Potsdam Institute for
Climate Impact Research

# The Potsdam Earth Model
# POEM

# Why POEM?

*"In addition to the classic global climate models, we need fast and slim Earth System Models. These models should focus computing power on the slow components of the climate system rather than on simulating weather."*

*Prof. Stefan Rahmstorf, Co-Chair of Earth System Analysis*

Climate science today is facing a number of **Grand Challenges**, which include:

- Simulation and understanding of numerous feedbacks in the Earth system that involve its different components, including e.g. ice sheets and marine and terrestrial biosphere and carbon and nitrogen cycles
- Understanding and predicting the risk of crossing dangerous tipping points that may lead to abrupt and/or irre versible changes in the Earth system
- Realistic simulations and quantitative understanding of past climate changes in Earth's history, particularly past episodes of hothouse climates and abrupt changes
- Systematic exploration of planetary boundaries and the safe operating space for humanity.

The standard approach to climate modelling, pursued at most modelling centers, is to build ever more complex models at ever higher resolution, close to the limits of what computing power allows. Historically these models have been built around atmospheric general circulation models derived from weather forecasting models, with other components like oceans, biosphere and ice sheets added later (in most cases this is still ongoing). While this is valuable and leads e.g. to increasingly detailed regional simulations, this approach is not very suitable to address the challenges listed above.

*Flow dynamics and surface melt of the Greenland Ice Sheet are simulated in POEM by the state-of-the-art PISM ice sheet model, developed by PIK jointly with the University of Alaska.*

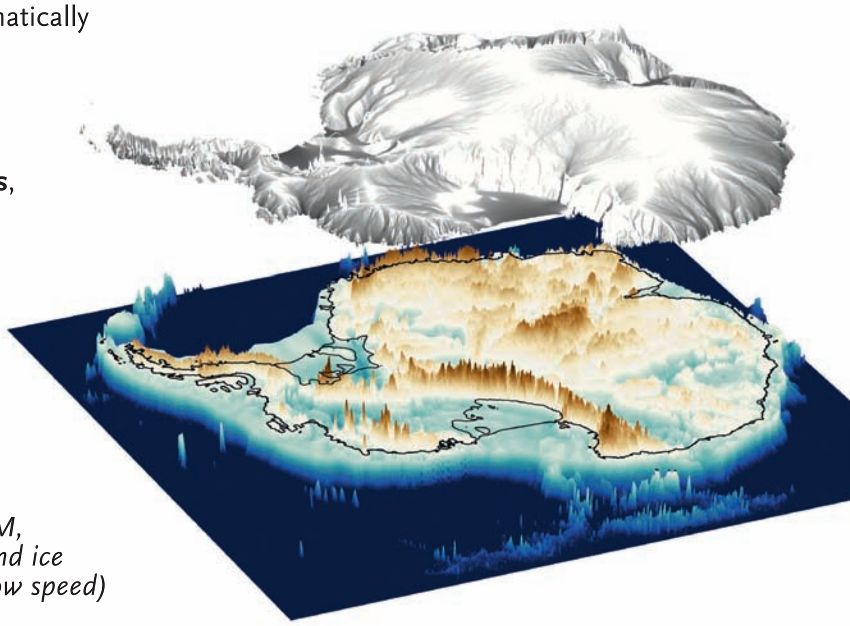
# POEM – a new, fast and versatile Earth System Model

Rather than building the most complex models feasible, PIK has over two decades of experience with the alternative, complementary approach of models that are only as complex as needed for the task being tackled, sometimes called "intermediate complexity" models. While these have some limitations they also offer a number of distinct advantages:

- They allow a thorough **testing and tuning** of models through a large number of targeted experiments.
- They allow a **thorough validation** for large climatic changes (not just present-day climate) through paleo-climate simulations, including the response of slow components like the continental ice sheets, deep ocean and carbon cycle.
- They allow a thorough **exploration of uncertainties and nonlinearities** (e.g. threshold behaviour) by simulations of large ensembles with systematically varied parameters.
- They make it easier to build comprehensive Earth System Models with **many components**, like ice sheets, dynamic vegetation and marine biogeochemistry, as well as interactions with human societies.

An example of a ground-breaking study exploiting several of these advantages is Robinson et al. (2012), where a large ensemble of simulations for the last 200,000 years was performed and data for the size of the Greenland Ice Sheet from the Eemian interglacial were used to constrain the realistic range of model parameters. In this way the critical warming threshold for the Greenland Ice Sheet was determined in a more robust way, which resulted in a revised assessment of this crucial tipping point for future climate change in the fifth IPCC report.

