collection, homogenization and visualization of marine proxy data

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We present a software tool that allows the efficient homogenization of large paleoclimatic data sets into consistent compilations and data products. The software combines a graphical user interface with a simple document-based database and functionality for documentation, stratigraphy, age modelling and semi-automatic data processing and extraction. Data can be imported from Excel or text files, are stored locally in netCDF format and can be easily exchanged between collaborating scientists. The stand-alone software will be available both for Windows and iOS and does not require web access. The current version has been designed for foraminiferal stable isotope data (both benthic and planktic foraminifera), but future versions will include functions for the management of other proxies.

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Representing ocean and sediment biogeochemistry under glacial variations of land-sea mask in MPI-ESM

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Glacial cycles are accompanied by pronounced sea level changes between glacials and interglacials. In particular, during the warming phase of the last glacial cycle, sea level rose by ~80 m due to the melting of ice sheets. The concomitant flooding turned land areas – with nutrient and carbon stored in land vegetation and soils – into continental shelves, exposed to erosion in the ocean. At the same time, sedimentation rates are generally high in shallow waters; that means the extension of the shallow shelf regions during deglaciation potentially increased the global sedimentation of organic and inorganic material. All these changes have effects on the uptake and storage of carbon in the ocean. In order to conduct transient simulations of the last glacial cycle and to quantify the contributions of different marine processes (such as the biological pump and calcium carbonate compensation) to the variations in atmospheric pCO_2, it is necessary to account for the effects of the shelf area expansion caused by sea level rise on ocean biogeochemistry.

We use the Max Planck Institute Earth System Model (MPI-ESM) which computes marine biogeochemistry including an interactive sediment module in the Hamburg Ocean Carbon Cycle model (HAMOCC). Until now, changes in the land-sea mask due to dynamic sea level changes have not been accounted for; the model uses a static land-sea distribution. Here, we extend the model to allow for consistent adjustment of marine carbon cycle state variables with dynamic land-sea distributions. In particular, the model is planned to capture the release of terrestrial carbon and nutrients to the ocean compartment during deglaciation. This novel development is essential for long-term ESM simulations on glacial time scales.

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Regional isotope-enabled simulations for the Arctic region

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The concentration ratio of the stable water isotopes H218O and H216O (δ18O) closely reflects the phase change history of atmospheric water and condensation temperatures. For this reason, δ18O in ice cores can be used for quantitatively evaluating paleo climate simulations of isotope-enabled general circulation and regional models. To allow an optimal comparison between the δ18O in ice core samples and simulations within PalMod, an isotope-enabled version of the regional climate model COSMO-CLM (CCLM) is used for a dynamical downscaling of the global simulations.

To this end, we implemented isotope physics into all relevant components of CCLM (atmosphere, TERRA ML – both in close cooperation with ETH Zurich –, ice sheets, and sea ice). To validate the isotope physics in CCLM, we compared present-day simulations for the Arctic region against an extensive set of isotope observations, including remote sensing observations, in situ measurements of near-surface water vapor, precipitation samples of the GNIP, campaign data from central Greenland, and top core samples from ice cores.

We find a good agreement with the different multi-platform isotope observations from the Artic region. In particular, the isotope-enabled CCLM is capable of capturing the observed spatial distribution of the δ18O of top core samples. The RMSE between the modeled and the observed δ18O of top core sample is only 1.7‰ (improvement compared to the RMSE obtained with the global ECHAM5.4-wiso: 3.6‰). The validation study confirms a reliable implementation of the most important isotope physics in CCLM.

Based on LGM simulations (PMIP 3) with the global ECHAM-wiso, we have performed regional paleo climate simulations for Greenland. We find good agreement between the modeled δ18O for LGM conditions and corresponding ice core samples (RMSE: 2.0‰). For the PMIP 3 LGM scenario, this points to a realistic model representation of climatic conditions in Greenland.

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Timescale Dependent Uncertainty for Paleoclimate Reconstructions: Models and Analytical Expressions for the Power Spectra of the Errors.

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Understanding the uncertainties associated with proxy-based reconstructions of past climate is critical if they are to be used to validate climate models and contribute to a comprehensive understanding of the climate system. Here we present two related and complementary approaches to quantifying proxy uncertainty.

The proxy forward model (PFM) "sedproxy" bitbucket.org/ecus/sedproxy numerically simulates the creation, archiving and observation of marine sediment archived proxies such as Mg/Ca in foraminiferal shells and the alkenone unsaturation index Uk'37. It includes the effects of bioturbation, bias due to seasonality in the rate of proxy creation, aliasing of the seasonal temperature cycle into lower frequencies, and error due to cleaning, processing and measurement of samples.

Numerical PFMs have the advantage of being very flexible, allowing many processes to be modelled and assessed for their importance. However, as more and more proxy-climate data become available, their use in advanced data products necessitates rapid estimates of uncertainties for both the raw reconstructions, and their smoothed/derived products, where individual measurements have been aggregated to coarser time scales or time-slices. To address this, we derive closed-form expressions for power spectral density of the various error sources. The power spectra describe both the magnitude and autocorrelation structure of the error, allowing timescale dependent proxy uncertainty to be estimated from a small number of parameters describing the nature of the proxy, and some simple assumptions about the variance of the true climate signal.

We demonstrate and compare both approaches for time-series of the last millennia, Holocene, and the deglaciation. While the numerical forward model can create pseudoproxy records driven by climate model simulations, the analytical model of proxy error allows for a comprehensive exploration of parameter space and mapping of climate signal re-constructability, conditional on the climate and sampling conditions.

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Massive Atlantic Mid-Depth Ocean Cooling and Thermocline Depth Shoaling during the Last Glacial Maximum

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Understanding the thermal structure of the Atlantic Ocean during major climate changes is of crucial importance to constrain the flow of energy from the surface into the oceans interior. Within the ocean, the effect of anthropogenic global warming is mostly traceable in the upper 700m of the water column and leads to a deepening of the thermocline. In this depth range cold-water corals represent a valuable paleo-archive. During the Last Glacial Maximum (LGM) a decrease in solar insolation and extension of polar ice sheets likely caused a cooling of the global ocean including a heat loss of the oceans interior, which was recently estimated to -2.57±0.24°C (Bereiter et al., Nature, 2017). This implies a shoaling of the thermocline. Eddy-resolving global ocean circulation models predict LGM to modern interior ocean temperature anomalies of 2-3°C and regionally even up to 7°C (annually and zonally averaged) (Ballarota et al., Climate of the Past, 2013).
Here, we present a compilation of temperature reconstructions based on Li//Mg ratios in aragonite skeletons of cold-water corals collected from 300-1000m water depths from northern and southern hemisphere regions throughout the Atlantic (62°N to 25°S) that were analysed over the last 5 years. The precisely U-series dated cold-water corals cover the past 35ka. Averaging over all sites reveals a thermocline temperature anomaly of roughly 5-7°C. North-east Atlantic sites exhibit mid-depth temperatures for the LGM close to 0°C implying maximal differences of more than 8°C in agreement with results by eddy resolving models (Ballarota et al., Climate of the Past, 2013). This strongly suggests a major shoaling of the thermocline. We suggest that the massive glacial cooling in depths of 300-1000m reflects dramatic changes in export of polar waters towards the Equator resulting in an enhanced thermal stratification.

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The role of vegetation and soil dynamics on the global carbon cycle during deglaciation

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Carbon storage in the terrestrial biosphere played an important role in the deglaciation phase from 21ka BP until present. During Last Glacial Maximum (LGM) atmospheric CO_2 concentration was almost 100 ppm lower than the pre-industrial concentration. Ciais et al., 2012 suggest that the terrestrial carbon storage in LGM was 330 PgC lower but a 700 PgC larger permafrost carbon than under pre-industrial conditions. Biomass differences are seemingly attached to vegetation distribution, but the contribution of soil carbon to terrestrial carbon storage are still uncertain. We provide a consistent model simulation with LPJmL, which includes dynamic vegetation, permafrost and wetland dynamics taking into account peatland accumulation. This allows us to estimate the terrestrial carbon storage and the distribution of wetlands during the LGM and the transition from LGM to pre-industrial conditions. We provide estimations of methane and CO_2 emissions during LGM and deglaciation and the change in
vegetation distribution. Furthermore we investigate the change in wetland and permafrost distribution to present a comprehensive picture of the LGM and the transition from LGM to pre-industrial conditions.

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Factors controlling atmospheric oxidative capacity and CH4 lifetime during the LGM

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In-depth interpretation of atmospheric methane (CH4) paleo records requires comprehensive estimates of the climate-driven variations of its sources and sinks. The former, being difficult to estimate even for the present day conditions, are by large of biogenic origin and typically require rather complex parameterisations in modelling approaches. The latter, in contrast, can be reckoned with somewhat greater certainty about basic principles defining the atmospheric oxidative capacity (AOC), because tropospheric CH4 is predominantly removed in reaction with hydroxyl radical (OH). In this study, we employ the comprehensive AC-GCM EMAC [1] for quantifying the contribution of different components of the climate system to the sensitivity of AOC changes between the present day (PD) and the Last Glacial Maximum (LGM, ~20ka BP). The LGM setup of the EMAC accounts for relevant changes to the climate forcing, atmosphere physical state, kinetic chemistry, photolysis rates and emissions of trace gases from the biosphere, biomass burning and lightning sources vs. that in the PD.

Our simulation results suggest that the AOC in the LGM is principally driven by the emissions of reactive nitrogen oxides from lightning (LNOX). The stark influence of LNOX on the OH buffering in the free troposphere is reduced by the anthropogenic emissions of reactive C and N compounds in the PD. We further evaluate the adequacy of LNOX source distributions resulting from different parameterisations available in EMAC. The most realistic ones suggest that convective activity shutdown (over the ice-covered high-latitude areas) and enhancement (over the enhanced continental areas in the tropics, foremost Oceania) in the LGM causes the migration of the LNOX source to the lower latitudes, however without a substantial loss of its strength. This results in tropospheric CH4 lifetimes comparable to that of preindustrial or PD (9–11 years) and hence a large reduction (a factor of 4–5 vs. PD) in the CH4 surface sources that should fit the observations in the LGM. We subsequently propose a set of parameters required for an efficient CH4 lifetime and OH distribution parameterisation suitable for models dealing with CH4-inclusive climate-scale (transient) simulations.

References

[1] Jöckel, P., et al.: Development cycle 2 of the Modular Earth Submodel System (MESSy2), Geosci. Model Dev., 3, 717–752, doi: 10.5194/gmd-3-717-2010, 2010.

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A recipe for producing pseudo-proxies for the last 21000 years

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Our knowledge about past climates depends on information from paleo-observations, i.e. proxies, and climate simulations. Comparing simulations and proxies requires approaches to bridge the gap between both and address their specific uncertainties. One way are so called pseudo-proxies. These in turn depend on an understanding of the uncertainties of the real proxies, i.e. the noise-characteristics disturbing and modifying the original environmental signal contained in the proxy archive. Here we provide a simple but flexible noise model for sedimentary climate proxies for temperature on millennial time-scales including, for one simulation, the pseudo-proxies themselves. The noise model considers the influence of other environmental variables, a dependence on the climate state, a bias due to changing seasonality, modifications of the archive (e.g., bioturbation), potential sampling variability, and a measurement error. The noise model should allow to develop new ways of comparing simulation data with proxies on long time-scales.

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Enabling adaptive mesh refinement for tracer transport in ECHAM6

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Paleo-climate simulations as carried out in the German PalMod project allow for relatively low resolution due to computational restrictions. Often this resolution is unable to represent important transport processes with sufficient accuracy. Since many of these processes (examples include dust transport, volcanic ash dispersion, etc.) are local in nature, local adaptive mesh refinement (AMR) can accommodate for the increased local resolution requirement without exhausting the computational resources.

