New Frontiers in Computational Geodynamics

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In collaboration with

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BIOGEODYNAMICS

Schweizerischer Nationalfonds

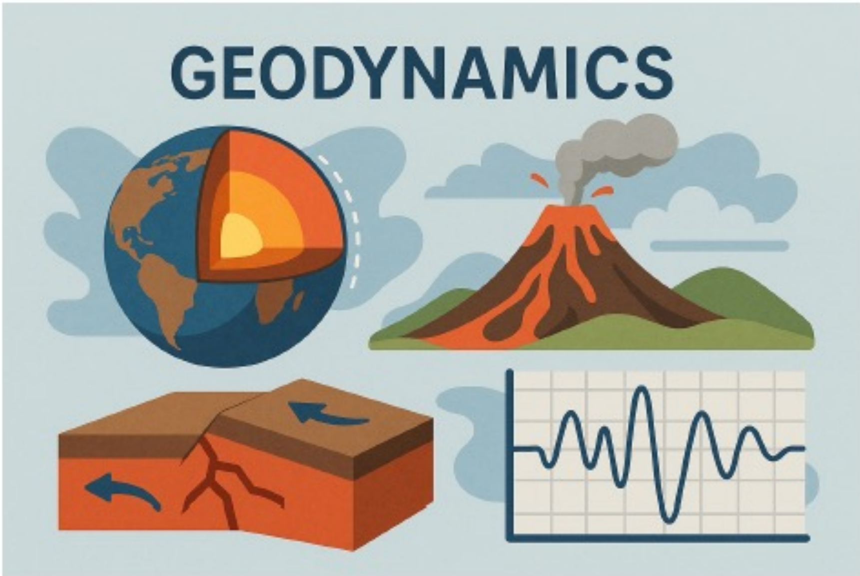
INTERNATIONAL LITHOSPHERE PROGRAM

cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

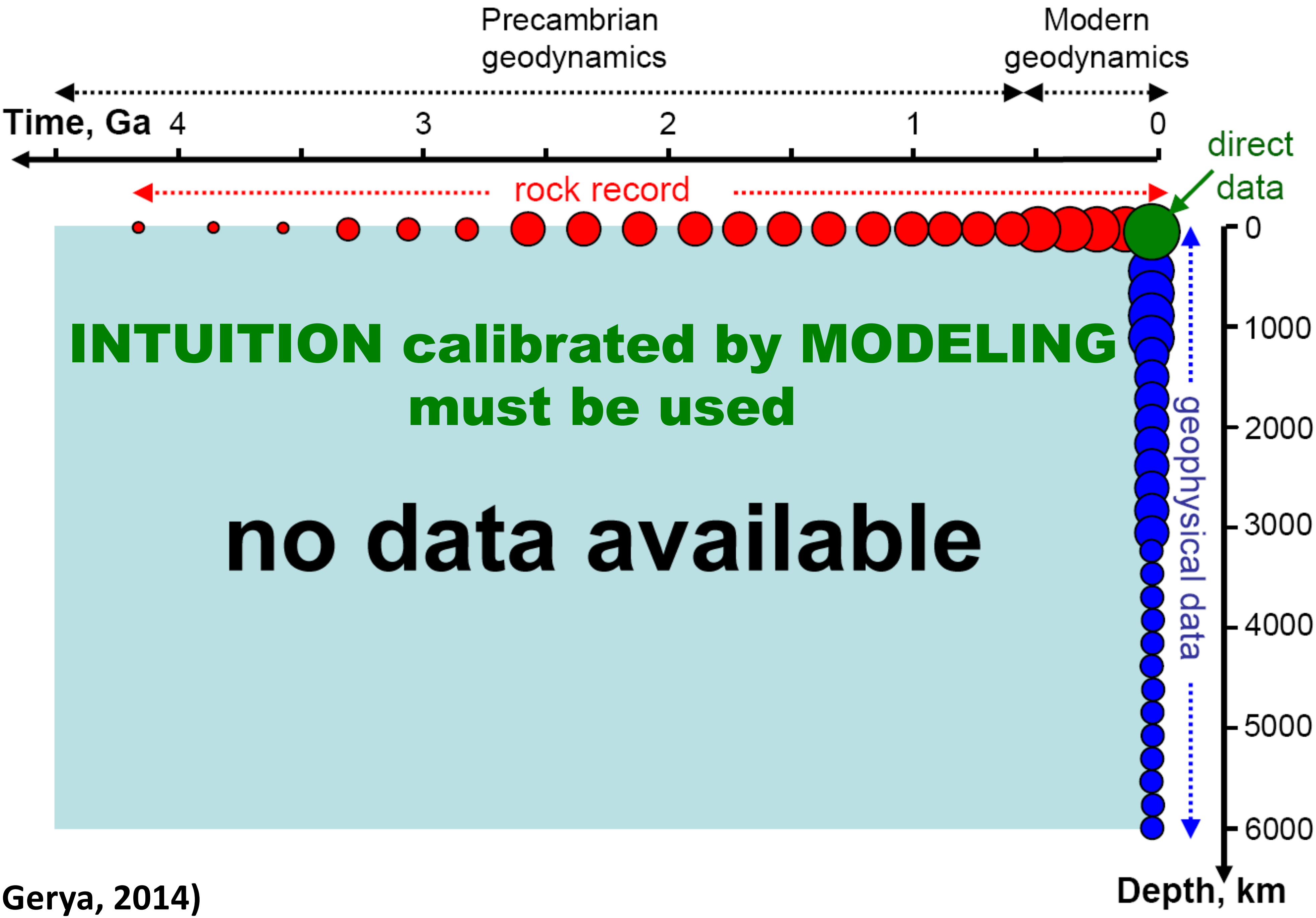
ETH zürich

What is Geodynamics?

- Studies the processes shaping Earth's interior and surface
- Focus on phenomena like mantle convection, plate tectonics, earthquakes, and volcanism
- Crucial for understanding Earth's evolution mechanisms
- Useful for natural hazard assessment, resource management, and reconstruction of geological history



Geodynamical approach: modeling-based



(Gerya, 2014)

1970 - 2026

 (1970)

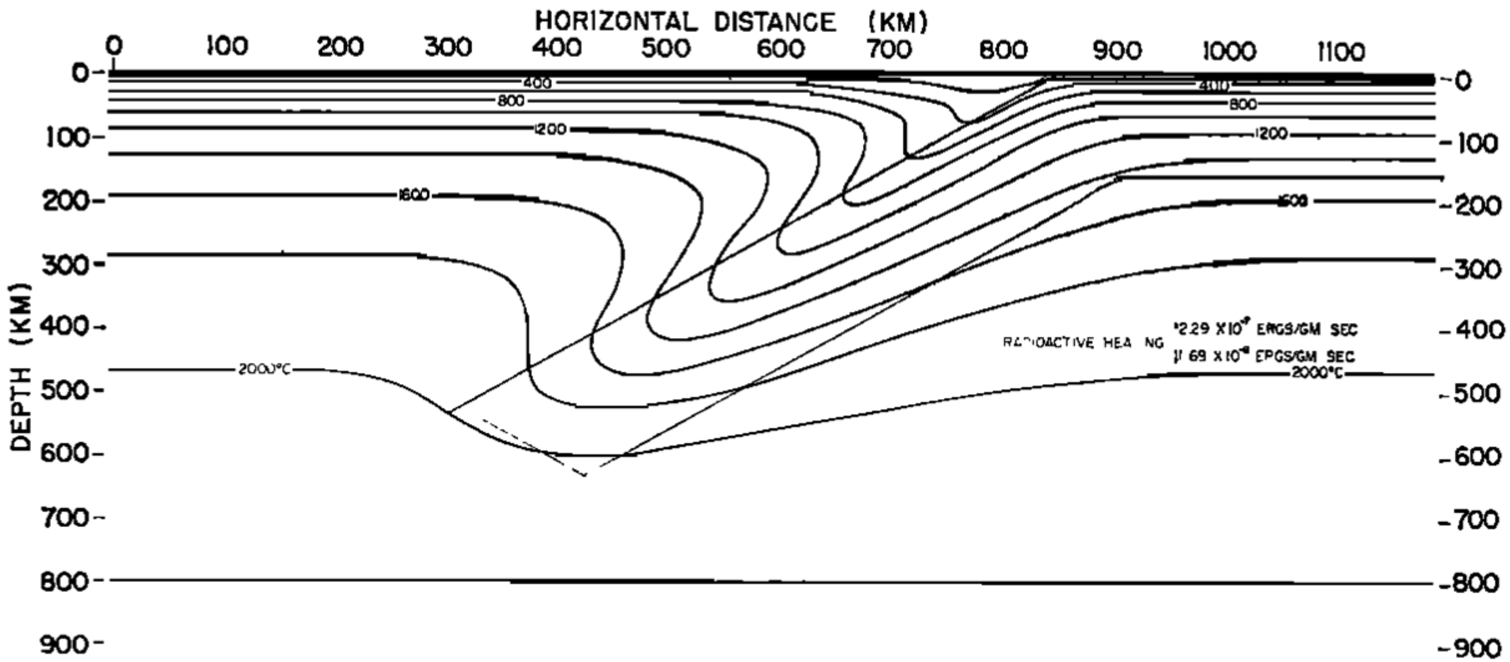


Fig. 5. Temperature regime for a spreading velocity of 1 cm/yr with conductive heat transfer only.