Advances in computing power as well as our new atmosphere model Aeolus now make it possible to take the next leap and build a flexible, new type of climate model: POEM, the Potsdam Earth Model. This is why we develop POEM.



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*The Antarctic Ice Sheet in PISM, showing bedrock topography and ice streams (grey shades denote flow speed)*

# The structure and status of POEM


"Key to the success of POEM is the thorough scientific testing, validation and development to obtain a high-quality simulation of the components of the Earth system through a close collaboration of ocean, atmosphere, ice-sheet and marine and land biosphere experts."

*Dr. Georg Feulner, Head of the POEM development and paleoclimate expert*

POEM in its current prototype form consists of three components: the Aeolus atmosphere model (recently developed at PIK), the MOM ocean model (which we adopt from GFDL in Princeton) and the LPJmL dynamic global vegetation model (the development of which has a long tradition at PIK). We are currently working to couple the PISM ice sheet model (co-developed over the past years by PIK with the University of Alaska).
The key to the fast performance of POEM is the Aeolus atmosphere, which does not explicitly simulate weather variability, which for many applications is not required.
The first three components (Aeolus, MOM and LPJmL) are already coupled and perform in a very promising way: on our present high-performance computer, 450 model years can be run in a day on 48 (out of our current 6.624) processors, with major scope for optimisation which has not yet been our focus thus far. In the future we expect to run parallel ensembles of experiments with thousands of model years each per day, with fully 3-D ocean model at 2x3° spatial resolution and our state-of-the-art biosphere and ice-sheet models, opening up many applications not possible today. The use of LPJmL currently makes this the only Earth System Model with a realistic simulation of not only natural vegetation dynamics and hydrology, but also global agriculture including climate-dependent harvests, multi-cropping, irrigation and bioenergy plantations.

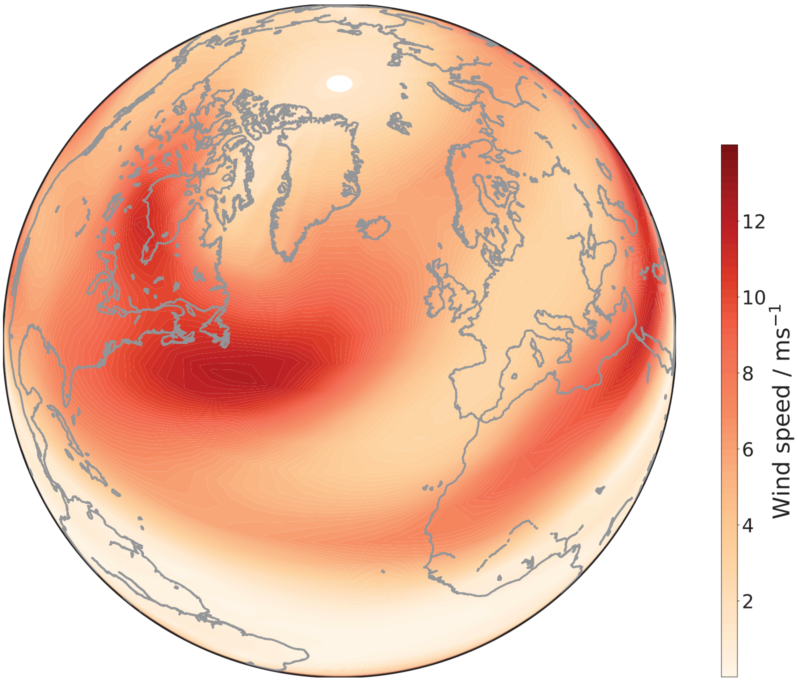
Our POEM implementation uses GFDL's flexible modelling system, FMS, which allows us to use a hierarchy of atmosphere and ocean models (including atmospheric GCM and slab ocean).

# Aeolus atmosphere model

The Aeolus atmosphere model has been completely developed at PIK. It is a dynamical statistical model, which makes use of the notable gap in the atmospheric power spectrum between weather and climate variability.
The former is not explicitly resolved in Aeolus, leading to major time savings. Conventional atmosphere models spend the majority of computer power on simulating weather, even if the main research interest is climate.
Nevertheless Aeolus is able to reproduce the average statistical properties and effects of many aspects of weather variability, including storm tracks, the jet stream and planetary waves.
The model has been thoroughly tested in stand-alone mode and the results are published (Coumou et al, 2011; Eliseev et al, 2013; Totz et al., 2018).