In this study we present an approach that adds advanced data structures to an existing earth system model's atmospheric component, namely ECHAM6, in order to enable AMR for the transport scheme. Adopted from the original Flux-Form Semi-Lagrangian (FFSL) scheme in ECHAM6 the new numerical method is still mass conservative and allows large Courant numbers for efficiency. The data structure supports cell-based AMR and ensures compatibility with the overall ECHAM6 data layout.

The performance of the new scheme is demonstrated by idealized test cases that show similar convergence rates of the new AMR scheme and the original method. Furthermore, fewer grid cells are required to attain similar accuracy as on uniformly fine meshes.

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Assimilating Southern Hemisphere proxy records into a climate modelling framework

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The assimilation of palaeoclimate proxy records into climate modelling frameworks allows for the reconstruction of past climatic fields. By combining the real-world information recorded by the proxies with the dynamical information encoded within the models, data assimilation (DA) represents an integrated approach whereby climate modelling becomes part of the process of palaeoclimate reconstruction.

Here, the potential of DA is demonstrated by presenting an assimilation of Southern Hemisphere proxy records into a climate model. An offline approach is employed, whereby the model simulations are completed first and the assimilation is performed second. To generate a model ensemble, the CSIRO Mk3L climate model is used to simulate the evolution of the global climate from 801 to 2000 CE. A 50-member ensemble is generated by initialising the model from different years of a pre-industrial control simulation. The ensemble is then forced with best estimates of changes in the Earth's orbit, anthropogenic greenhouse gases, solar irradiance and volcanic eruptions.

The records chosen for assimilation are the temperature-sensitive Southern Hemisphere proxy records synthesised by the PAGES 2k Network. A cost function is defined and used to generate a weighted mean of the climate model ensemble, thereby using the proxy data to constrain the state of the model. The reconstruction generated through this process is shown to have greater skill than any of the individual ensemble members.

A distinct advantage of offline approaches towards DA, such as the one presented here, is that they can be applied to existing climate model ensembles. Thus DA can be performed without performing dedicated model simulations. Further work will extend the assimilation further back in time to span the Holocene. Preliminary results are presented using a three-member ensemble of simulations spanning the past 8,000 years, demonstrating the potential to implement DA over longer timescales.

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Role of relative polar ocean densities in determining equilibrium deep ocean circulation across a broad range of CO_2, orbital and ice sheet forcings

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Over the past few million years, the circulation of the deep ocean could have responded to changes in atmospheric CO_2 concentrations, Earth's orbital geometry and terrestrial ice sheet size through a daunting number of theoretical mechanisms. Here we assess many of these mechanisms according to the GFDL Earth system model, by applying forty different combinations of the three external forcings and integrating the model to equilibrium. We find that, despite myriad interacting factors, the volume contribution of Antarctic vs. North Atlantic polar waters to the deep ocean consistently scales with the relative density of Antarctic vs. North Atlantic deep water formation sites. The relative density of Antarctic water increases at low CO_2 and low obliquity as it becomes very salty, passes through a minimum near present CO_2, and increases under high CO_2 as North Atlantic waters become relatively warm. Meanwhile, a large Laurentide ice sheet steers atmospheric circulation so as to strengthen North Atlantic Deep Water formation and transport, but cools the Southern Ocean remotely, greatly enhancing Antarctic sea ice export and leading to very salty Antarctic waters. These changes are generally consistent with proxy reconstructions of late Cenozoic climates, and suggest that increasing sensitivity of the deep ocean to orbital forcing under low CO_2 contributed to the development of ice age cycles. However, the simulations do not reproduce reconstructed glacial Southern Ocean surface nitrate and deep ocean oxygen depletions, suggesting that unresolved aspects of ventilation and/or ecosystem processes may be critical elements of the ocean biogeochemical response.

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Towards High Resolution Climate Reconstruction Using an Off-line Data Assimilation and COSMO-CLM 5.00 Model

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Recent paleoclimate studies using data assimilation (DA) have mostly performed low or intermediate resolution global simulations. In an ``on-line'' paleo-data assimilation, the proxy time resolution is often too long for the dynamical models and the forecast state usually has no skill. For an ``off-line'' DA, the re-initialization cycle is completely removed after the assimilation step. We set-up two sets of experiments by using on-line and off-line DA strategies for parameter and state estimation. Set 1: We investigate the assimilation of tree-ring-width (TRW) chronologies into an atmospheric global climate model using ensemble Kalman filter (EnKF) techniques and a process-based tree-growth forward model as an observation operator. Our results, within a perfect-model experiment setting, indicate that the "online DA" approach did not outperform the "off-line" one, despite its considerable additional implementation complexity. Set 2: We conduct a set of offline DA experiments using a static EnKF and precomputed COSMO-CLM 5.00 simulations as the background. In order to test the approach, we first assimilate yearly pseudo observations into an ensemble of COSMO-CLM high resolution regional climate model (RCM) simulations over Europe, where the ensemble members slightly differ in boundary and initial conditions (by domain shifting of RCM model). We test the sensitivity of the DA method to the noise levels of pseudo-observations. The impact of the RCM's domain selection on the forecast skill is addressed. Finally, real seasonal observations of Holocen (pollen-based temperature reconstructions) are assimilated into the RCM time-slice simulations (6 different time-slices during the Holocene). For evaluation of the results, we use an independent reconstruction dataset. We conclude that for the paleoclimate studies the DA set-up is a promising tool for creating high resolution climate field reconstructions.

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The effect of obliquity-driven changes on paleoclimate sensitivity during the late Pleistocene

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Some studies suggest that specific equilibrium climate sensitivity S might be state-dependent. Reanalyzing existing paleodata of global mean surface temperature ΔTg and radiative forcing ΔR of CO_2 and land ice albedo for the last 800,000 years we show that this state-dependency of S is only found if ΔTg is based on reconstructions, and not when ΔTg is based on model simulations. Furthermore, during times of decreasing obliquity (periods of land-ice sheet growth and sea level fall) the multi-millennial component of reconstructed ΔTg is diverging from atmospheric CO_2, while in simulations both variables vary more synchronously. For a reconstruction-based extrapolation of S to the future we eliminate these periods due to an expected sea level rise. Consequently, S determined from proxy-based reconstructions without these data with strong ΔTg-CO_2 divergence is less statedependent or even constant (state-independent), and yields into an equilibrium warming for $2 \times CO_2$ of 1.9–3.8 K.

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Sensitivity of marine biogeochemistry dynamics to different glacial climate conditions in MPI-ESM

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Further insight into ocean carbon cycle during the last glacial maximum (LGM), especially in terms of marine carbon sequestration and release, is crucial for understanding mechanisms that cause the large glacial-interglacial variations in atmospheric CO2 concentration. First model results from the Hamburg Ocean Carbon Cycle model (HAMOCC), which is a component of the Max Planck Institute Earth System Model (MPI-ESM), show that the glacial marine biogeochemical dynamics are strongly influenced by the ocean physical conditions. The changes of marine biogeochemical conditions between LGM and pre-industrial show distinct patterns among ocean basins. These interbasin differences are caused by: 1) different mechanisms that govern biogeochemical processes and 2) the different response of the ocean physical conditions (e.g. AMOC) to climate in different basins. Yet, the state of the overturning circulation during the last glacial maximum (LGM) remains unconstrained, resulting in uncertainties in marine biogeochemistry dynamics.

We adjust HAMOCC to represent glacial ocean biogeochemical conditions. A specific focus here is on an advanced representation of stable carbon isotope 13C, which is essential for constraining the ventilation of the ocean by either northern- or southern-sourced deep water masses. We explicitly simulate 13C in all carbon pools, that is, dissolved inorganic carbon, calcium carbonate, phytoplankton, cyanobacteria, zooplankton, detritus and dissolved organics. Furthermore, we include temperature-dependent fractionation during air-sea exchange and the fractionation during photosynthesis that depends on water temperature and on the partial pressure of CO2 in water. To evaluate model performance, we apply the extended model to the pre-industrial state and compare modelled δ13C against observations.

To investigate the response of ocean biogeochemical dynamics to various climate and ocean physical conditions (circulation, temperature, etc.) during LGM, we carry out a number of simulations. First, we conduct one reference LGM run with glacial orbit, land-sea mask, topography, ice sheets and with a glacial atmospheric CO2 concentration of 190 ppm. Next, we carry out sensitivity experiments, which are driven by atmospheric CO2 concentration of 170, 150, 130 and 110 ppm, respectively. The motivation for such a sensitivity study is that previous simulations (without HAMOCC) suggest that in MPI-ESM, a relatively low atmospheric CO2 concentration (<190 ppm) is needed to produce an overturning state that agrees with the glacial state inferred from proxy data. Finally, we conduct an additional simulation, in which the ocean circulation model (MPIOM) is forced by a relatively low atmospheric CO2 concentration (<190 ppm) but HAMOCC “sees” an atmospheric CO2 concentration of 190 ppm. Model results concerning the above mentioned runs will be presented and discussed in the context of proxy data.

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Glacial CO_2 drawdown due to particle ballasting by aeolian dust: an estimate using the ocean carbon cycle model MPIOM/HAMOCC

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Particle ballasting refers to the acceleration of sinking organic soft tissue in the ocean by aggregation with denser particles such as calcite shells, opal shells, or mineral dust. The acceleration of organic soft tissue due to, for example, higher aeolian dust deposition rates, may have led to a more effective biological carbon pump during glacial periods compared to interglacial periods. Particle ballasting changes may thus have contributed to the variability of atmospheric CO_2 concentrations during glacial-interglacial cycles.

Here we quantify the effect of dust ballasting changes on the ocean-atmosphere CO_2 fluxes during the last glacial cycle using the Hamburg Ocean Carbon Cycle model HAMOCC. We introduce a new parameterisation of particle ballasting that accounts for the acceleration of the sinking of detritus by denser particles, including the effect of mineral dust. Sensitivity experiments with respect to glacial-interglacial aeolian dust deposition changes indicate that the acceleration of detritus by enhanced dust deposition during glacials played a small role, contributing about 5 ppmv to the reconstructed 90 ppmv drawdown of atmospheric CO_2 concentrations. Our results further suggest that the additional iron input associated with the increased dust deposition played a more important role, leading to a reduction of atmospheric pCO_2 by at least 8 ppmv, comparable to previous estimates of 10 to 30 ppmv.

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Modelled changes in the Si drawdown and the Si:N ratio in the glacial Southern Ocean, and their biogeochemical consequences

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Elevated Si:N drawdown and export ratios in the present-day Southern Ocean lead to a low Si:N ratio in the unused nutrients from the Southern Ocean that are transported to low latitudes via mode and intermediate waters. It has been hypothesised that iron fertilisation of the Southern Ocean in the last glacial has led to a lower Si:N drawdown ratio there and hence changed stoichiometry of nutrients in low latitudes, with consequences for phytoplankton community structure and carbon cycling. Here we investigate this hypothesis using a global biogeochemical model with variable stoichiometry in its two phytoplankton compartments. The model of of diatoms is based on simple assumptions on the regulation of silicon uptake and has been tuned to reproduce lab experiments with diatoms under different limitations. We show that the model reproduces the observed pattern of elevated Si:N drawdown in the present-day Southern Ocean. In the last glacial maximum the increased Si:N in diatoms decreases somewhat when iron limitation of the Southern Ocean is reduced strongly. This, and an overall reduction in Southern Ocean diatom production lead to an increase of silicate in AAIW, in most parts of the glacial ocean. AAIW Silicate is reduced strongly, however in the eastern equatoral Pacific, leading to a shift of decrease of diatoms production from the equatorial Pacific to the Atlantic, in agreement with several sediment cores. This also leads to an overall shift of silicate from the deep Pacific to the deep Atlantic. We discuss how this affects ocean carbon fluxes and storage. We also compare these changes to those driven by other glacial-interglacial changes that we seen in our model runs, such as an extended Southern Ocean sea-ice cover and a reduced overturning circulation.