56 years of Computational Geodynamics

Methodological Frontiers

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Computational Challenges

- Geodynamic processes are strongly nonlinear and span vast spatial and temporal scales
- Simulations require high resolution and long runtimes to capture dynamics
- Stiff PDEs often lead to ill-conditioned systems (e.g. $\kappa > 10^{25}$)
  ➜ Huge variations in physical quantities (e.g. velocity vs. pressure)
- Performance and time-to-solution
  - Advanced numerical methods
    ➜ efficient solvers for large sparse problems
  - Hardware acceleration
    ➜ exploit modern heterogeneous and distributed systems

State of The Art Solvers

- Many solvers have been developed over the years
  - Most written in older compiled languages (C, C++, or Fortran)
- GPU support is limited or experimental
- PETSc is commonly used to provide solver infrastructure
  ➜ partial GPU support
- MPI support more widely used
  ➜ often through PETSc
- Monolithic and CPU-centric design
- Integration with AI/ML tools rarely supported

Methodological Frontiers

State of The Art Solvers

Solver	GPU Support	PETSc	MPI
ASPECT	❌ Not supported	✅	✅
CitcomS	⚠️ Experimental CUDA port	❌	✅
I2ELVIS / I3ELVIS	❌ Not supported	❌	❌
GAIA	✅ Native (CUDA + hybrid)	❌	✅
LaMEM	⚠️ Experimental	✅	✅
pTatin3D	⚠️ Via PETSc backend	✅	✅
StagYY	❌ No native support	✅ (via StagBL)	✅
Underworld2	❌ No native support	✅	✅

Solvers for long-term lithospheric dynamics

Strengths of Current Solvers

✅ Strengths

- Scientifically mature and well validated through decades of research
- Support complex physics and advanced numerical methods
- Scalable on large CPU-based HPC systems using MPI
- Widely adopted and trusted within the geodynamics community
- Many solvers offer partial GPU support

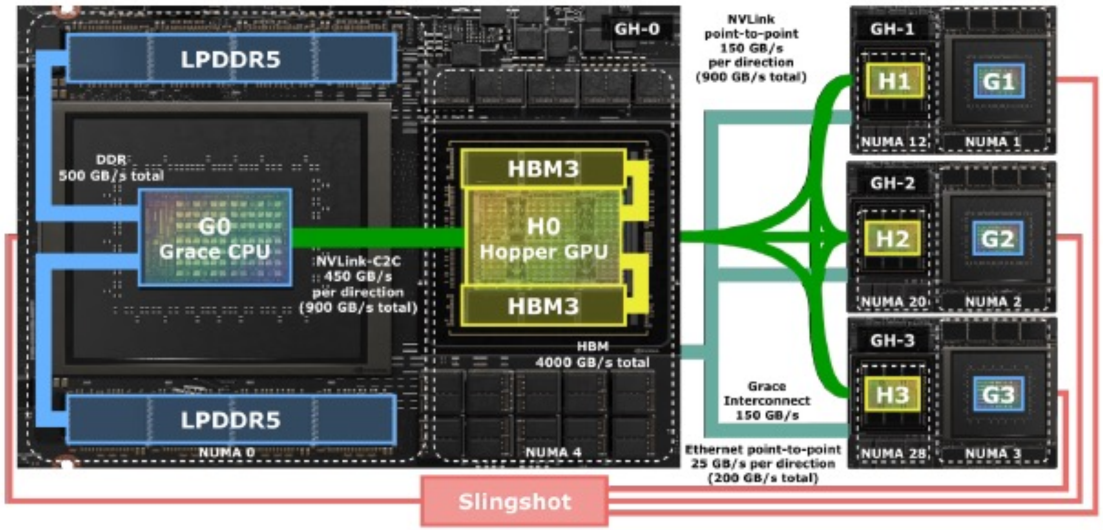
Limitations of Current Solvers

❌ Limitations

- Designed for CPU-centric architectures and written in C/C++/Fortran
- Monolithic structure with tightly coupled components
- Difficult to extend or modify without expertise in both physics and HPC
- High barrier to entry
  ➜ low-level programming, performance tuning, and parallelization
- Limited and fragmented GPU support
  ➜ GPUs are second-class citizens
- Heavy reliance on PETSc, which itself is monolithic and not GPU-native

General Trends in Scientific Computing

- Increasing gap between legacy simulation codes and modern hardware
- GPUs and heterogeneous systems becoming the dominant HPC platforms
- Growing demand for productivity, extensibility, and faster experimentation
- Similar pressures in other communities
  ➜ e.g. climate science, CFD, materials science and AI



Understanding data movement in tightly coupled heterogeneous systems: A case study with the Grace Hopper Superchip. arXiv preprint arXiv:2408.11556.

Lessons Learned So Far

- Existing solvers are scientifically mature and numerically robust
- Most are built around:
  - monolithic architectures
  - CPU-centric design assumptions
- GPUs are typically treated as secondary accelerators
- Extending or modifying codes requires deep expertise in physics and HPC
- This limits accessibility, experimentation, and long-term evolution

What Can We Learn from Others?

- Large scientific codes can be modernized without sacrificing performance
- Proven patterns:
  - modular and composable software design
  - device-agnostic programming models
- GPUs treated as first-class execution targets
- Python increasingly used as a high-level language for scientific computing
- Performance-critical kernels still implemented via compilation and optimized libraries

What Can We Improve?

Before	After
Monolithic solver design	Modular, composable frameworks
CPU-first, GPU offload later as add-on	GPUs are first-class citizens, device-agnostic programming
Tight coupling between physics, numerical methods and infrastructure	Clear separation of concerns
High barrier to entry	Lower technical barrier for domain scientists
Difficult integration with AI/ML tools	Native compatibility with modern HPC and AI ecosystems

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Pyroclast

- Pyroclast – combination of
  - "Pyroclastic rock" ≈ explosive volcanic eruptions
  - "Py" prefix to indicate Python language
- Simple, extensible and modular
  ➜ reusable code
- Fast ➜ combine different technologies to achieve high performance
- Parallel ➜ shared memory / MPI / GPU
- Written in simple Python ➜ fast to iterate ideas
- Natively supports ML/AI frameworks

PYROCLAST
SCALABLE GEOPHYSICS

Research Frontiers

1. Computational geodynamics is an expanding young science. Its key idea is that anything in Earth and Planetary Sciences can be modeled, quantified and explained on physical-mathematical basis.