"Our Aeolus atmosphere model is unique in the world in the way it directly simulates the mean climate without resolving all the short-term weather variability."

*Dr. Vivien Matthias, senior scientist, atmospheric dynamics expert*

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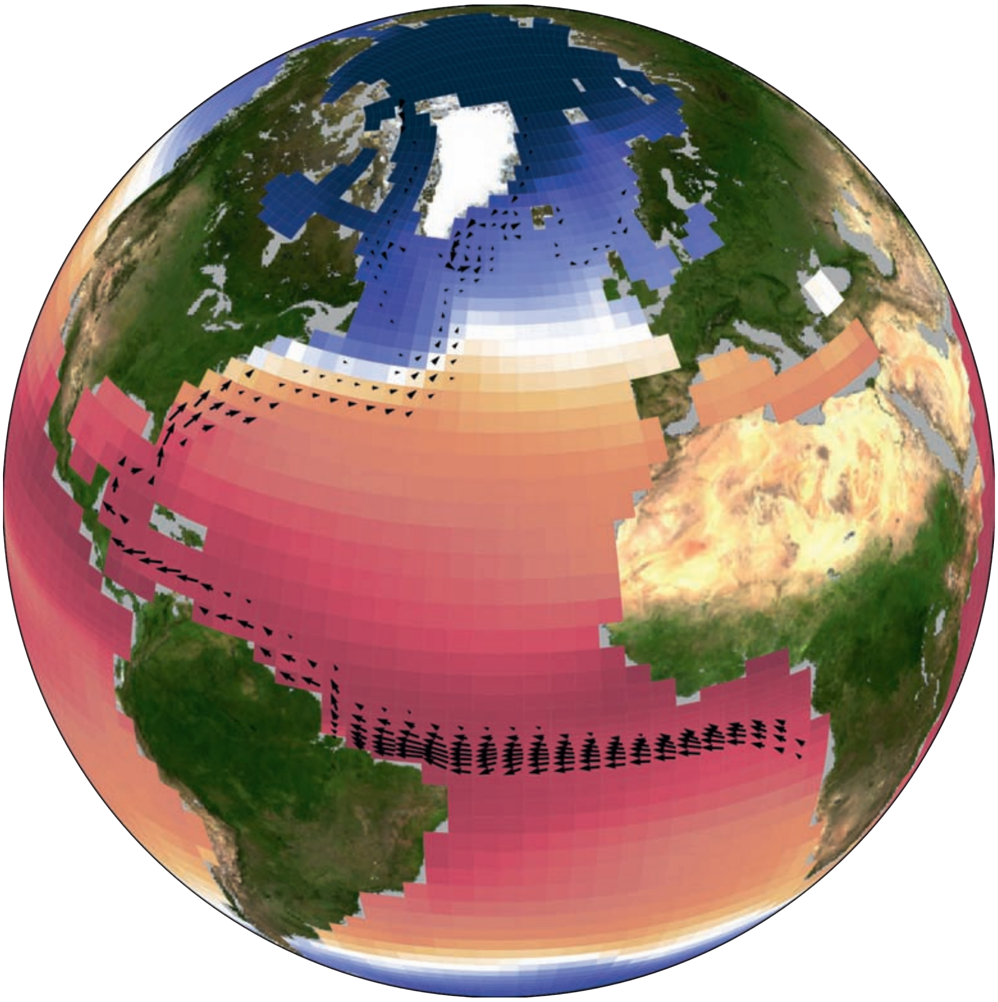
*The Figure shows the wind speed at 3,000 m height in the northern hemisphere winter as simulated by Aeolus, highlighting the polar and subtropical jet stream.*
*The polar jet meanders induced by a strong planetary wave activity.*



↑ *A view of the Atlantic Ocean in POEM. The coloured boxes show the sea surface temperatures on the tripolar model grid. The arrows indicate strong surface currents and reveal the upper branch of the Atlantic overturning circulation, also known as Gulf Stream System.*

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*The ocean's capacity to store and transport heat is of paramount importance for the climate system.*