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Simulating Termination 1 in the coupled climate—ice sheet model LOVECLIM/PSUIM

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Climate—ice sheet coupling processes, such as meltwater discharge and sea-level rise, can substantially modulate the global ocean circulation and climate. Here, we explore the role of such coupling mechanisms and their impact on the Atlantic meridional overturning circulation (AMOC) in transient simulations of Termination 1. The simulations are performed with the 3-dimensional climate model of intermediate complexity LOVECLIM coupled to the Pennsylvania State University ice model (PSUIM) in the Northern Hemisphere and Antarctica. LOVECLIM includes a parameterisation of the transport through the Bering Strait, which opened during Termination 1 due to sea level rise. Our simulations illustrate that the Bering Strait transport can stabilise the AMOC in periods of fast ice retreat and strong freshwater discharge.

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A particle filter method to estimate the state of the ocean during the Last Glacial Maximum

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Combining ocean general circulation models with proxy data via data assimilation (DA) is a powerful means to obtain more reliable estimates of the past ocean's state. The Last Glacial Maximum (19-23 ka BP, LGM) was a climatic state substantially different from today and the large-scale ocean circulation patterns during this time remain uncertain. At present, only a few attempts on using data assimilation to estimate the ocean's state during the LGM exist and it is unclear which data assimilation methods are suitable for this application where data is comparatively sparse and uncertain.

We present a new particle filter method that combines ensemble runs of an ocean general circulation model with (pseudo-) proxy data to estimate several parameters of the atmospheric forcing used to drive the model. The method is based on the Bayesian framework and explores the multidimensional probability density function (pdf) of the parameters in an efficient way, without the requirement of a Gaussian assumption, using a few iterations of model simulations and re-sampling steps. It yields an approximation of the pdf and therefore an estimate of the parameters and their uncertainties. The resulting model ensemble provides an estimate of the state of the global ocean and its uncertainty. We employ the MIT general circulation model (MITgcm) in a global configuration that uses a cubed-sphere grid with 192 x 32 horizontal grid cells and 15 vertical levels. A water-isotopes module incorporated in the model is used to simulate stable water isotopes such that global oxygen-isotope data from the whole water-column can be assimilated.

In the framework of PalMod this sub-project serves as benchmark for the application of DA methods to more complex and expensive models. The resulting estimates can aid in validating specific time slots within long transient runs performed within PalMod.

To validate the method we carried-out an experiment with pseudo-proxy data sampled at MARGO locations from a target model run. The method is capable of efficiently estimating 6 parameters (the mean air temperature and mean precipitation over the Atlantic, the Pacific and the Indian Ocean) and their uncertainties using less than 10 iterations. The Atlantic Meridional Overturning Circulation (AMOC) of our target run yields a maximum of 18.7 Sv which is successfully reconstructed in the experiment: We obtain 28 model simulations for which all parameters lay within one standard deviation of the estimated parameters, the respective max. AMOC values range from 18.2 to 19.1 Sv with a mean of 18.7 Sv. Pro's and con's of the particle filter method will be discussed.

We will apply the method to estimate the state of the global ocean during the LGM. To that end, we use the seasonal MARGO sea-surface temperature reconstruction and a global collection of oxygen-isotope data from benthic and planktonic foraminifera from different sources. We will present results from these experiments and discuss climatic implications of our findings.

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Reconstructing past changes in atmospheric circulation during the Holocene using a pollen-based gridded climate reconstruction

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Much of the spatial and temporal variability in surface temperatures in the extra-tropical latitudes of the Northern Hemisphere is closely associated with the atmospheric circulation, which in turn is associated with specific teleconnection modes. Understanding changes in these modes is critical to understanding and forecasting much of regional climate change, particularly in the mid-latitudes where the impacts are often largest. Here we use the spatial surface temperature fingerprint of these modes to reconstruct changes in atmospheric circulation throughout the Holocene based on a pollen-derived gridded and seasonally resolved temperature record for the Northern Hemisphere. This has allowed us to determine the changing role of the main teleconnections, as well as the possibility of non-stationarity in teleconnection patterns. We evaluate our findings through comparison with independent terrestrial and marine records thought sensitive to these modes, as well as against transient model simulations.

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Constructing a Bayesian model for spatio-temporal climate reconstructions of the last deglaciation

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Spatio-temporally resolved reconstructions of past climate are important to understand the large scale behavior of the climate system and the response to changes in forcings. Unfortunately, they are subject to large uncertainties, have to deal with a complex proxy-climate structure, and a physically reasonable interpolation between the sparse proxy observations is difficult. In theory, Bayesian hierarchical models (BHMs) are well-suited to deal with these problems.
We present a BHM to reconstruct the spatio-temporal temperature evolution during the last deglaciation on continental to hemispheric domains. The approach is inspired by the model of Tingley and Huybers (2010) for reconstructions of the common era, but we make several adjustments to deal with the different behavior during the last deglaciation compared to the common era. The focus is on centennial to millenial scale variations due to the low sampling resolution of available proxy data.

Our BHM is non-stationary in space and time and it can reconstruct gradual as well as abrupt climate changes. Gaussian Markov random field techniques are used for computational efficiency. Inference is performed using a Metropolis-within-Gibbs MCMC approach.
Pseudo-proxy experiments for Eurasia with the CCSM3 TraCE-21ka simulation of the last deglaciation (Liu et al. 2009) examine the reconstruction skill of the BHM.
Finally, we look at the physical interpretation of model parameters and deduce possible extensions to increase the physical consistency of the reconstructions and to include additional sources of information.

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Combining pollen records and climate simulations for spatial reconstructions of Asian climate

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Spatial reconstructions of past climate are important to compare the state of the climate under different forcing conditions. Pollen records can be used for local climate reconstructions, while equilibrium global climate simulations contain information about possible large scale structures given a set of external forcings. We present spatial reconstructions of Asian climate for the Mid Holocene (MH, 6K BP) and the Last Glacial Maximum (LGM, 21K BP) using a Bayesian framework that combines the strength of Pollen records and of climate simulations.

Our framework combines pollen-climate transfer functions with a spatial prior distribution that is computed from a set of climate simulations. The local climate reconstructions from the pollen network are performed with the well-known WA-PLS algorithm. To create the spatial prior distribution, we calculate a mixture of Gaussian distributions, where each mixture component corresponds to a different climate model taken from the PMIP3 database for the MH and LGM time slices. Our inference strategy uses analytical computations as well as a Metropolis coupled MCMC algorithm.

We include pollen records which cover large parts of China and Siberia. They were synthesized at the Alfred Wegener Institute. Previous analyses identified mean temperature of the warmest month (MTWA) and mean annual precipitation (Pann) as the most promising variables for climate reconstructions. Therefore, we choose these two variables for our reconstructions.
Our inference framework allows us to calculate a posterior probability distribution including a spatially dependent uncertainty structure, to compare the performance of different PMIP3 models given a set of pollen records, and to assess the skill of the reconstructions in different sub-regions using a cross-validation approach with proper score functions.

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Terrestrial CH4 emissions from LGM to preindustrial

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The time between last glacial maximum (LGM) and preindustrial (PI) is a highly interesting time with regard to atmospheric methane concentrations. Between LGM and 10 ka BP atmospheric CH4, as reconstructed from ice cores, nearly doubled, with very rapid concentration changes of about 200 ppb occurring during the Younger Dryas and Bolling Allerod transitions. Although atmospheric CH4 is nearly identical for 10 ka BP and PI, CH4 decreased by 15% between 10 ka and 5 ka BP, with a subsequent increase back to the PI concentration.

Terrestrial wetlands are the largest natural source of CH4, and we use a methane-enabled version of MPI-ESM, the Max Planck Institute Earth System Model, to investigate changes in terrestrial methane emissions from LGM to PI. We extended JSBACH, the MPI-ESM land surface component, with a TOPMODEL-based module determining wetland extent, as well as a methane production and transport model, modified from Riley et al. Modules for CH4 emissions from fire and termites are included as well. We initialise MPI-ESM for time slices at LGM, 15 ka BP, 10 ka BP, 5 ka BP, and PI, as well as 13 ka and 11.5 ka, with climate states derived from a transient model experiment from LGM to PI recently performed with MPI-ESM.

We will present wetland distributions and CH4 emission patterns for these periods in order to determine the factors leading to the reconstructed changes in atmospheric CH4.

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Dynamical sequence of ocean, atmosphere, and sea ice changes during an abrupt stadial-to-interstadial climate transition

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Marine Isotope Stage 3 (MIS3; ~ 60 ka to 30 ka BP) was punctuated by abrupt climate transitions between colder stadial and warmer interstadial climate conditions. The fluctuations are known as Dansgaard–Oeschger (D-O) events which are featured by a rapid warming from stadial to interstadial in a few decades as recorded by the Greenland ice cores.

In this work, using a state-of-the-art climate model, the Norwegian Earth System Model (NorESM) configured for paleoclimate simulations (two-degree atmosphere and one-degree ocean), we investigate the transient response of the climate system from a stadial to interstadial climate state. The stadial state is realised by applying freshwater flux to a MIS3 control simulation. With support from a high-resolution marine sediment core in the Nordic Seas (MD99-2284), we addressed the key role played by sea ice in modulating the Greenland temperature change during the transition, and identify a sequence of changes in the ocean and its interactions with sea ice and the atmosphere. We found that in agreement with proxy reconstructions, changes in the ocean (e.g. AMOC and heat/salt transport) precede deep convection and melting of sea ice in the Nordic Seas, with the latter process occurring simultaneously with rapid changes in Greenland temperature.

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Mineral Dust during the Last Glacial

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There are indications from ice cores that the deposition of mineral dust was twice as strong or even stronger at the Last Glacial Maximum (LGM) than at present. This is assumed to be due to a combination of changes in the vegetation cover and an altered atmospheric circulation with impacts on the wet deposition. Dust has several important effects in the Earth system. For example, airborne dust can affect the radiative budget directly and indirectly via change of cloud properties. Dust, when deposited on ice and snow may reduce the albedo and, thus, accelerate melting processes. Deposition over the oceans has a fertilizing effect and impact on the carbon cycle. Thus, it becomes clear that mineral dust is a necessary part of the numerical simulations of the last glacial cycle envisaged within the PalMod project.

The goal of PalMod is to simulate in its first phase the deglaciation starting from the LGM. The inclusion of dust and all its interactions in the Earth system model MPI-ESM is computationally very expensive. In order to resolve this challenge, we use the ECHAM6 atmospheric general circulation model, which is the core of MPI-ESM, coupled to the HAM aerosol model. In an initial approach dust shall be considered as a passive tracer which is emitted, transported and deposited and may affect the ice albedo. At a later stage, also the radiative effects of airborne dust shall be taken into account. Dust sources are determined interactively in the model based on land cover. Results from time slice simulations under LGM and pre-industrial conditions will be shown which allow for an assessment of the representation of the dust cycle in a cold climate.

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How do uncertainties in Earth structure and glaciation history affect sea-level reconstructions during the last deglaciation?