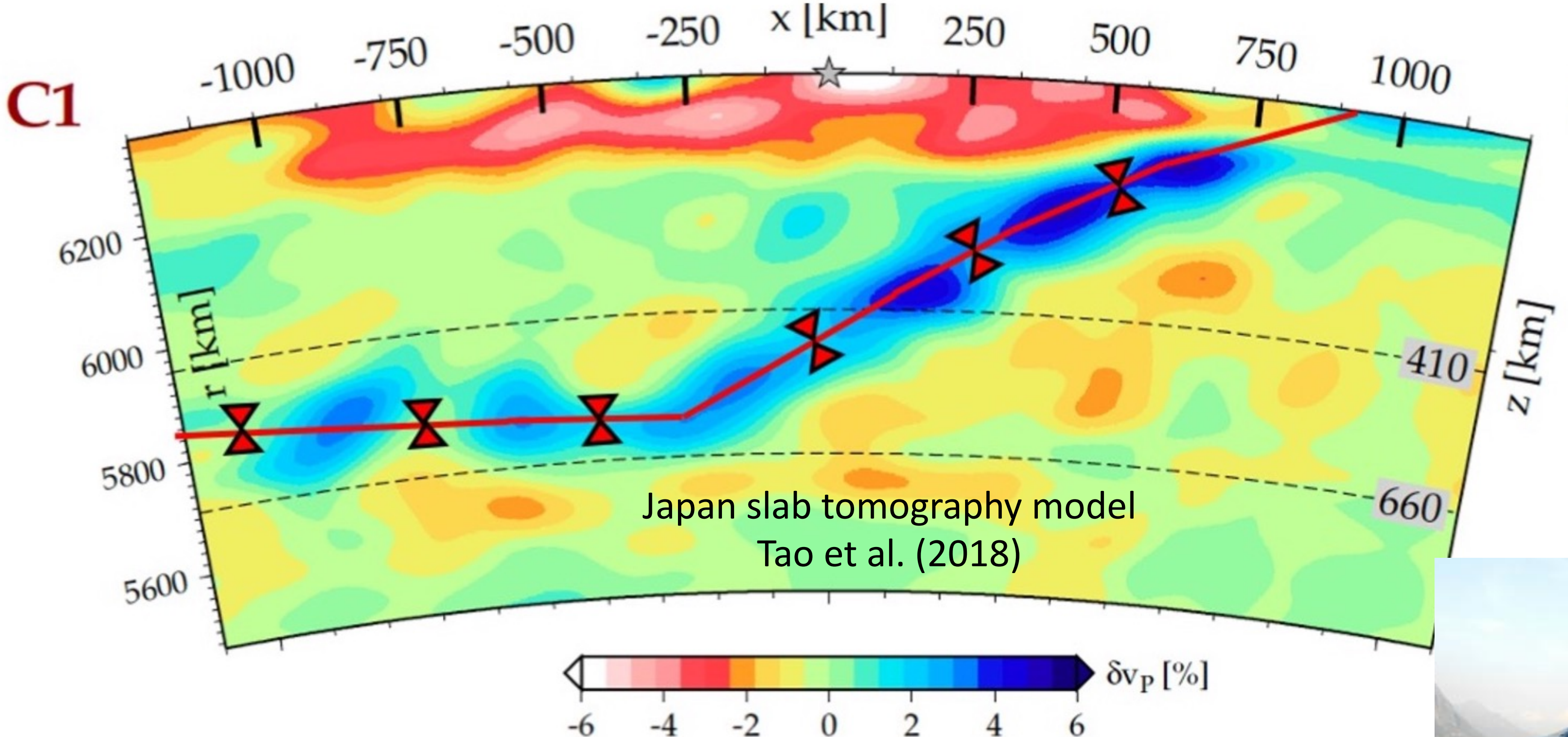
2. As the result, new frontiers in computational geodynamics are defined by its expansion to other fields:

Geodynamics + Seismology
Geodynamics + Landscape Science
Geodynamics + Geochemistry
Geodynamics + Climatology
Geodynamics + Planetology + Astronomy
Geodynamics + Biology + … = **Biogeodynamics**
Biogeodynamics + Social Sciences = **Future Dynamics**

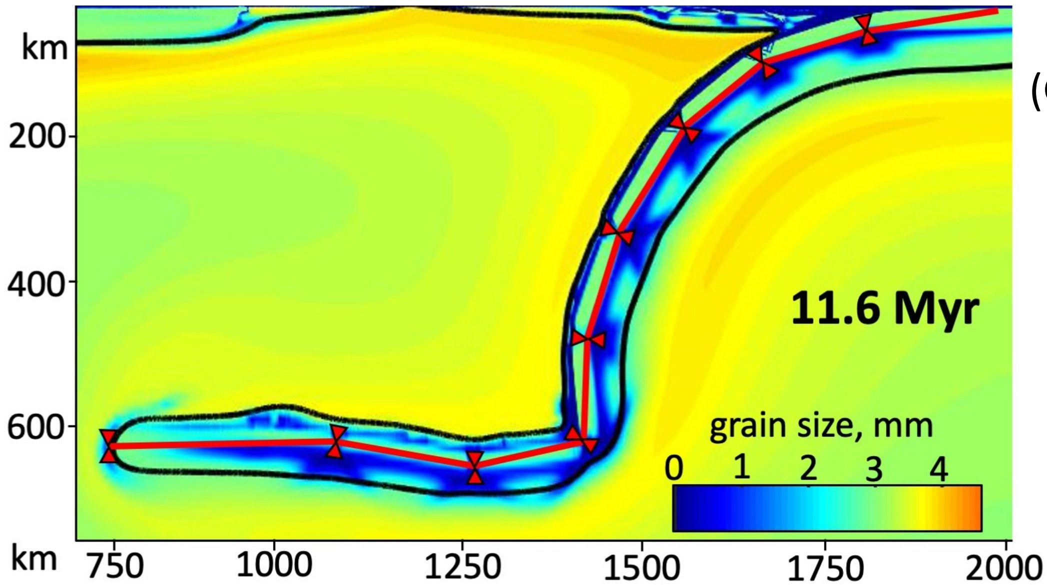
3. Computational Geodynamics helps discovering new processes and phenomena

Geodynamics + Seismology

Discovery of slab segmentation



Japan slab tomography model
Tao et al. (2018)



Model
(Gerya, Bercovici, Becker, 2021)