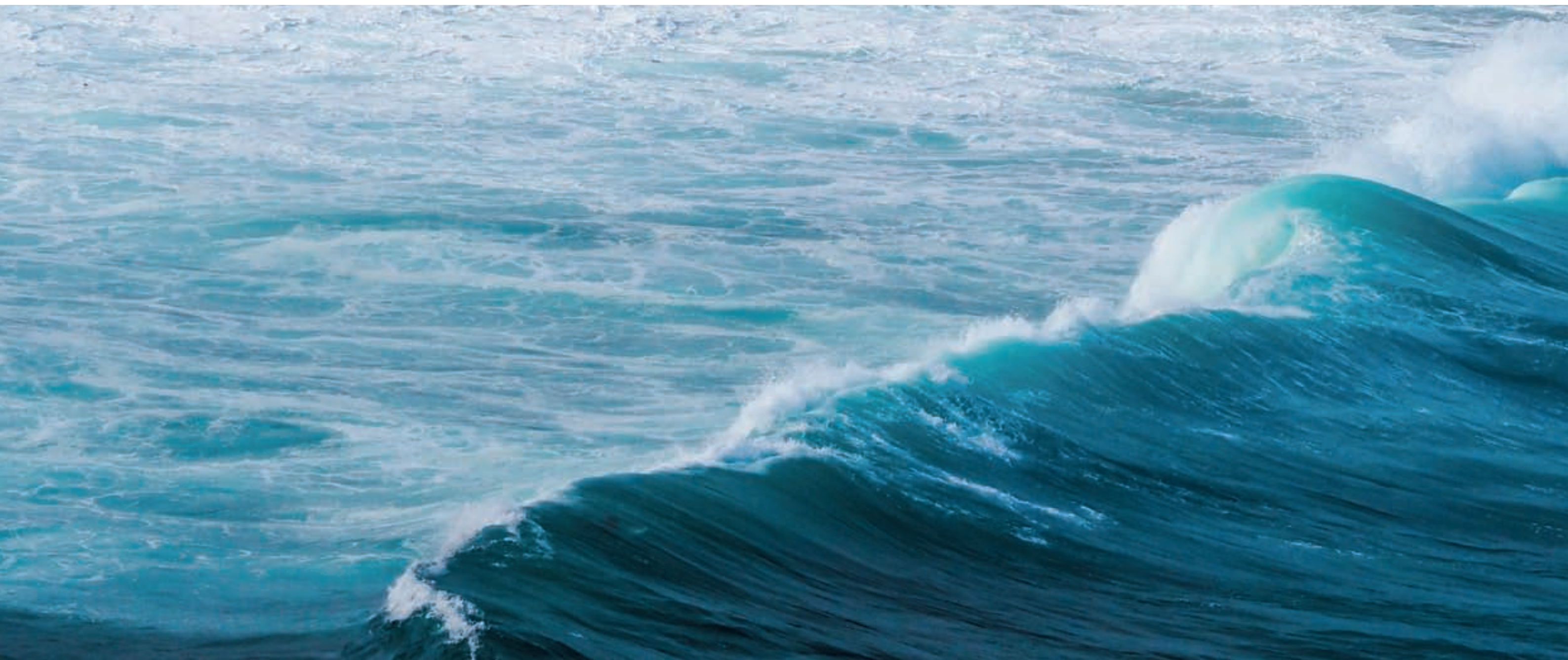
*"Ocean circulation dynamics, such as changes in the Gulf Stream System, are key for understanding major climate changes both in the past and the future."*

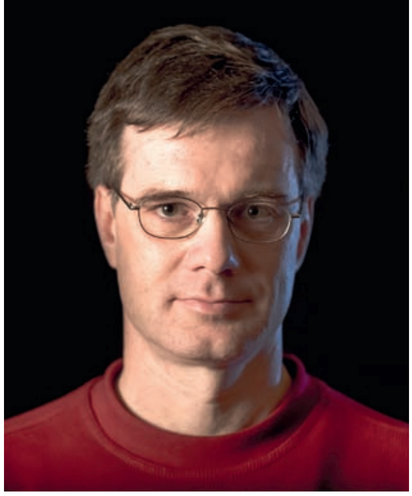
*Willem Huiskamp, PhD, postdoc, ocean circulation and paleoclimate expert*

# MOM ocean model

We use the current MOM5 ocean general circulation model of GFDL in Princeton as the ocean component of POEM.
MOM5 is a canonical large-scale ocean model based on the "primitive equations", i.e. the basic equations of ocean dynamics. It is formulated on a tri-polar horizontal grid, allowing for fast computation (Griffies 2012). MOM5 can utilize either a scaled-geopotential height or pressure as a vertical coordinate and therefore has a free surface, an important advantage for sea-level studies.
This model utilizes the finite volume method for discretization, enabling more accurate conservation of tracer fluxes, and it includes models for sea ice (SIS, Delworth et al. 2006) and the fast marine biogeochemistry model BLING (Galbraith et al. 2011) which allows simulations on millennial timescales.