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Glacial isostatic adjustment (GIA) plays an important role for the reconstruction of relative sea level and paleo topography/bathymetry during the last glacial cycle. Regions temporarily covered by ice-sheets (e.g. Laurentide ice sheet, Fennoscandian ice sheet) adjust to the loading by vertical depression and corresponding sea-level change of several hundred meters. In the far-field, relative sea level change is dominated by ocean-volume change and by surface deformation to ocean load changes. Because this viscoelastic response of the Earth strongly depends on less constrained parameters in earth structure and glaciation history, the quantification of the corresponding uncertainties is essential for the overarching goal in PalMod to simulate the feedbacks between lithosphere, ice-sheets, ocean bathymetry and coastal environments. In a series of model simulations, key parameters of the earth's viscosity structure and the possible range of ice-sheet distributions are varied. The resulting variability in relative sea-level change is analyzed in a spatial temporal context. The simulations are performed in an uncoupled schema with different predefined loading scenarios and earth structures applying the global numerical model VILMA (VIscoelastic Lithosphere and MAntle). Using VILMA, the simulation of relative sea level change and paleo topography/bathymetry considers the conservation of mass between ice and ocean, geoid change due to mass reconfiguration, and change of ocean basin due to surface deformation.

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Modeling ice sheet – solid earth – climate interactions during deglaciation

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We study the interactions of ice sheets with the other components of the climate system in a new modeling system that encompasses a wide range of interactions between ice sheets, their mass balance, the solid Earth and the climate. Forcing the model with increasing greenhouse gas concentrations allows us to study the full interactions of the different climate system components and thus deepen our understanding of the processes relevant during deglaciation.

The system consists of the modified Parallel Ice Sheet Model (mPISM), the Viscoelastic Lithosphere and Mantle model (VILMA), and the Max Planck Institute Earth System Model (MPI-ESM). The surface mass balance of the ice sheets is computed with an energy balance model, shelf basal melt from temperature and salinity of the adjacent ocean. By applying VILMA, sea-level change due to ice loads is calculated considering surface deformation, eustasy and geoid change. In MPI-ESM, glaciers, topography, rivers, coastlines and bathymetry adapt to changes in ice sheets and topography. The model system is forced only with transient orbital parameters and greenhouse gas concentrations.

In our experiments, the retreating ice sheets leave behind vast periglacial lakes and marginal seas. Gigantic ice sheet surges into these basins lead to the formation of large ice shelves with low surface elevations causing strong melt. Where the basins are connected to the open ocean, basal melt and calving increase the ice loss at the shelves. Over time, the retarded sea-level response shrinks the periglacial basins again. This study presents first experiments that include the full range of interactions between ice sheets, solid Earth, atmosphere and ocean circulation.

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Effects of evolving topography and bathymetry during the last termination in a coupled climate model

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Running coupled climate models through a whole deglaciation is essential to understand the strong climate fluctuations occurring during that period of time. Here, we present results of the first set of Earth System Model
(ESM) simulations of the last deglaciation with continuously evolving topography, coastlines and bathymetry. Because ESMs are generally not constructed to deal with time varying topography, land-sea masks etc., this presents a strong technical and scientific challenge. At the same time, it is a crucial step towards fully coupled simulations with interactive ice sheets and solid earth.
Changes in topography strongly influenced the climate during deglaciation. Directly, the opening of passages, as well as changes in throughflow depth and width influence the exchange between different ocean basins.
The retreating ice sheets led to the flooding of vast shelf areas and freed the path for wind systems. Indirectly, small-scale changes in the surface topography could lead to drastically different river pathways, and could thus
change the locations of freshwater inputs from the decaying ice sheets, with strong consequences on ocean circulation and deep-water formation.
Here we present first results from a set of transient simulations with the coarse resolution version of the Max Planck Institute Earth System Model (MPI-ESM) forced with the ICE-6G reconstructions of ice sheets and topography. Our runs cover the period of time between 26 kyr BP and present day. Orography and glacier mask
for the atmosphere component, river pathways, land-sea mask, and ocean bathymetry are automatically updated
every 10 years. The simulations are designed to highlight each individual effect (e.g. ocean bathymetry, land-sea
mask, river routing). For the discussion of these effects, we also take advantage of a set of age and water mass tracers allowing to assess ventilation changes in the deep ocean as well as enabling comparison with deep sea proxy records.

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Volcanism and climate over the last glacial cycle

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Radiative forcing resulting from major explosive eruptions has been the dominant natural driver of past climate variability, at least over the past few hundred years. On glacial timescales, there is speculation that volcanic activity may play an important role in major climate transitions such as the last deglaciation and in Dansgaard-Oeschger and Heinrich events. Volcanic forcing has, however, largely been neglected in studies of climate variability on glacial timescales, due in large part to incomplete knowledge of the history of volcanism beyond the last 2500 years. Ice core volcanic sulfate records provide the information upon which most reconstructions of volcanic forcing are based, and could be used to reconstruct volcanic activity and radiative forcing for the Holocene (10ka BP - present)--work on this front is currently in progress. Extending reconstructions of the frequency and magnitudes of volcanic eruptions beyond the Holocene will however require synthesis of multiple lines of evidence, including ice cores, terrestrial, lacustrine, peat, and marine volcanic tephra records, and numerical models. In this presentation, we will advocate for the necessity of including volcanic forcing in the long-term climate models simulations, and show how the reconstruction and implementation of volcanic forcing in climate model simulations of the past glacial cycle could be readily achieved within phase 2 of PalMod.

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Towards a better understanding of coupling strategies by use of a prototypical 1D ocean-ice interaction

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In earth system models (ESM) a number of sub-components, like atmosphere, ocean, terrestial and cryospheric systems are coupled with each other. Most often these sub-systems communicate with each other by exchanging boundary values or fluxes at their interfaces. In many cases the communication intervals are relatively large due to the different time scales of the corresponding sub-components or simply due to computational cost considerations.

A rigorous mathematical analysis of the sensitivity of such coupling strategies on the overall system state (the solution of the system) is very difficult and to the author's knowledge has not yet been performed. In order to gain quantitative information on the effect of different coupling strategies - in particular coupling time scales and quantities, and convergence properties - a prototypical one-dimensional model of heat transfer between ice and ocean has been employed to test different coupling strategies. This „toy problem" can be solved semi-analytically for both phases simultaneously such that a system solution is available. Loose coupling by exchange of boundary values on long time intervals, tight coupling by overlap regions and iterative adjustments as well as higher order coupling by exchanging boundary values with higher order moments are compared to the system solution and show significant differences. As a preliminary conclusion, our study suggests to investigate currently used coupling strategies with more rigor and in particular for long term paleo-climate simulations.

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A study of glacial–interglacial variations of the marine stable carbon isotope record using a non-Redfield biogeochemical model

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We investigate glacial–interglacial variations in the marine stable carbon-isotope record applying the marine ecosystem and biogeochemistry model RECOM, which is forced with model output from fully coupled climate simulations. Different to most other marine biogeochemistry models, RECOM does not rely on fixed stoichiometric ratios of phytoplankton organic matter. Instead, the composition of phytoplankton organic matter is calculated as a response to light, temperature and nutrient supply, which allows for assessing potential stoichiometric shifts between the past and present. We consider carbon-isotopic fractionation of marine phytoplankton during photosynthesis, studying different biogenic fractionation parametrisations and their influence on model–data comparisons for the Last Glacial Maximum and the Holocene.

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Estimates of Deglacial Land Biosphere Carbon Stock Changes – A Model Sensitivity Study

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The sign and magnitude of deglacial changes in the land biosphere carbon stock (Δland) are uncertain. Estimates range from releases of 200-400 GtC (Zimov et al., 2006, Science; Zech et al., 2011, Climate of the Past) to uptakes as high as 1300 GtC over the deglacial period (Adams et al., 1990, Global and Planetary Change). Recent estimates locate Δland around an uptake of 300-400 GtC (Ciais et al., 2012, Nature Geoscience; Menviel et al., 2017, Paleoceanography). These studies invoke ocean δ13C measurements in an isotopic mass balance for the ocean, land, and atmosphere following earlier studies (e.g. Shackleton, 1977, in: The fate of Fossil Fuel CO2 in the Ocean). However, the exchange of carbon and isotopes with the geosphere through ocean-sediment interactions and weathering is neglected.
We quantify the impact of sediment/weathering fluxes on estimates of Δland using the Bern3D model by conducting pulse-release and deglacial ("LGM-PI") sensitivity experiments in combination with observational constraints.

In the pulse-release experiments, "land carbon" is removed instantaneously from the model atmosphere. Experiments are done in a "closed" and "open system" configuration, where either sediment/weathering fluxes are neglected or enabled. These experiments permit us to elucidate the response time scales and the influence of the weathering/sediment fluxes on the isotopic mass balance approach.
Initially, the δ13CO2 perturbation of the atmosphere is removed much faster than the CO2 perturbation itself as gross exchange with the ocean and land biosphere dilutes the isotopic signal. On multi-millennial to 100-kyr timescales, the 13C perturbation is removed by weathering/sediment exchanges. Over timescales such as the deglacial, sediment/weathering interactions further mitigate the isotopic perturbation, leading to an underestimation of the initial change by 20-30% when relying on a closed system assumption.

Many processes potentially affected past isotope evolution. For the LGM-PI sensitivity experiments, we apply in a factorial setting idealized changes in Δland, remineralization depth (oceanic org. C), CaCO3/org. C export ratio (oceanic alkalinity), wind stress forcing (circulation), and organic weathering rates on land (weathering/burial changes) in addition to standard LGM forcings (GHG, orbital, ice-sheet and albedo, coral reef regrowth, fresh water pulses). Observational and reconstructed δ13Catm, δ13CDIC, marine [CO32-], and atmospheric CO2 are used as targets for the results.
Response sensitivities from the factorial experiments are used to build simple substitute models. In a Monte-Carlo framework, combinations of the idealized forcings that match the targets within their uncertainties are sought. Promising combinations are checked and further investigated using the Bern3D model. This allows us to explore a large space of process combinations.

The data-constraint results clearly indicate that the land carbon stock increased over the deglacial, rendering suggestion of a larger land carbon stock at the LGM compared to the late Holocene very unlikely. Further, Δland seems to have been larger than 300-400 GtC when considering ocean-sediment interactions and observational and reconstructed constraints, possibly more in the range of 500 to 1000 GtC.

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Enhanced Greenland melting: Effect of mesoscale ocean dynamics on distribution, timing and impact

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Enhanced melting of the Greenland ice sheet during warm phases (interstadials) of the last glacial cycle is generally considered to have reduced the formation rate of deep water in the subpolar North Atlantic. The consequent and potentially strong weakening of the Atlantic meridional overturning circulation may explain the inevitable return to a cooler climate (stadial). The particular role of mesoscale eddies in distributing the meltwater and influencing timing and intensity of the meltwater impact is studied in a series of 100-year long experiments with a global coupled climate model.

Our model setup is part of the new Flexible Ocean and Climate Infrastructure (FOCI) at GEOMAR. The infrastructure is based on the atmosphere model ECHAM6 (grid T63L95) and the ocean-sea ice model NEMO/LIM2 (grid ORCA05.L46). While the global ocean grid with 0.5° spatial resolution necessitates the parameterization of mesoscale eddies, regional refinement of the North Atlantic between 30°N and 85°N by an ocean nest (VIKING10) of 0.1° resolution implemented within the global climate model enables the explicit simulation of eddies in subpolar latitudes.

We apply a step function of enhanced, spatially and seasonally varying Greenland runoff to the model, which enables us to measure the response time of the ocean and climate system to this instantaneous change and to derive the climate response functions (CRFs) associated with Greenland melting (Marshall et al., 2017, GMD). The enhanced runoff is derived from the data of Bamber et al. (2012, GRL), which we scaled to match an annual total freshwater flux of 0.05 Sv. This forcing is weaker than in past hosing experiments, which used a uniform forcing of 0.1 Sv or more, in order to tease out the role of ocean dynamics in the subpolar North Atlantic.