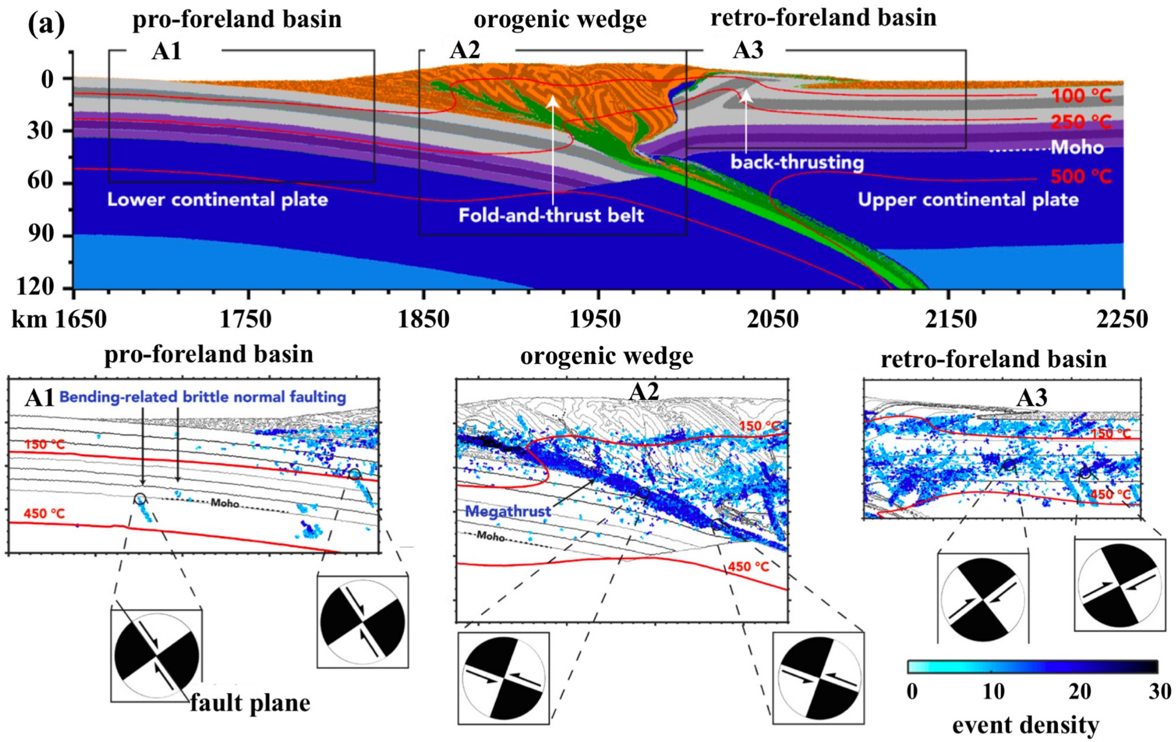
Taras Gerya

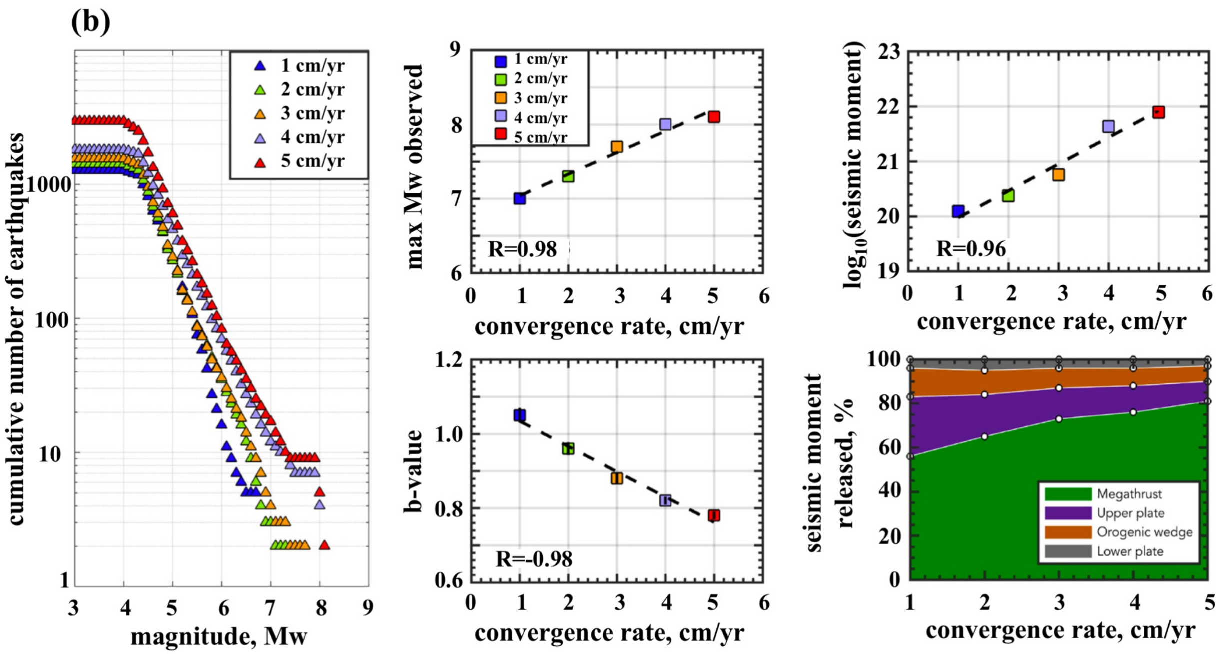
Dave Bercovici

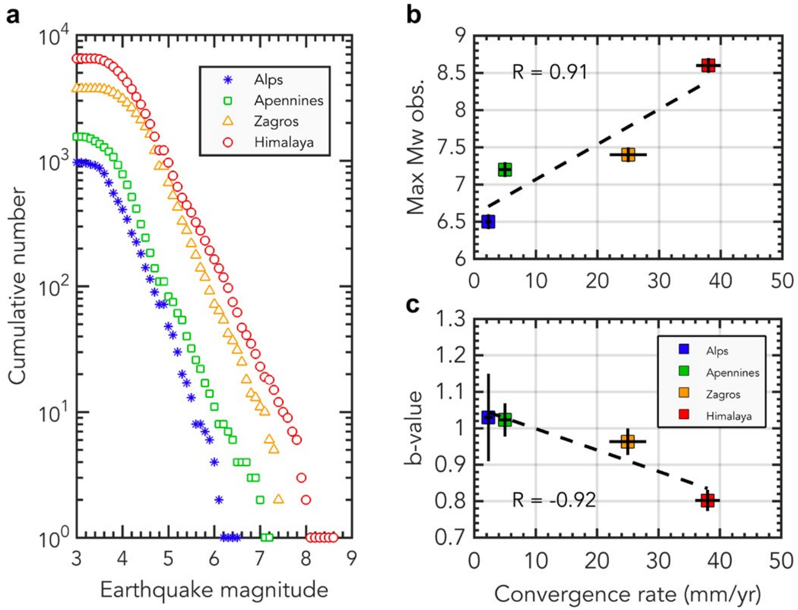
Thorsten Becker

Geodynamics + Seismology

Discovery of seismicity controls







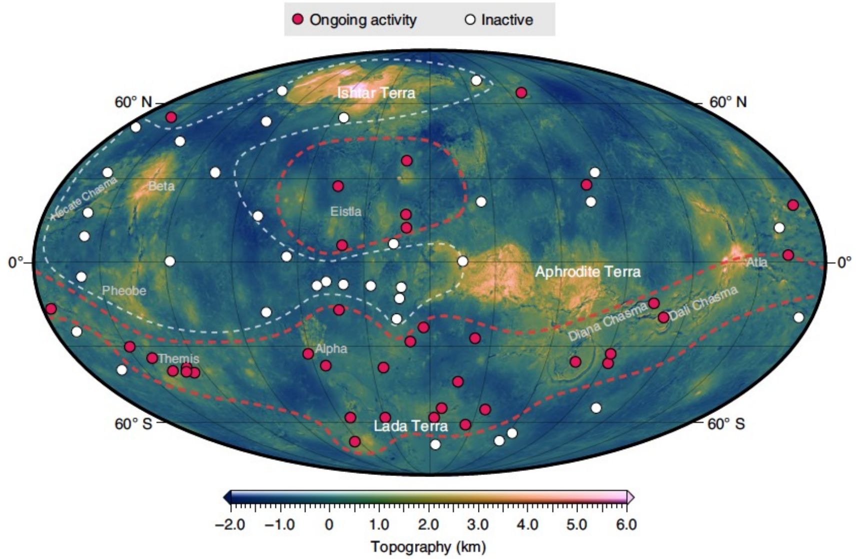
(Dal Zilio et al., 2018)

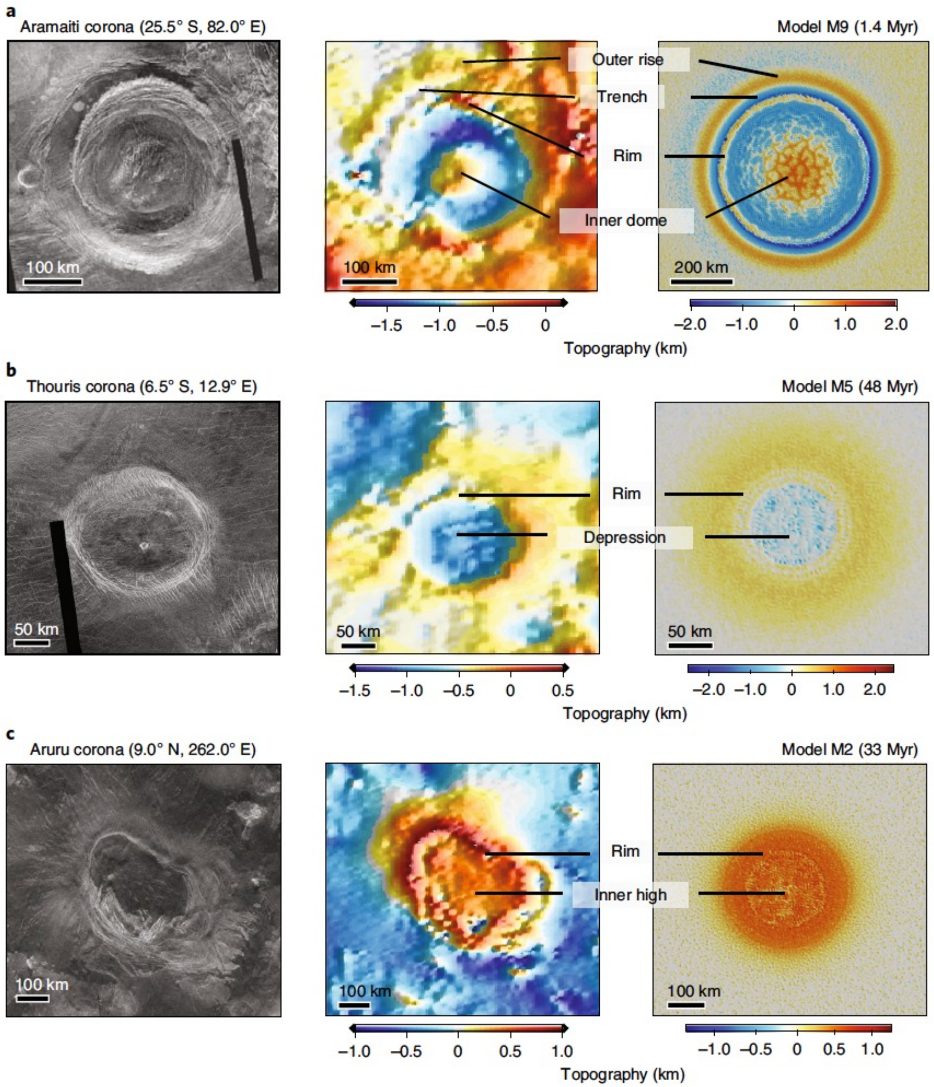
Geodynamics + Planetology

Discovery of Venus "ring of fire"

Anna Gülcher

Gülcher et al. (2020)






CNN World Africa Americas Asia Australia China Europe India Middle East United Kingdom Edition

Venus has crown-shaped hotspots that form its own 'Ring of Fire'