Within POEM, the largest share of computing power is in fact devoted to the ocean component rather than the atmosphere, consistent with the fact that on climate (rather than weather) time scales, ocean dynamics are of prime importance.
This has to do with the intrinsic time scales of the oceans, where the time it takes for water to travel into the interior and back to the surface can take thousands of years.
The ocean's large storage capacity for heat (for example, more than 90% of the extra heat energy absorbed by Earth in the course of the current global warming is stored in the oceans), carbon, and biogeochemical tracers and its resulting influence on determining the Earth's climate make accurate simulation of its processes of paramount inportance.





*"With POEM, we will have the world's first Earth System Model which allows state-of-the-art simulations of both natural vegetation and managed land."*

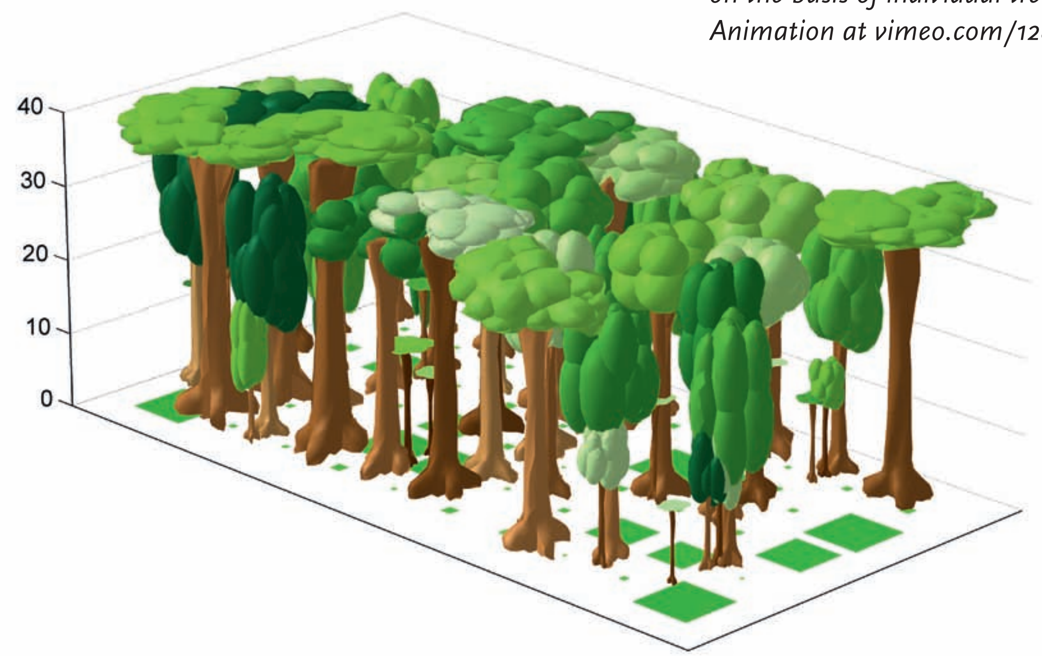
*Prof. Wolfgang Lucht, Co-Chair of Earth System Analysis*

# LPJmL land biosphere model

LPJmL is an internationally leading process model of the terrestrial biosphere, mainly developed and hosted at PIK. It is unique in its ability to realistically simulate the dynamics of both natural and managed vegetation (agriculture, bioenergy plantations, irrigation) coupled with the global carbon and water cycles at high spatial and temporal resolution. The current model version LPJmL4 (Schaphoff et al. 2018a, b) integrates advances in crop and water management simulation and process-based fire and permafrost dynamics, while the latest model development includes the nitrogen cycle (LPJmL5, von Bloh et al. 2018).