First results show that the prescribed Greenland meltwater flux is able to shut down deep convection in the Labrador Sea within 5 years in the coarse resolution model using eddy parameterization. In contrast, deep convection persists much longer in the eddying simulation with the 0.1° ocean nest weakening over several decades. This hints at the possibility of a too rapid response to Greenland melting in coarse resolution climate models. We discuss the effect of parameterization choices regarding eddy transport, diffusivity and viscosity on the quality of the coarse resolution model results.

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Probabilistic spatial reconstruction constrained by physically motivated fields

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Climate reconstructions are usually performed using proxy data such as plant pollen that are only valid locally in space and time. However, the reconstructions exhibit errors that complicate spatial interpolation between locations. Using prior knowledge from a General Circulation Model (GCM) we define a dynamical stochastic process to estimate dominant spatial structures on global or regional scale. These physically motivated structures are used to constrain and interpolate the sparse proxy information using data assimilation. We estimate the expected state as well as the uncertainties in form of the error covariance matrix. This permits the combined estimation of e.g. summer and winter temperatures in space including an assessment of the uncertainties.

Further, the method requires the inverse covariance matrix, which can potentially be retrieved in a novel approach directly from the stochastic process without inversion of a large matrix. The approach allows to incorporate different types of information such as continental and marine proxies as well as to perform quality control of the input data. Within a Bayesian Hierarchical Model (BHM) it is further possible to identify the contributions of different sources of errors. The resulting probability density can finally be used to sample full climate fields for verification of GCM as well as generating initial conditions.

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Addressing the challenges of capturing the present day transient state of the Antarctic Ice Sheet by ice flow modelling

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Ice sheets constitute the largest and most uncertain potential source of future sea-level rise. The quality of predicted future sea-level contributions from ice sheets based on flow modelling strongly depends on how well the models are able to represent the present-day state of the ice sheets. Previous and ongoing model intercomparison efforts (e.g. SeaRISE and ISMIP6) have identified large uncertainties in sea-level projections based on model initialization and spinup.

Here we use the Parallel Ice Sheet Model (PISM v0.7.3) to perform spinup simulations for the Antarctic Ice Sheet consisting of an equilibrium spinup with steady present-day climate forcing and a paleo-climate spinup configuration for ice sheet initialization. The paleo spinup starting at 220 ka BP utilizes a glacial index approach (ice core data) combined with GCM-time slice climate anomalies (atmosphere and ocean) for the Last Interglacial and the Last Glacial Maximum to generate time dependent and spatially variable climate forcing fields during the model run.

We compare the simulated ice geometry, ice discharge and surface speeds with observations for both spinup configurations. We further asses to what extent our paleo model spinup is able to reproduce observed changes in the model climate forcing (e.g. surface mass balance) as well as in the model response (e.g. surface elevation, grounding line position) for the recent past on millennial to decadal time scales.

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Regional COSMO-CLM simulations for present day and LGM climate conditions in Greenland

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Global climate simulations are not able to resolve the accumulation and ablation of ice sheets over steep topography gradients adequately. Within the PalMod project, we aim to develop parameterisations to account for the effects of such unresolved scales and to optimize existing parameterisations. Simulations with the non-hydrostatic regional climate model COSMO-CLM allow estimating mesoscale effects on the ice sheet surface mass balance, i.e. accumulation and melting of ice sheets.

We adapted and set up COSMO-CLM for simulations of the present day Greenland ice sheet. The model is driven with reanalysis data from the European Centre for Medium-Range Weather Forecast (ECMWF) Interim Reanalysis (ERA-Interim) with a horizontal resolution of 0.7° on 60 vertical levels. An optimized model set up was identified by validation of the results with an ensemble of observations and gridded reanalysis datasets for the period 1995-2015. This optimized model uses the CORDEX-Arctic region as modeling domain on 0.22° and includes sea ice. Results show that the mean of precipitation and temperature generally agree well with observation data although biases are present, depending on the region and season. We obtain a realistic surface mass balance, although melting is still slightly too high in summer. The application of 40 years present day MPI-ESM GCM data to the optimized model also shows a realistic pattern of the Greenland surface mass balance as well as realistic magnitudes.

For the application of LGM data, we need to further adapt the model setup. For example changes in the orography and atmosphere conditions like the CO_2-concentration are necessary. Results of short simulations with LGM conditions show also a plausible surface mass balance over the Laurentide ice sheet. In a next step long-term climate simulations of LGM conditions will be performed. Furthermore, surface exchanges contributing to the Greenland surface mass balance will be analysed and parameterisations will be developed.

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Simulated abrupt climate change during Bolling-Allerod under continuous glacial meltwater

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During the last deglaciation, a major global warming was punctuated by several abrupt climate changes, likely related to Atlantic Meridional Overturning Curculation (AMOC). A transient simulation from the Last Glacial Maximum (21,000 years ago) to Bolling-Allerod (BA, 14,000 years ago) is conducted using an atmosphere-ocean coupled general circulation model. Changing insolation, greenhouse gas concentrations and glacial meltwater fluxes are applied based on reconstructions. An abrupt recovery of the AMOC occurred at around the period of BA, even under the glacial meltwater flux that is equivalent to a sea level rise of approximately 5 meters in 1,000 years. The simulated transition of Greenland climate occurs in approximately 100 years, which is consistent with reconstructions. The results indicate that the increasing summer insolation and greenhouse gas concentration could trigger an abrupt recovery of the AMOC without large fluctuations of glacial meltwater flux in the North Atlantic.

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Applying sea-level indicators to validate reconstructions of relative sea level during the last glacial termination phase

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Observations of sea-level variations allow the validation of numerical models used to reconstruct past and predict future sea-level change. Sea-level indicators (SLIs) are used as the main source for deriving relative sea level (RSL) variations during previous epochs for which tide-gauge and satellite measurements were yet not available. However, the levelling of an SLI relative to present sea level does not provide a direct measure of former RSL, but only an indication according to the conditions under which the sample was deposited. This information depends on the sample type and on its environment and has to be mapped to RSL by an appropriate transfer function. The respective data has to be extracted by an objective procedure from primary information usually provided in geological or palaeontological literature of different primary focus, quality and detailedness. In addition to the height information, also the precision of dating varies between different indicators and in case of radiocarbon-dated material, a further calibration of the dated age has to be applied.

In order to improve the reliability of the sea level indicators for sea-level reconstructions, the visualization framework SLIVISU is developed at GFZ-Potsdam. It allows access to a relational database system that contains compilations of sea level indicators obtained from the literature where the respective meta information is stored. First, likelihood functions are derived incorporating the indicative meaning as available error information in order to evaluate model-based sea-level predictions against the respective SLI. Then the radiocarbon dated material is calibrated considering information from the sample's metadata.This procedure is accompanied by applying the visual analytic tool SLIVISU.

Depending on the statistical significance, the analysed SLIs will serve as validation data for the viscoelastic lithosphere and mantle model VILMA. The VILMA model is currently part of the German Paleo-Climate Modelling Initiative PalMod (https://www.palmod.de/en), serving as the solid-earth response in the earth-system models applied in this initiative. This study contributes to the validation of SLIs as proxy data for sea-level reconstructions during the last glacial cycle.

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Modelling the Collapse of the British-Irish Ice Sheet: the role of climate and sea-level changes

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The pattern and timing of retreat of the last British Irish Ice Sheet has been constrained in more detail than any other palaeo ice sheet, thanks to the efforts of the ongoing BRITICE-CHRONO project. We are modelling the climate-ice sheet interaction in two contrasting catchments of the British Irish Ice Sheet. By combining the glacial geomorphology and Quaternary geology data with numerical modelling, we test the mechanisms and processes of ice sheet advance and retreat during the last glacial period.

We use BISICLES, an ice sheet model capable of accurately and efficiently simulating marine ice sheets, to simulate two sectors of the ice sheet. For the Minch Palaeo Ice Stream, we simulated an instability in ice stream retreat beginning at a point where bathymetry deepens and bed friction increases. This suggests that the process of marine ice sheet instability played a role in the timing and retreat dynamics of the Minch ice stream during the last deglaciation. For the Western Ireland sector of the ice sheet, the dynamics of retreat have been tested with an ensemble of experiments, highlighting the importance of the uncertainty in climate inputs. Across the entire ice sheet simulations show the importance of climate not only in driving overall change, but also triggering internal instabilities within the ice sheet.

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Modeling of water stable isotopes in the fully coupled Earth system model MPI-ESM: current status and perspectives

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The hydrological cycle is a fundamental component of the Earth's climate system. Modeling the time response of this cycle and the implied physical processes challenges the general circulation models (GCM) used to study the climate system and to project future climate. Water stable isotopes (H216O, H218O and HD16O) are integrated tracers of climate processes occurring in various branches of the hydrological cycle. Changes of the isotopic composition, which can be measured in various natural climate archives, have been used, for example, to reconstruct past temperatures changes at high resolution or to study the past dynamics of the monsoon. The explicit modeling of these isotopes in GCMs allows to evaluate their performance and to study the past and present-day hydrological cycle evolutions.

We present here the first results, under present-day and Last Glacial Maximum (LGM) conditions, of the ongoing implementation of water stable isotopes in the fully coupled Earth system model MPI-ESM, called hereafter MPI-ESM-wiso. It includes the atmospheric model ECHAM6, the dynamic vegetation module JSBACH and the ocean/sea-ice module MPIOM. In addition to classical variables (temperatures, precipitation amount…), we evaluate the isotopic composition of precipitation, water vapor, ocean, etc. simulated by MPI-ESM-wiso against available observations. Our analyses concentrate also on a detailed comparison to the previous model release, COSMOS-wiso [1], and potential improvements in simulating the water stable isotopes signal (spatial variability, link with the local temperature…) due to overall model enhancements.

This work will be an important contribution to the Paleoclimate Modelling Intercomparison Project. Indeed, the models with an explicit water stable isotope diagnostics make it possible to perform direct comparisons, at different time periods, with environmental records and to reduce the uncertainties resulting from the interpretation of these records in terms of climate signals in model-data comparisons. The project is part of the PalMod initiative ("Paleo Modelling: A national paleo climate modelling initiative"), funded by the German Federal Ministry of Education and Science (BMBF).

[1] Werner et al., 2016, Geosci. Model Dev., 9, 647-670.

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Climate variability patterns from synoptic to orbital time scales

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Over the past million years, marine, polar ice core and terrestrial records all highlight the sudden and dramatic nature of glacial terminations, the shifts in global climate that occurred as the world passed from dominantly glacial to interglacial conditions. These climate transitions provide the most compelling evidence available in the climate record for the role of greenhouse gases and feedbacks as non-linear amplifiers in the climate system. It is such evidence of the dramatic effect of non-linear feedbacks that shows relatively minor changes in climatic forcing may lead to abrupt climate response.

In order to evaluate the climate responses on orbital timescales, long-term numerical experiments using the Earth System models COSMOS and CLIMBER with varying orbital parameters are performed. Our model shows a polar amplification of the orbital forcing. In the frequency domain, significant temperature and precipitation variability at mid-latitudes are dominated by precession, high latitudes by obliquity. The precessional response is related to nonlinearities and/or seasonal biases in the climate system. The wind-driven ocean circulation is dominated by obliquity (more a linear response), whereas the large-scale Atlantic Meridional Overturning Circulation (AMOC) show pronounced precessional (20 kyr) and obliquity (40 kyr) peaks due to nonlinearities and a winter bias. Our model integrations and analysis confirm that convection and deep-water formation serves to rectify the zero annual-mean precessional forcing, resulting in 20 kyr energy in the ocean.