By Ashley Strickland, CNN

Updated 1502 GMT (2302 HKT) July 20, 2020

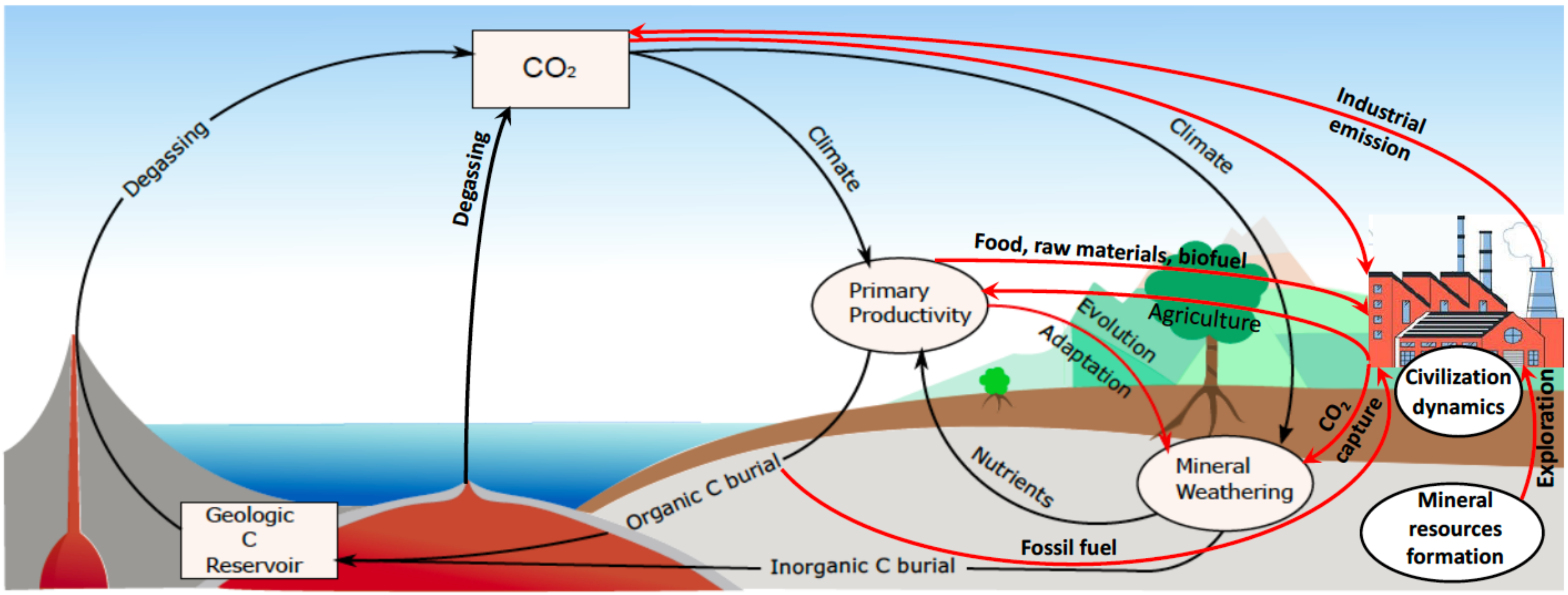
Geodynamics + Biology + … = Biogeodynamics

Biogeodynamics is a new innovative trans-disciplinary field that focuses on understanding and quantifying how the **long-term** interior and surface evolution of Earth and Earth-like planets interact to modulate landscape, atmosphere, oceans, climate, life and human civilization.

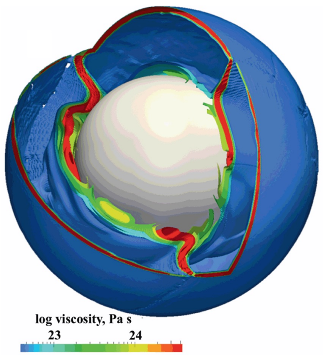
Biogeodynamics explores the interface between the disciplines of geodynamics, geomorphology, climate and atmosphere science, geobiology, ecology and social sciences.

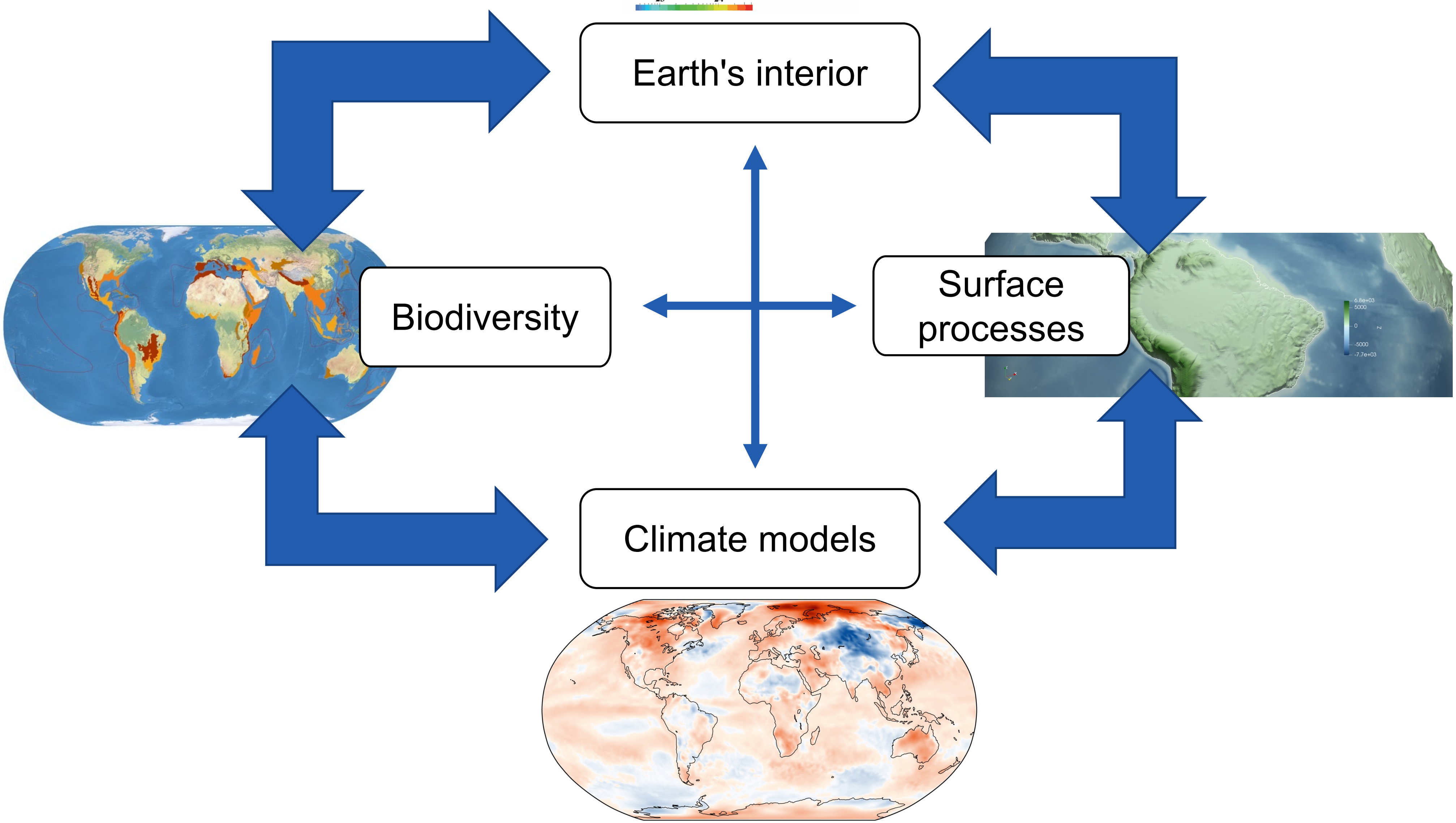
This emergent field aims to understand and quantify these dazzlingly complex relationships by combining observational and hybrid modeling approaches, and development of new hybrid computational tools in which relevant physical, chemical, biological, atmosphere/ocean/climate and geomorphological processes are intrinsically coupled.

Biogeodynamics seeks to investigate different global and regional geodynamical evolution scenarios to gage their influence on biosphere evolution (including humans).