These features enable applications such as assessments of interacting land- and freshwater-based planetary boundaries (along with societal options for maintaining them; Heck et al., 2018), as well as the study of nonlinear terrestrial ecosystem dynamics (Sakschewski et al., 2016), and the risk of biogeochemical destabilisation of the Earth's biosphere (Ostberg et al., 2015). LPJmL provides the opportunity for fast simulations of key linkages of natural and anthropogenic processes on the land surface with climate and ocean dynamics.

↓ *Illustration of a snapshot from a simulation with a novel version of PIK's dynamic vegetation model that simulates diverse forest communities on the basis of individual tree growth. Animation at vimeo.com/128978485*

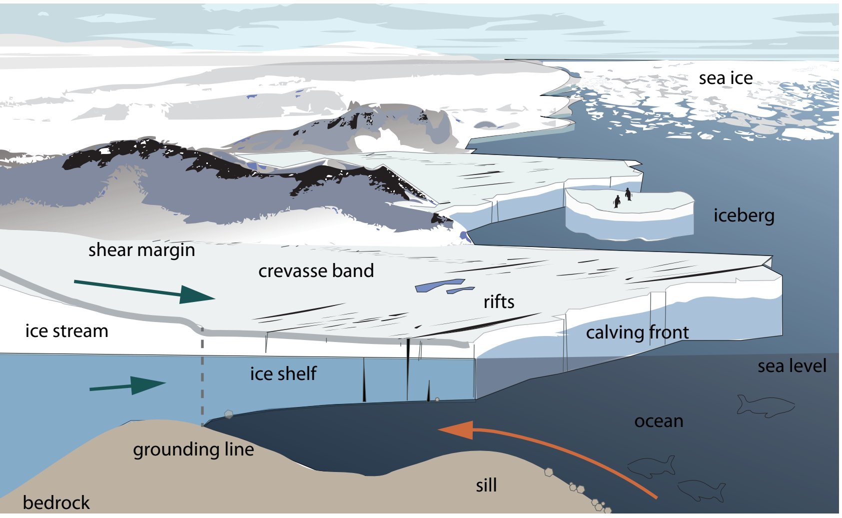


# PISM ice sheet model

The Parallel Ice Sheet Model PISM is jointly developed at the University of Alaska, Fairbanks, and at PIK (Winkelmann et al. 2011). It is a thermomechanically-coupled, three-dimensional ice-sheet model that is freely available and applied in more than 20 research groups worldwide (open source code: http://www.pism-docs.org). PISM solves a hybrid-type solution of the momentum balance and employs a finite-difference scheme, making it computationally very efficient and particularly suited for large-scale and long-term applications. Calving front positions and grounding lines of the floating ice shelves can evolve freely, based on a stress-based calving law and the flotation criterion, respectively (Levermann et al. 2012; Albrecht et al. 2011). PISM accounts for bedrock deformation using the fast-fourier transform. PISM is currently developed and used intensively at PIK in a stand-alone mode, to assess the stability of the Antarctic Ice Sheet (Feldmann & Levermann 2015; Winkelmann et al. 2015; Mengel & Levermann 2014), to study its past evolution during the Holocene (Kingslake et al. 2018) as well as the role of dynamic processes for the ice sheet's response to climate change (Winkelmann et al. 2012), and to make future sea level rise projections. Recently the Potsdam Ice-shelf Cavity mOdel (PICO) has been developed and implemented as a module in PISM which can serve as an efficient link between large-scale ice-sheet and ocean models (Reese et al. 2018). PISM+PICO will be coupled into POEM in the coming years, allowing a range of new questions to be investigated that require the simulation of the interaction of ice sheets with the surrounding ocean and atmosphere.

**"The PISM ice sheet model has already proven its value in simulation of Ice Age climate and the future. Including it in POEM will open up many exciting research possibilities!"**

*Junior Professor Ricarda Winkelmann, ice sheet expert*




↑ *A schematic view of an ice shelf system at the rim of the Antarctic Ice Sheet. Capturing the most relevant processes in POEM will allow studies of ice-sheet instability and future sea-level rise.*

# POEM: A model for the climate challenges of the coming decades

With POEM we intend to deliver a fast but comprehensive Earth System Model which will help to keep PIK at the forefront of international climate science over the next two decades. In its construction and its applications, POEM will be complimentary to the usual global climate models, including the CMIP5 models used for the last IPCC report and new developments such as the German National Strategy Earth System Modelling. We intend to make POEM available to the international research community, initially by building partnerships with selected institutions.