One major objective of PalMod is to investigate the spatio-temporal pattern of temperature changes as derived from integrations with comprehensive global climate models. Past time periods provide the means for evaluating the performance of general circulation models for glacial and interglacial periods. One key finding is that the models do not capture the magnitude of the sea surface temperature (SST) anomalies derived from marine proxy records for interglacials. The model-data differences on long time scales suggest that mechanisms leading to long-term feedbacks are not well represented in current climate models. We show that the underestimated regional responses can be partly reconciled by the initial condition, missing resolution and the representation of the eddy kinetic energy cascade in ocean circulation models affecting the local variance in SST. As another factor affecting variability, we identify the feedback of atmospheric circulation on synoptic time scales with long-term variations of sea ice and AMOC. Finally, high-resolution Greenland ice core data reveal that such pattern show pronounced natural variability on decadal to millennial timescales.

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The impact of model physical circulation state on marine biogeochemical parameter optimisation in an intermediate-complexity climate model

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Automated calibration of marine biogeochemical models is a powerful tool for understanding their limitations. We present results from a 9-member test of the University of Victoria Earth System Climate Model in which identical biogeochemical parameter calibrations are conducted using varied physical model configurations. Vertical mixing coefficients of the 9 members are tuned to produce maximum northern hemisphere meridional overturning strength within a 95% confidence interval with respect to observations. Low (15 Sv), medium (17.5 Sv), and high (20 Sv) overturning strengths are used in three vertical mixing schemes (Bryan-Lewis, constant vertical mixing, and tidal mixing). Results from the calibrations (the parameter values and associated misfits with respect to gridded observations) are compared.

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Satellite Study of Cryosphere-Climate Interactions Through The Correlation of Ocean-atmosphere-cryosphere interactions with Climate Variability, Sea-level Variability Mechanism , Sub-Mesoscale Dynamics To Develop Cryosphere Climate Predicting Models (CCPM).

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There are places on Earth that are so cold that water is frozen solid. These areas of snow or ice compose the cryosphere. The term "cryosphere" comes from the Greek word, "krios," which means cold e.g. Greenland and Antarctica
Lately (Feb'17), Researchers in University of Washington ,USA & University of Edinburgh found that the pools underneath the glacier, Thwaites, are draining out at an unprecedented rate and emptying themselves. Thwaites, which is on the edge of West Antarctica, Amundsen Sea is 4000m thick and is considered key to making projections of global sea level rise. The study finds four interconnected lakes drained in the eight months from June 2013-Jan'2014 with the increased speed by 10% of the glacier melting. This unstoppably melting of the glacier into the ocean mainly because of warmer seawater lapping at its underside.
Prof. Peter Clark, OSU attributed that the Glacier retreat was due to rising levels of Carbon Dioxide and other GHG, as opposed to other types of forces. If, this continues then the most of Glaciers would disappear in the next few centuries & the Glaciers loss in future will contributing to rising sea levels & environmental pollution. This ocean- atmosphere-cryosphere (OAC) interaction is more evident over the Antarctic & Southern Ocean region resulting the significant changes in Climate parameters. Its also evident on North pole as the temp raised above freezing point on 20 Dec'15.(Canadian Scientist 01/01/2016-HT)
Hence, efforts art on Co-evolution of climate and life in the Antarctic & Southern Ocean through Correlation of Ocean-atmosphere-cryosphere interactions with Climate Variability & to evaluate correlation between the rise of GHG level , rising of sea level, retreat ,melting of the glaciers, vis-à-vis climate variability.
Next, how can these be controlled through chemical processes e.g. creating the Temperature Absorption Sinks (TAS) to control unstoppably melting of the glaciers into the ocean mainly because of warmer seawater lapping at its underside & Carbon Absorption Sinks (CAS),GHG Detoxifiers to check the rising levels of Carbon Dioxide and other GHG as well as to develop Cryosphere Climate Predicting Models (CCPM).
Also, an attempt would be made through (CCPM). to study the Correlation of Antarctic- Southern Ocean Regional Ocean-Atmospheric-cryosphere (OAC) Variability Mechanism , Sub-Mesoscale Dynamics & its impact on ,Climate Variability. Antarctic- Southern Ocean regional Variability of the Sub-Mesoscale Dynamics study includes to examine satellite imageries with emphasis on the large scale kinematic and thermodynamic behavior of selected mesoscale convective systems.
The kinematic features of the mesoscale convective systems over Antarctic- Southern Ocean regions would be correlated with ocean-atmosphere-cryosphere variability on time & Space Scales; at the local, regional and global levels through the extracted Sea Surface Temperature (SSTs) over the grid box , attributing the regional change to natural and anthropogenic radiative forcing agents & to bring out a few optimum values of these to develop (OAC – CCPM)

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Comparing the Response of Ocean and Climate Models to Freshwater Fingerprints and Hosing

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In paleoclimate simulations, glacial runoff is usually injected as freshwater in large bands across the North Atlantic. However, results from Condron and Winsor (2012) demonstrate that the distribution of glacial runoff in the open ocean (ie. beyond the Western Boundary Current) disagrees with the commonly used hosing regions. Furthermore, using realistic glacial discharge routing for injecting glacial runoff into non-eddy permitting ocean models introduces biases due to unresolved eddies and coastal boundary currents. We address these issues through use of novel freshwater fingerprint products and use the Bolling Allerod(BA)-Younger Dryas(YD) transition as a case study. Traditionally the BA-YD transition is considered to have been initiated by re-routing of glacial runoff due to deglaciation (Broecker et. al, 1989). The BA-YD transition has been modelled extensively across a range of Earth system models varying in complexity. In these experiments freshwater injection generally resulting in cooling across the Northern hemisphere due to reduced northward heat transport and overturning circulation.

Condron and Winsor's study uses an eddy permitting model configuration for a Last Glacial Maximum (LGM) background climate with associated changes to land-sea mask and model bathymetry. We use this configuration, along the Community Earth System Model (CESM), to explore the biases surrounding the use of the traditional freshwater hosing regions. We compare the responses of each of these models to freshwater injection using the traditional freshwater hosing region to freshwater fingerprints generated using the eddy permitting glacial ocean model. We seek to quantify these models biases (eg. northward heat transport and overturning) and overall climate associated with glacial runoff injection in models too coarse to resolve small features such as eddies and boundary currents.

Broecker, W.S., et. al., Routing of meltwater from the Laurentide Ice Sheet during the Younger Dryas cold episode. Nature, 341 (6240), 318–321, 1989
Condron, A., Winsor, P., Meltwater routing and the younger dryas. 109(49):1992819933, doi:10.1073/pnas.1207381109, 2012

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ENSO sensitivity in an ensemble of transient simulations over the last 408,000 years

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The El Niño–Southern Oscillation (ENSO) is the largest source of interannual climate variability on our planet. ENSO has undergone substantial changes throughout the Holocene with periods of weak and strong activity alternating on multidecadal to centennial timescales. There is also mounting evidence from paleo-proxy reconstructions of ENSO for a period of reduced ENSO variance about 3,000 – 5,000 years ago. The extent to which this modulation can be attributed to orbital forcing or arises from internal dynamics still remains elusive.
To further explore the response of the ENSO system to external forcings, we employ a novel transient ensemble modeling approach covering the orbital forcing of the past 408,000 years. Using an ensemble of orbitally accelerated transient simulations conducted with the Community Earth System Model (CESM), we study systematically, how and why ENSO's amplitude changes on orbital timescales. As orbital forcing essentially modulates the seasonal cycle of incoming solar insolation, we focus our analysis on the interaction between the simulated ENSO modes (Central Pacific and Eastern Pacific ENSO) and the seasonal cycle. Furthermore, we will quantify the stability of ENSO's teleconnections to other areas relative to the orbital configuration using the Combination Mode framework. This analysis will be relevant to assess the fidelity of remote ENSO proxies (such as fossil corals from Papua New Guinea) to record changes in ENSO's SST variance.

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Development of the central European landscape in response to North Atlantic SST and global atmospheric CO2 change during MIS3 (60.000 – 27.000 BP)

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The organic carbon content in a lake sediment core from the dry maar of Auel (Eifel Germany) reveals the identical succession of warm MIS3 interstadials as known from the North Atlantic and Greenland temperature time series. Each cold stadial of MIS3 was characterized by dust activity, which was inactive during the interstadial phases. This patterns indicates a primary influence from the North Atlantic SST on the central European weather and general aridity/humidity changes during the entire MIS3.
Pollen and botanical macroremains in the maar lake sediments are used to reconstruct the vegetation of the Eifel during MIS3. The summer insolation maximum of the early MIS3 is marked by a spruce forest with abundant thermophilous trees. The subsequent time from 49 000 – 27 000 BP is marked by stepwise changes of the landscape from the early MIS3 spruce forest to boreal forest, steppe, tundra and polar desert, which is characterized by absence of all vegetation but reveals annual dust storms after 23 000 BP. The four transitions between these landscape zones are coincident with the MIS3 maxima in global atmospheric CO_2 gas content. Apparently, the central European landscape reaches a new equilibrium with every step in the decline of the global CO_2 content.

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Deglacial North Pacific deep-ocean stratification dynamically coupled with enhanced intermediate water formation

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The millennial-scale history of CO_2 releases during the last deglaciation from either Northern or Southern Pacific abyssal waters remains enigmatic. This is due to conflicting indications about subarctic Pacific physical ventilation changes based on various marine proxies, especially for the cold Heinrich Stadial 1 (HS-1). Here, we use a complex Earth System Model to discuss deglacial North Pacific circulation changes in response to Atlantic meltwater events, and the resulting control on Pacific intermediate-to-deep ocean stratification. Our modelling results show a stronger and deepened North Pacific Intermediate Water (NPIW) formation during HS-1, controlled by a weakened surface halocline compared to the Last Glacial Maximum (LGM), with a comparable, yet extremely cold surface ocean in winter. Together with available paleoceanographic evidences, our results indicate a less saline and thus less dense NPIW, corresponding to a larger convection of freshwater from surface to intermediate depths. As a consequence, the intermediate-to-deep Pacific ocean stratification strengthens during HS-1. Such enhanced separation largely precludes potential release of North Pacific abyssal CO_2 during HS-1-type meltwater events, fostering instead the prolonged preservation of an isolated deep oceanic carbon pool that was ultimately released either in other oceanic regions, or at a later deglacial phase.

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Mid to late Holocene tropical climate trend and variability from a multi-complexity ensemble simulations

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The Holocene is characterized by long term changes in seasonality induced by insolation that has altered monsoon and ENSO characteristics. How different feedbacks from the surface hydrology, vegetation or dust have shaped these tropical climate characteristics is not well understood. We consider a multi-complexity ensemble of mid to late Holocene simulations with the IPSL Earth System model that allows testing soil hydrology, dynamical vegetation, dust, and land-sea closure of the fresh water flux. Considering this ensemble we'll discuss common long term Holocene characteristics in the tropics. A particular focus will be put on the relationship between trend and variability in Indian and African monsoon regions, as well as on teleconnections between the precipitation in these regions and the long term evolution of the ENSO phenomenon in the Pacific. The analyses will also emphasize vegetation changes and their possible amplification role in the timing of the southward shift of monsoon precipitation over Africa and India. Limitations will also be discussed from the differences between the simulations and comparisons with various climate reconstructions.