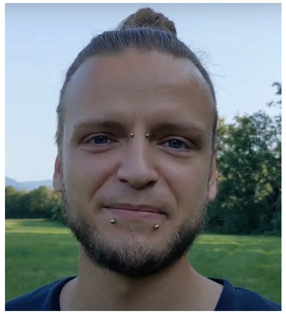
Biogeodynamical Modelling



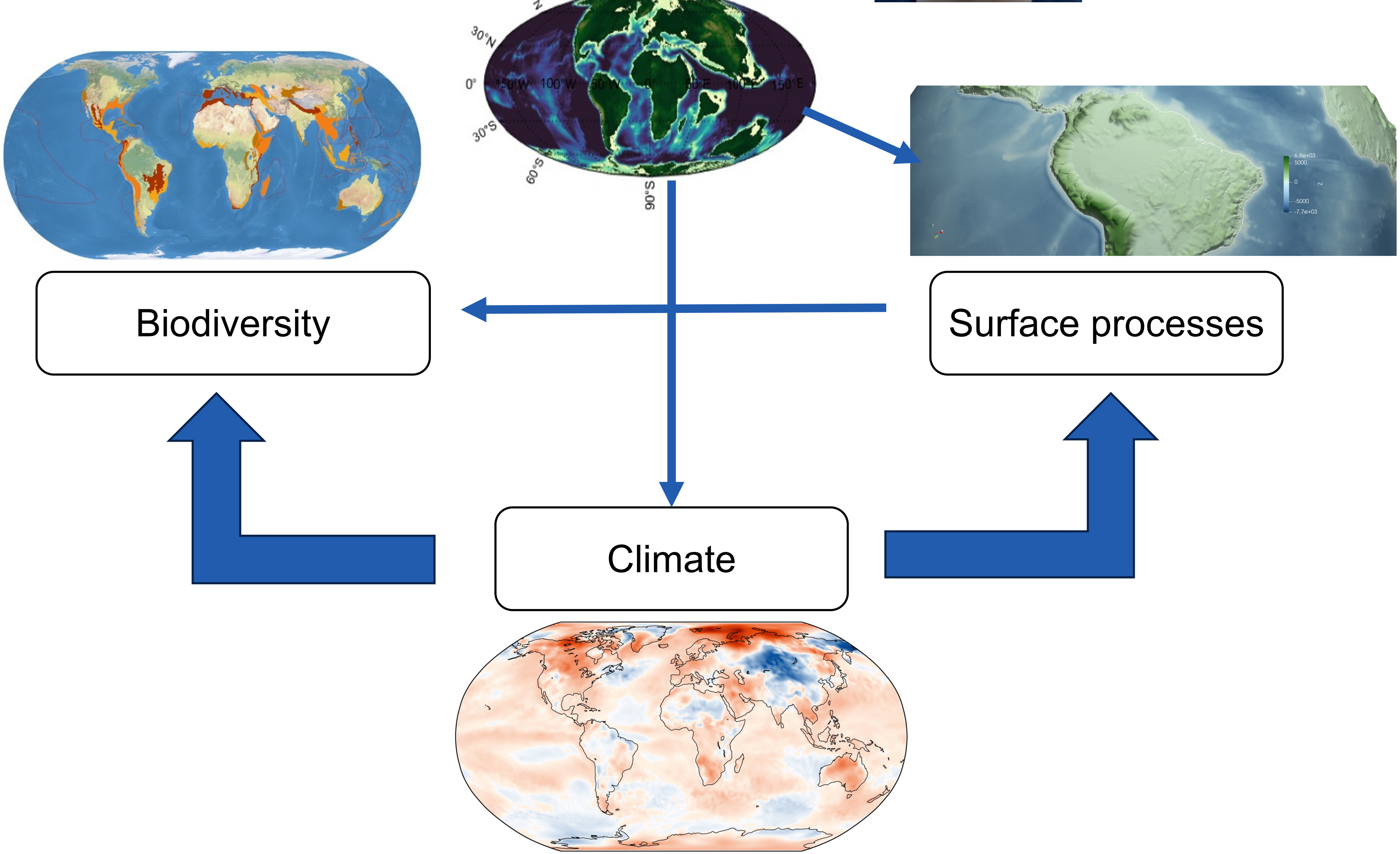


Biogeodynamical Modelling

simplified workflow

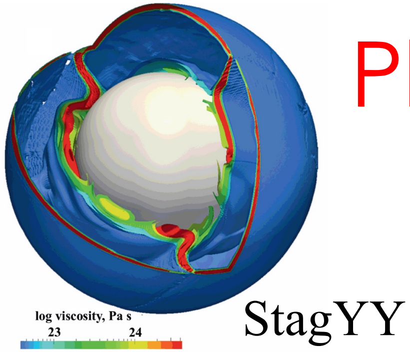


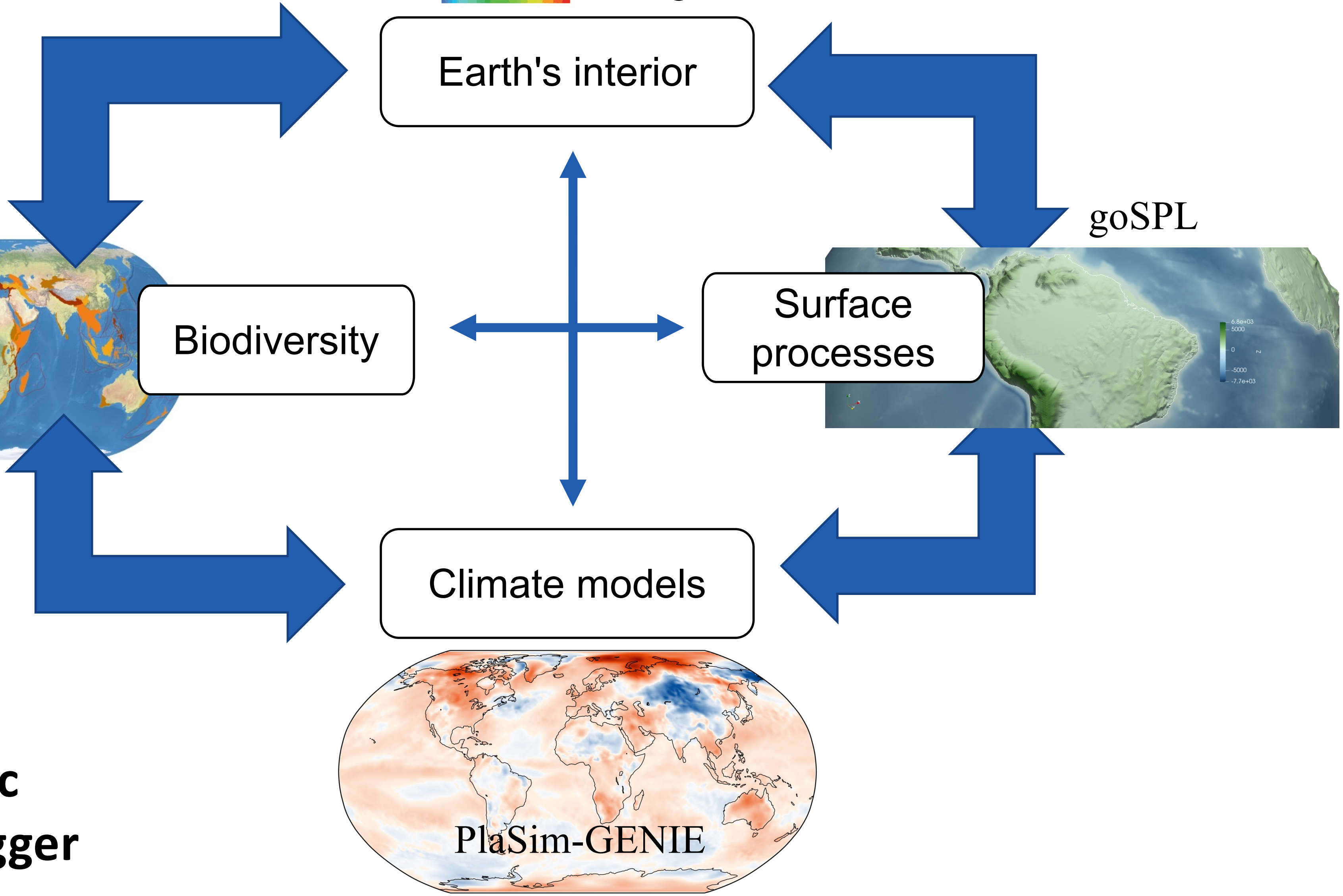
PhD
Dominic
Stemmler

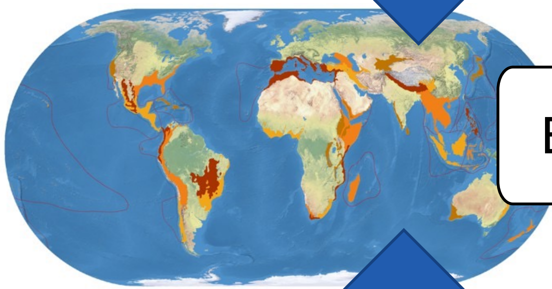


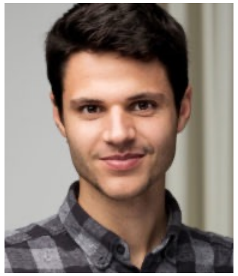
Biogeodynamical Planetary Modelling

advanced workflow

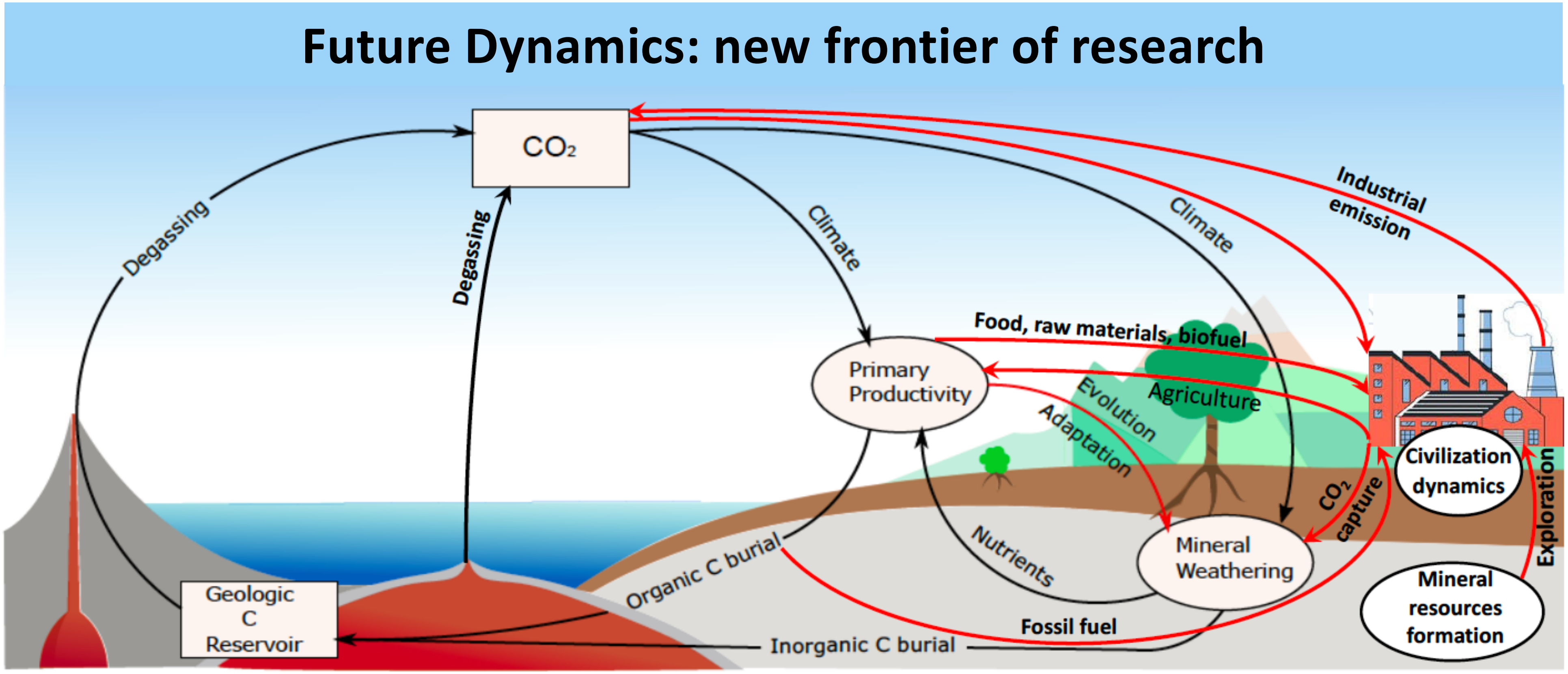








Postdoc
Julian Rogger



Future Dynamics: new frontier of research
CO2
Degassing
Degassing
Climate
Climate
Industrial emission
Food, raw materials, biofuel
Primary Productivity
Agriculture
Evolution
Adaptation
Civilization dynamics
CO2 capture
Exploration
Mineral Weathering
Nutrients
Organic C burial
Geologic C Reservoir
Fossil fuel
Inorganic C burial
Mineral resources formation

Questions and Answers

Boring answer

Exciting Answer

Are we alone?

Questions and Answers

Boring answers

Exciting Answers

Are we alone?

What should we do?

How should we do it?

What do we need?

Questions and Answers

Boring answers	Questions:	Exciting Answers
	Are we alone?	
Yes.		No!
	What should we do?	
Survive.		Search for Aliens!
	How should we do it?	
Align with Earth.		Broadcasting into the space!
	What do we need?	
Future Dynamics.		Gigantic radio stations!

Are we alone?

Yes.

scientific reports

Check for updates

OPEN

The importance of continents, oceans and plate tectonics for the evolution of complex life: implications for finding extraterrestrial civilizations

Robert J. Stern[1] & Taras V. Gerya[2]

No any extraterrestrial civilizations communicate with us☹. Why is that?

1. Civilizations can only be expected on planets with Continents, Oceans, and Plate Tectonics (COPT)