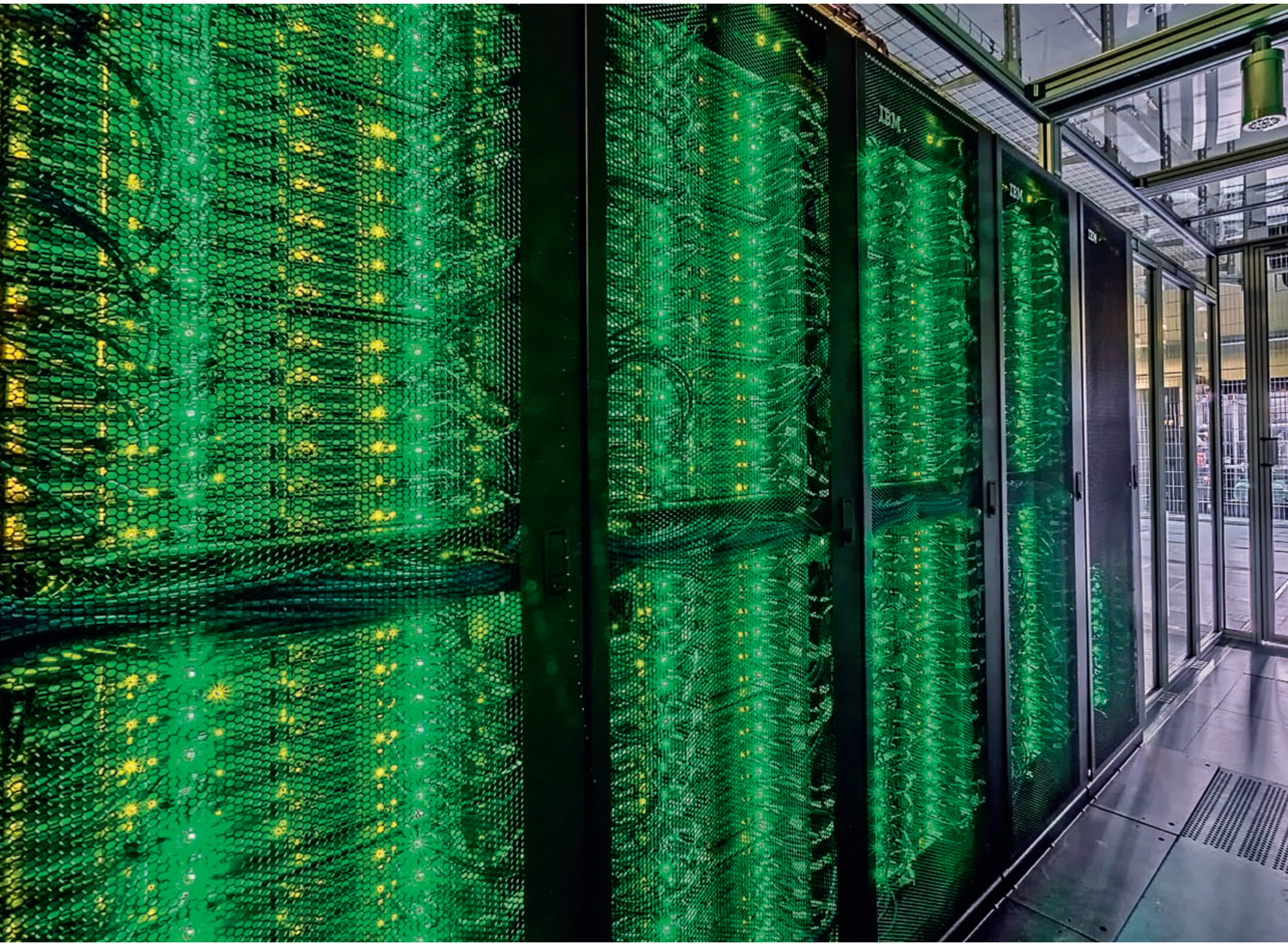
**Contact us at *poem@pik-potsdam.de* if you are interested in collaboration.**

"POEM is one of the main pillars of the future modelling strategy of the Potsdam Institute. We look forward to collaborating on this exciting project."

*Dr. Stefan Petri, scientific programmer*

"I'm very pleased that as a student I was able to make substantial contributions to the POEM development. Working at the frontier is much more fun than just applying an existing model!"

*Levke Caesar, PhD student*



*PIK's high-performance computing cluster.*

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