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Synthesis of dust records, vegetation reconstructions and speleothem growth for eight key areas of the global climate system during the last 60 000 years

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Published literature on the dust content in terrestrial and marine sediment cores is synchronized with terrestrial and marine pollen data and speleothem growth phases on a common time scale for eight selected key areas of the global climate system during the last 60 000 years. Records have different time resolution and are dated by different methods, but still are brought to a synthesis for each of the regions. All regions shows speleothem growth during the early MIS3, sometimes continued into the middle MIS3, but sometimes confined to interstadial times only. Dust is common during the entire MIS2, but dust deflation in some regions start in the middle MIS3. It is not always apparent if the dust deflation is confined to stadial phases only, because the time resolution is often not sufficient to resolve the stadial/interstadial phases precisely. A major problem for the middle and early MIS3 are the limitations of 14C dating. Finally, we detect only three regions where a MIS3 synthesis of dust, vegetation and spelothem growth results in coherent pattern. These regions are central America, central Europe and central Asia.

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Part 2. Taming ice sheets in coupled ice sheet-climate simulations: Towards realistic transient response of the coupled system

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The wide range of response time scales of the atmosphere, ocean and ice sheets poses a major challenge for coupled ice sheet-climate simulations over a full glacial-interglacial cycle. Previous modeling studies of the climate states during the Last Glacial Maximum (LGM) and other periods of the last glacial cycle have demonstrated that even moderate changes in ice-sheet geometries may lead to strong and rapid responses in the atmospheric and ocean circulations. In contrast, the dynamics and geometries of continental ice sheets at any moment are an integrated result of previous states of climate and ice sheets themselves spanning multi-millennial time scales. Although ice-sheet margins respond rapidly to changing ocean and atmosphere, these changes propagate into the continental ice-sheet sectors in a highly heterogeneous manner, both in time and space, and typically with a delay on the order of `10^2 - 10^3` years. The modeling challenge associated with the range of time scales comes together with a poor performance of ice-sheet models with respect to processes that govern marginal ice-sheet dynamics and a lack of reliable constraints on past ice-sheet configurations. While a growing data set based on glacial geomorphology and geochronology documents ice-sheet extents since the LGM, our knowledge of 3-dimensional ice-sheet geometries, especially for pre-LGM ice sheet states, remains elusive. To address this issue we use a large ensemble of asynchronously coupled ice sheet-climate simulations exploring the parameter space and system sensitivity in order to spin up the coupled model to a realistic state at the LGM (with respect to both climate and ice sheets). Our approach capitalizes on the critical importance of deriving realistic ice sheet geometries in coupled ice sheet-climate simulations rather than letting them evolve freely and uncontrollably, since freely growing undocumented ice masses introduce irreversible degradations of the modeled climate state that will accumulate and grow as the coupled model runs forward in time. The LGM state, which is most consistent with available paleoclimate proxy data and evidence from glacial geomorphology, is then used as a starting point for an ensemble of asynchronously coupled deglaciation runs that keep the fit between the modeled and data-based ice sheet changes under control and infer parameter changes throughout the deglaciation. This approach is expected to (1) improve the ice-sheet model performance under deglacial forcings with respect to mechanisms that are currently oversimplified or excluded from ice-sheet models but are critical to the correct deglaciation process, and (2) provide a first guess for the principle ice-sheet model parameters to be used in synchronously coupled ice sheet-climate simulations of the deglaciation and full glacial cycle.

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DO like oscillations and deglaciation in MIROC AOGCM

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During the last termination of ice age cycle (deglaciation), Heinrich event 1 as well as B/A, Antarctic Cold Reversal (ACR) and Younger Dryas occurred as millennial scale climate changes. Here we ran several deglaciation experiments as well as sensitivity experiments using a coupled atmosphere and ocean GCM (MIROC4m AOGCM) developed in Japan and analyzed the stability of AMOC and climate. The model was also run for 10000 years under many different conditions with constant Greenhouse Gas levels with glacial ice sheet and with and without freshwater flux into North Atlantic region. The results show large oscillation of AMOC and high latitude temperature change similar to B/A and D-O cycles, comparable with ice core data and deep-sea data for some cases. We show that the D-O like oscillation and B/A type change occur under limited range of CO2 and freshwater forcing. The conventional hysteresis curve of stability diagram of AMOC is also analyzed by changing gradually the freshwater flux in the North Atlantic. Implication on the mechanism of the millennial scale climate changes is discussed.

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North Pacific meltwater events linked to glacial ocean circulation changes

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Episodes of massive freshwater discharge to the North Atlantic (NA) are related to cold conditions in the NA realm, so-called Heinrich stadials (HSs). In contrast, the meltwater history of the North Pacific (NP) realm remains unclear, leading to persistent debates on inter-basin responses of millennial-scale climate variability between the NP and NA during HSs. Here we show evidence regarding freshwater injections to the northeastern NP during HSs in the last 50,000 years based on a diatom oxygen isotope (d18O) record and outputs from a water-isotope enabled climate model. Our proxy records show that a 2-3‰ decrease in surface seawater d18O coincides with enhanced ice-rafted debris deposition and slight sea surface cooling in the northeastern NP during HS1 and HS4, but not during HS3. Modelling results corroborate the existence of a dynamical linkage of millennial-scale in-phase meltwater events between the NA and NP, accounting for the events during HS1 and HS4. however, background climate also plays a pivotal role in the linkage by modulating subsurface sea temperature in the NP, providing a potential explanation of its absence during the HS3. Our results thus demonstrate a nonlinear role of the complex atmosphere-ocean-background climate interactions on shaping glacial millennial-scale inter-basin teleconnections.

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A three-dimensional model of the marine nitrogen cycle during the Last Glacial Maximum constrained by sedimentary isotopes

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Nitrogen is a key limiting nutrient that influences marine productivity and carbon sequestration in the ocean via the biological pump. In this study, we present the first estimates of nitrogen cycling in a coupled 3D ocean-biogeochemistry-isotope model forced with realistic boundary conditions from the Last Glacial Maximum (LGM) ~21,000 years before present constrained by nitrogen isotopes. The model predicts a large decrease in nitrogen loss rates due to higher oxygen concentrations in the thermocline and sea level drop, and, as a response, reduced nitrogen fixation. Model experiments are performed to evaluate effects of hypothesized increases of atmospheric iron fluxes and oceanic phosphorus inventory relative to present-day conditions. Enhanced atmospheric iron deposition, which is required to reproduce observations, fuels export production in the Southern Ocean causing increased deep ocean nutrient storage. This reduces transport of preformed nutrients to the tropics via mode waters, thereby decreasing productivity, oxygen deficient zones, and water column N-loss there. A larger global phosphorus inventory up to 15% cannot be excluded from the currently available nitrogen isotope data. It stimulates additional nitrogen fixation that increases the global oceanic nitrogen inventory, productivity and water column N-loss. Among our sensitivity simulations, the best agreements with nitrogen isotope data from LGM sediments indicate that water column and sedimentary N-loss were reduced by 17–62% and 35–69%, respectively, relative to preindustrial values. Our model demonstrates that multiple processes alter the nitrogen isotopic signal in most locations, which creates large uncertainties when quantitatively constraining individual nitrogen cycling processes. One key uncertainty is the global response of nitrogen fixation, which decreases by 25–65% in the model during the LGM, due to the lack of observations in the open ocean most notably in the tropical and subtropical southern hemisphere. Nevertheless, the model estimated large increase to the global nitrate inventory of 6.5–22% suggests it may play an important role enhancing the biological carbon pump that contributes to lower atmospheric CO_2 during the LGM.

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Initialization of palaeo ice sheets

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The initialization of ice sheet models at the last glacial maximum (LGM) plays an important role for simulating the last deglaciation using state-of-the-art Earth system models (ESMs), which consist of general circulation models of the atmosphere and the ocean (AOGCMs) coupled to ice sheet models. As AOGCMs are computational rather expensive, the question appears how initialization of ice sheet models can be achieved and what are the minimum requirements for this. Ice sheet model initialization means to yield a sufficient accurate temperature-velocity field as initial condition at the time when the simulation of interest starts. Here, we employ the Earth system model of intermediate complexity CLIMBER-2 as an emulator of a complex ESM in order to find the minimum model time for obtaining a "correct" temperature field in ice sheets for initialization. Further on, we explore (i) the effect of the initial 3-D temperature field in the ice sheet, (ii) the role of climate biases in simulated LGM ice sheets, (iii) the impact of acceleration techniques of the climate model on the simulated LGM ice sheet and the deglaciation. CLIMBER-2 has the advantage that it is computational very efficient, what enables the model to simulate easily many glacial cycles. Therefore, the LGM state obtained from a simulation of the full last glacial cycle serves as reference state for comparison with the shorter simulations and helps us to decide how good different initialization techniques are for simulated LGM ice sheets.

We found that when utilizing the analytical Robin solution for yielding initial vertical temperature profiles, a run time of 20 kyrs is sufficient for proper initialization of LGM ice sheets. Acceleration of the climate component of the model of up to 10 can be applied. Among all explored factors, the emulated climate biases play by far the most important role in realistic simulations of the LGM state and deglaciation. Therefore, a proper representation of the surface mass balance of ice sheets in complex ESMs is vital for yielding a good initial condition for deglaciation simulations starting from LGM.

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Orbital modulation of ENSO seasonal phase locking

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Modern El Niño-Southern Oscillation (ENSO) events are characterized by their phase locking of variability to the seasonal cycle and tend to peak at the end of calendar year. However, in an idealized NCAR-CCSM3 simulation of the climate of the last 300 thousand years, ENSO seasonal phase locking is shifted periodically following the precessional forcing: ENSO tends to peak in boreal winter when perihelion is near vernal equinox, but peak in boreal summer when perihelion is close to the midst of autumnal equinox and winter solstice.

The mechanism for the change of ENSO's phase locking is proposed to be caused by the change of seasonality of the growth rate, or the intensity of ocean-atmosphere feedbacks, of ENSO. It is found that the December peak of 'winter ENSO' is caused by the continuous growth of ENSO anomaly from June to November, while the May-June peak of 'summer ENSO' appears to be caused jointly by the seasonal shift of higher growth rate in spring and relatively stronger stochastic noise in the first half of the year. Furthermore, the change of the seasonal cycle of feedbacks is contributed predominantly by that of the thermodynamic damping. The summer peak of ENSO is proposed to be caused by the following mechanism. A perihelion in the late fall to early winter forces spring cooling of sea surface temperature (SST) in the eastern equatorial Pacific (EEP) due to reduced insolation, which, reinforced by an oceanic process, leads to weakened latent heat flux damping. The EEP thus becomes more sensitive and favors the growth of the eastern Pacific-like ENSO (as opposed to the central Pacific-like ENSO). This is likely to generate more effective short wave-cloud-SST feedback and, in turn, increased instability in spring, ultimately benefiting the subsequent summer ENSO peak.

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Simulating the mid-Holocene Green Sahara using the dynamic vegetation model LPJ-GUESS

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The "Green Sahara" is a term used to describe a period when today's Sahara desert was transformed into a region covered with vegetation and lakes by orbital modulation. In this study, the 2nd generation dynamic vegetation model LPJ-GUESS is driven by different atmospheric forcings from coupled EC-Earth model mid-Holocene time-slice simulations in which the vegetation is either prescribed to be modern desert or artificially vegetatied consistent with Green Sahara reconstructions. The dynamic vegetation model simulates a vegetated Sahara covered by both herbaceous and woody vegetation types consistent with proxy reconstructions only in the latter scenario. This northward expansion of vegetation is associated with a substantially intensified West African monsoon (WAM), and sensitivity experiments further suggest that the increased precipitation is the main driver of the change. These offline LPJ-GUESS simulations provide constraints on simulated vegetation in CMIP6 mid-Holocene coupled earth system model studies with EC-Earth, and represent the first step towards a fully interactive multi-millennial coupled EC-Earth-LPJ-GUESS mid-Holocene simulation with the aim of capturing the vegetation-climate feedbacks believed to be associated with the observed transitions into and out of the Green Sahara period.