2. Such planets form a very small (<<1%) fraction of habitable planets with primitive life.

(Stern and Gerya, 2024, Scientific Reports)

Where should we look for advanced life?
On planets with oceans, continents and plate tectonics (COPT)

$$f_i = f_{oc} \cdot f_{pt} = <0.00003 - <0.002$$

f_i *is the fraction of planets with life that evolve* ***intelligent life***

$f_{pt}=<0.17$ *is probability for a planet to have* ***plate tectonics***

$f_{oc}=0.00016 – 0.011$ *is probability for a planet to have coexisting* ***oceans and continents***

(Stern and Gerya, 2024, Scientific Reports)

Letter to the Editor

SCIENCE PROGRESS

Potential incompatibility of inherited behavior patterns with civilization: Implications for Fermi paradox

Science Progress
2024, Vol. 107(3) 1–6

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Olev Vinn[1]

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Abstract

All intelligent organisms presumably originally have a number of inherited behavior patterns (IBPs) that are not fine-tuned for conditions prevailing in civilized communities. Indeed, some IBPs may be highly incompatible with such conditions and have high potential to induce self-destruction. These patterns may include responses of social organisms seeking power over conspecifics in relation to harvesting and consuming energy. It is possible that all emerging civilizations could face problems associated with incompatible IBPs, which may partially explain why civilizations are apparently rare (since we have not detected any others in our galaxy).

Lifespan of technological civilizations can be short due to a (fatal) societal collapse (300-1000 years)

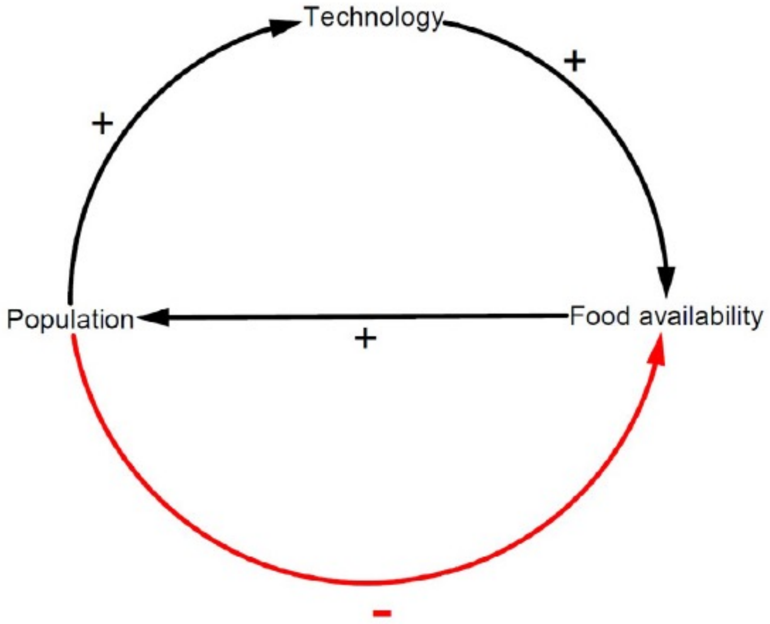
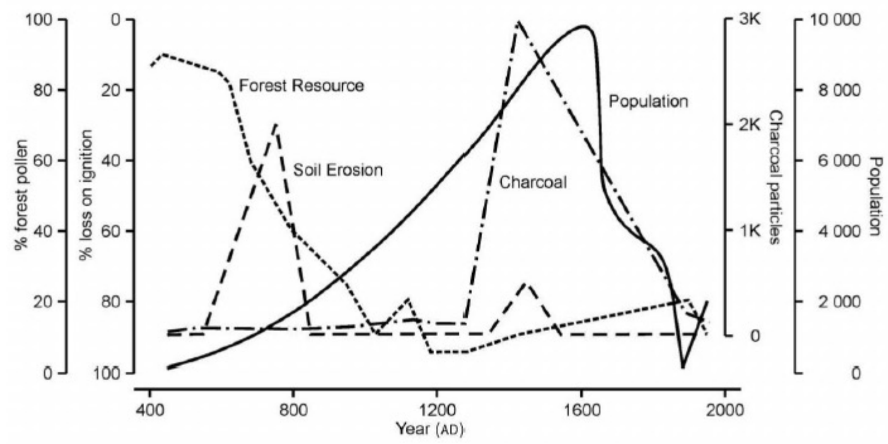