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Parallelization in time in geophysical flows with scale separation and the concept of the exponential integrator

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In trying to find algorithms to parallelize Cauchy problems in time very promising concepts and analysis were developed, especially in the recent 10 years [6]. It has been found that the straight forward implementation of the parareal algorithm in its native form [1] tends to lack the anticipated convergence and speed-up, especially when it comes to nonlinear hyperbolic PDE as the Shallow Water Equations (SWE). However, in order to uphold the ideas of parallelization in time two different methods are introduced allowing the efficient implementation of parareal:
The Averaging over fast waves in geophysical flows, introduced by [3]. And to do so, the second concept of the exponential integrator [2] and its approximations (e.g.with Krylov subspaces [4]) is mandatory. When wave equations like the SWE are considered, the averaging over fast waves allows a scale separation and therefore the numerical construction of a coarse solver for the underlying asymptotic structure of the PDE. This coarse solver is needed to obtain convergence and speed-ups when applying the Parareal algorithm. An introduction of both concepts and a benchmark against which the parareal algorithm is tested will be given during this talk. It should be mentioned, that neither the idea of averaging over fast waves nor the exponential integrator are new. Especially, the concept of the exponential integrator will be emphasized, since constructed (and approximated) once it allows propagation in time for almost arbitrary large time step sizes and therefore needs just one matrix-vector multiplication.

[1] & J.-L. Lions, Y. Maday, and G. Turinici & 2001 & Résolution d'EDP par un schéma en temps "pararéel". C. R. Acad. Sci. Paris Sér. I Math. 332 (2001), no. 7, 661–668

[2] & Moler and Van Loan & 2003 & Nineteen Dubious Ways to
Compute the Exponential of a Matrix, Twenty-Five Years Later

[3] & Andrew Majda & 2003 & Introduction to PDEs and waves for the atmosphere and ocean. Courant Lecture Notes in Mathematics, Vol. 9. NY University Courant Institute of Mathematical Sciences

[4] & Stefan Güttel & 2013 & Rational Krylov approximation of matrix functions GAMM-Mitt. 36, No. 1, 8 – 31

[5] & Wingate and Haute & 2014 & An asymptotic parallel-in-time method for highly oscillatory PDEs. SIAM J. Sci. Comput. 36(2), A693–A713.

[6] & Martin Gander & 2015 & 50 Years of Time Parallel Time Integration.

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How well does radiocarbon record deep-ocean ventilation changes? A coupled climate model study of the last termination.

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Ocean circulation plays an essential role in Earth's climate and the global carbon cycle. A prerequisite for improving confidence in future climate projections is the accurate numerical modeling of past deep ocean circulation changes. Unfortunately our understanding of such changes in terms of transport pathways and transit times is impeded by ambiguities in data-based reconstructions which heavily rely on radiocarbon. Interpreting the evolution of the deep-sea radiocarbon signal is indeed far from straightforward since this evolution might result from individual or concomitant changes in atmospheric levels, air-sea exchange rates, and ocean circulation.

Here, we investigate how deep-sea radiocarbon ages scale to the actual ventilation timescales during transient experiments over the last termination.

For this purpose we take advantage of a set of transient simulations performed with the Max Planck Institute Earth System Model (MPI-ESM) including the newly developed adaptative bathymetry and river routing components. The experiments, starting at 26 ka BP, are constrained with prescribed time varying ice sheets and topography. Changes in ice sheet volume naturally result in freshwater surges which affect the Atlantic Meridional Overturning Circulation (AMOC).

Ocean radiocarbon is included in the model. The atmospheric radiocarbon follows the INTCAL13 reconstruction while the impacts of varying wind speed, sea-ice cover, and atmospheric carbon dioxide on air-sea exchange rates are explicitly included. The model also includes a set of age and dye tracers documenting the role of specific surface areas in the deep ocean ventilation as reported by radiocarbon and ideal age, respectively.

We investigate the sequence of events in the deep ocean during periods characterized by significant changes in the AMOC. We particularly focus on the potential departures of radiocarbon based ages and transit times from the actual ventilation time scales.

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An Eulerian Iceberg Module for Climate Studies in the Max Planck Institute Ocean Model

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Iceberg studies are of great interest for understanding how fresh water is transported and distributed in the ocean, as water release plays an important role in ocean heat transfer and Atlantic meridional overturning circulation (AMOC). Main processes after the calving of an iceberg are the drift and change in size due to deterioration. The classical way of implementing icebergs is based on Lagrangian approach, which treats each iceberg as an individual particle and allows to calculate the trajectory and mass loss of standalone iceberg. Here we present an iceberg module in the Eulerian coordinate system integrated into the Max Planck Institute Ocean Model (MPIOM). This approach allows describing the iceberg's evolution within the MPIOM infrastructure, which simplifies the parallelization and reduces computation time. The latter is an advantage for long-term simulations, such as the last deglaciation, which is associated with large icebergs discharge events, the so-called Heinrich events. The Eulerian iceberg module uses the same parametrizations of drift and deterioration as the Lagrangian module but with modifications corresponding to the Eulerian representation of motion. Here we present first results of the integrated Eulerian iceberg module into the MPIOM.

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Flow-induced Coordinates and Reconstruction Techniques for Transient Advection-Diffusion Equations with Multiple Scales

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Simulation over a long time scale in climate sciences as done, e.g., in paleo climate simulations require coarse grids due to computational constraints. Coarse grids, however, leave important smaller scales unresolved. Thus small scale processes that significantly influence the resolved scales can either be neglected (which is not desired) or their influence has to be taken care of by different means. Such processes include (slowly) moving land-sea interfaces or ice shields as well as flow over urbanic areas. State-of-the-art dynamical cores represent the influence of subscale processes typically via subscale parametrizations and often employ heuristic coupling of scales.

We aim to improve the mathematical consistency of the upscaling process that transfers information from the subgrid to the coarse prognostic scale (and vice-versa). We investigate new bottom-up techniques for advection dominated problems arising in climate simulations [Lauritzen et al.,2011]. Our tools are based on ideas for multiscale finite element methods for elliptic problems that play a role, in oil reservoir modeling and porous media in general [Efendiev et al., 2009; Graham et al.,2012]. Modifying these ideas is necessary in order to account for the transient and advection dominated character that is typical for flows encountered in climate models.

We present a new Garlerkin based idea to account for the typical difficulties in climate simulations. Our modified idea employs a change of coordinates based on a coarse grid characteristic transform induced by the advection term in order to account for appropriate subgrid boundary conditions for the multiscale basis functions. The boundary conditions are essential for such approaches. We discuss drawbacks of this approach and propose a solution based on a reconstruction of small scale features in basis functions in a semi-Lagrangian framework. We also present results from sample runs for a simple advection-diffusion equation with rapidly varying coefficients on several scales.

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Dynamic Hydrological Discharge Modelling for Coupled Climate Model Simulations of the Last Glacial Cycle

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The continually evolving large ice sheets present in the Northern Hemisphere during the last glacial cycle caused significant changes to river pathways both through directly blocking rivers and through glacial isostatic adjustment. These river pathway changes are believed to of had a significant impact on the evolution of ocean circulation through changing the pattern of fresh water discharge into the oceans. A fully coupled ESM simulation of the last glacial cycle thus requires a hydrological discharge model that uses a set of river pathways that evolve with the earth's changing orography while being able to reproduce the known present-day river network given the present-day orography. Here we present a method for dynamically modelling hydrological discharge that meets such requirements by applying relative manual corrections to an evolving fine scale orography (accounting for the changing ice sheets and isostatic rebound) each time the river directions are recalculated. The corrected orography thus produced is then used to create a set of fine scale river pathways and these are then upscaled to a course scale. An existing present-day hydrological discharge model within the JSBACH3 land surface model is run using the course scale river pathways generated. This method will be used in fully coupled paleoclimate runs made using MPI-ESM1 as part of the PalMod project. Tests show this procedure reproduces the known present-day river network to a sufficient degree of accuracy.

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A Tale of Two Transitions: Attributing Simulated Changes in North Atlantic Jet Mean Latitude and Latitudinal Variability during the Last Deglaciation

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Some of the least well-constrained aspects of the last deglaciation are the changes to atmospheric dynamics, and yet they facilitate the redistribution of atmospheric moisture and heat and changes to surface ocean currents and sea ice distributions. Due to the fast response times of the atmosphere and relatively slow rates of change of ice sheet boundary conditions and orbital forcing, changes to atmospheric dynamics may be presumed to be gradual and incremental. However, if the atmosphere exhibits nonlinear, threshold-like behaviour to these slowly-varying background conditions, there is the potential for the atmosphere to play a critical role in fast climate transitions. In order to test such a hypothesis, one must identify associated responses that may be detectable in proxy measurements.

Idealized theoretical studies, and “snapshot” simulations indicate that between the Last Glacial Maximum (LGM) and the preindustrial period the North Atlantic eddy-driven jet weakened, became less zonally-oriented, and exhibited a greater range of latitudinal variability. However, there is less evidence to indicate whether this transition occurred smoothly or in an abrupt, non-linear fashion. If non-linear processes played an important role in these transitions, then the timing of such transitions is not easily predictable. The only published study employing a transient paleoclimate simulation to examine jet dynamics concluded that there exist two North Atlantic jet states: a strong, stable, zonal jet, and a weak, latitudinally-variable, tilted jet such as is observed today [1]. Lofverstrom and Lora (2017) argue that the transition between these two states was abrupt and occurred around the time of the separation of the Laurentide and Cordilleran Ice Sheets.

We have generated an ensemble of four transient deglacial simulations with different tuning configurations using the Planet Simulator coupled atmosphere-ocean-vegetation-sea ice model (atmospheric resolution of T42). These simulations are forced with the GLAC1-D deglacial ice sheet chronology, changing orbital configuration and greenhouse gas concentrations consistent with the Palaeoclimate Modelling Intercomparison Project 4 deglacial experiment. Unlike the prescribed meltwater fluxes in Lofverstrom and Lora (2017), our simulations use topographically self-consistent routing of surface runoff with no contribution from ice sheet mass changes. This allows us to assess the effects of ice sheet changes on ocean circulation as mediated by the atmosphere. These simulations exhibit multiple abrupt shifts in North Atlantic jet latitude and tilt over the last deglaciation. They also exhibit a separate change in jet variability from a latitudinally-restricted range to a state with a wide range of latitudinal variability. The timings of each of these transitions are consistent between all ensemble members, indicating that they occur in response to changes in the boundary conditions. Through these simulations and a suite of sensitivity experiments, we characterize these transitions and attribute their causes. We also identify signatures of these changes that may be detectable with proxy data sources.

1. Lofverstrom, M. and J. M. Lora, 2017. Geophysical Research Letters, 44, 8047–8055, doi:10.1002/2017GL074274.

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Sea level fall induced atmospheric CO_2 changes via enhanced marine volcanism: A negative feedback during glaciation

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Paleo-climate records and geodynamic modelling indicate the existence of complex interactions between glacial sea level changes, volcanic degassing and atmospheric CO_2, which may have modulated the climate system's descent into the last ice age. Between B85 and 70 kyr ago, during an interval of decreasing axial tilt, the orbital component in global temperature records gradually declined, while atmospheric CO_2, instead of continuing its long-term correlation with Antarctic temperature, remained relatively stable. Here, based on novel global geodynamic models and the joint interpretation of paleo-proxy data as well as biogeochemical simulations, we show that a sea level fall in this interval caused enhanced pressure-release melting in the uppermost mantle, which may have induced a surge in magma and CO_2 fluxes from mid-ocean ridges and oceanic hotspot volcanoes. Our results reveal a hitherto unrecognized negative feedback between glaciation and atmospheric CO_2 predominantly controlled by marine volcanism on multi-millennial timescales of about 5,000–15,000 years.