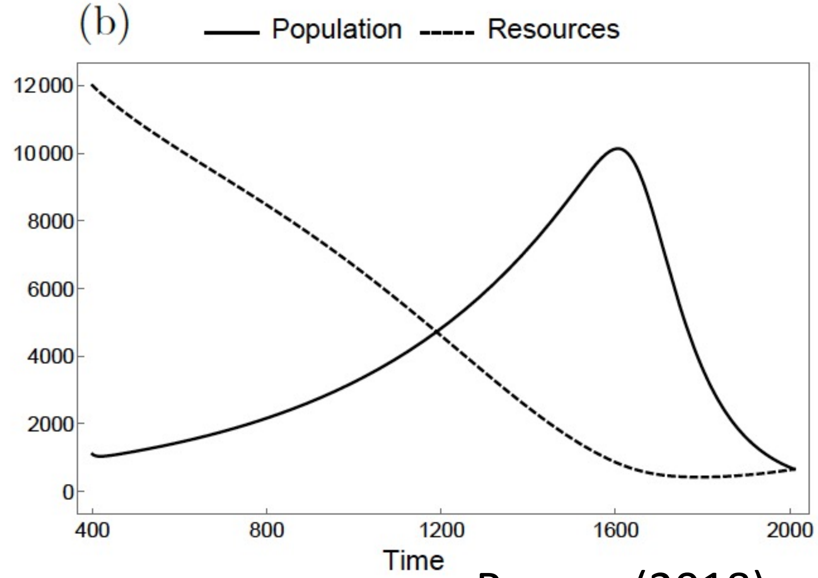
Fig. 1. A causal loop diagram (CLD) illustrating the relationship between population and food availability posited by Malthusian theory (lower half). An increase in population leads to a decrease in availability of food due to larger consumption. An increase in available food spurs an increase in population due to the higher amount of resources. The feedback tends to stabilise: any increase in population comes with a decrease in available food, which leads to a lower population. Boserup considers technology as adding a positive feedback loop (upper half), wherein a greater population leads to more technological innovation which allows more food production.[42]

Roman (2023)

(a) *Archaeological record of Easter Island*



(b) *Socio-Environmental Model*



Roman (2018)

What should we do?

Survive on geological timescales.

Figure 1. Galactic significance and responsibility of humans. Artist's conception of the Milky Way galaxy, our cosmic home, and Leonardo Da Vinci's Vitruvian Man. If intelligent life on Earth is unique, preserving it becomes a galactic responsibility.

How should we do it?

By aligning with Earth tempo and cycles.

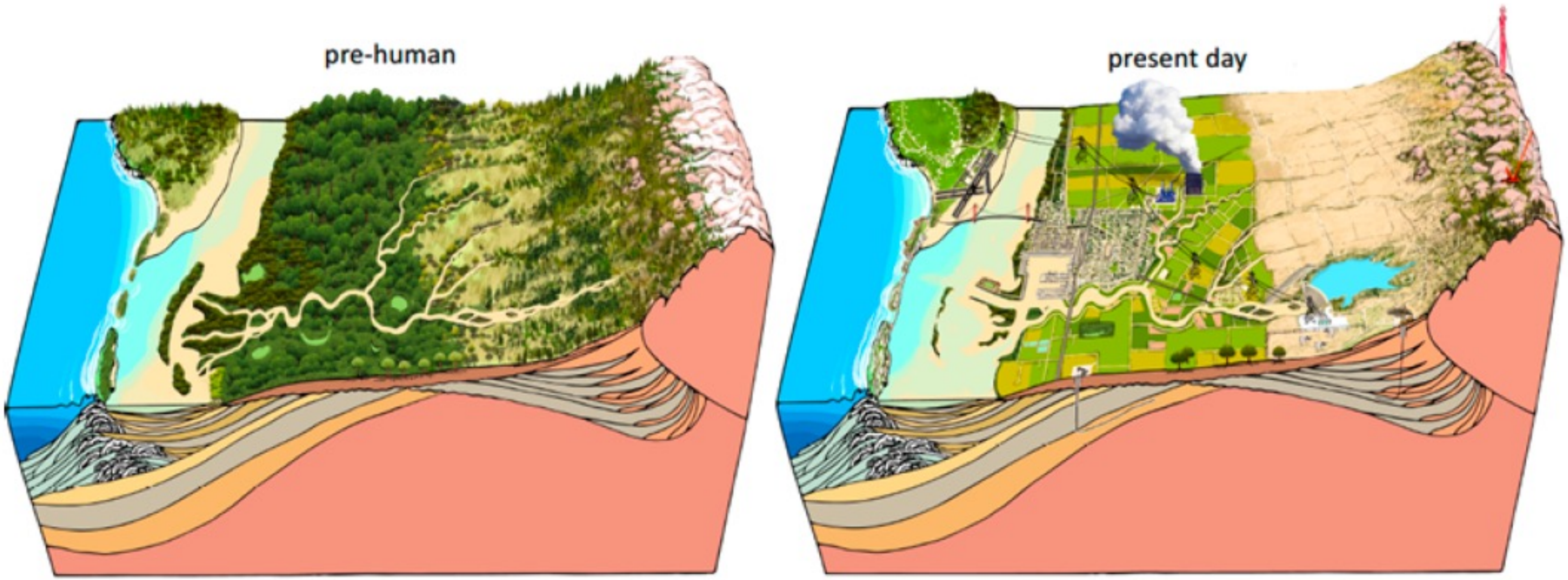
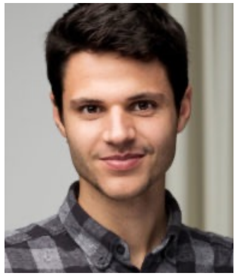


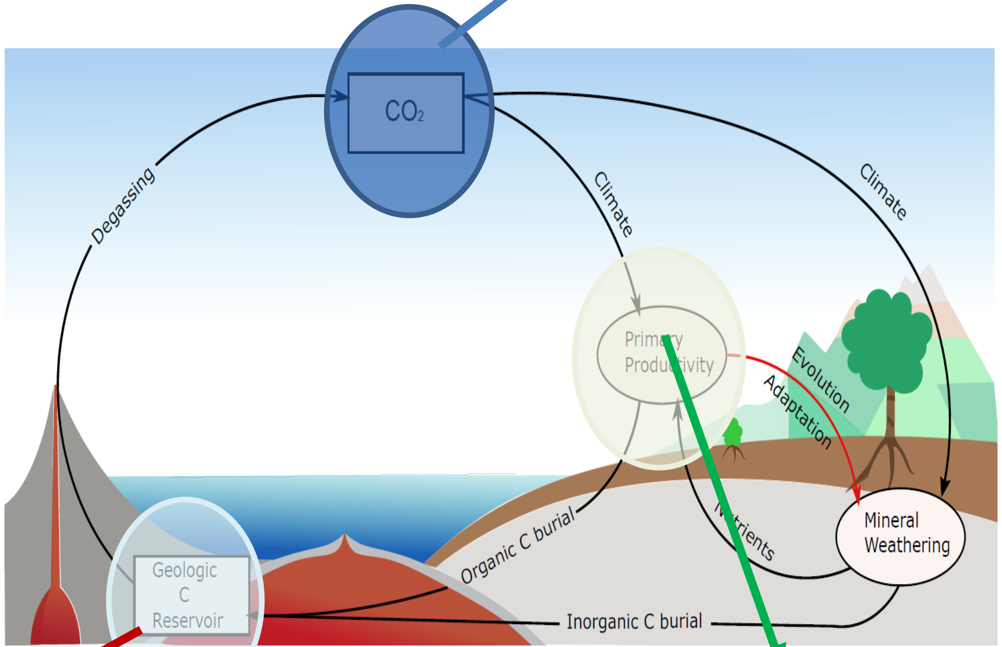
Figure 3. Effects of human civilization on the landscape and biosphere at continental margins. Despite undeniable major geological-biological influence of humans their effects remain surficial.

Biogeodynamical Carbon Cycle



Julian Rogger

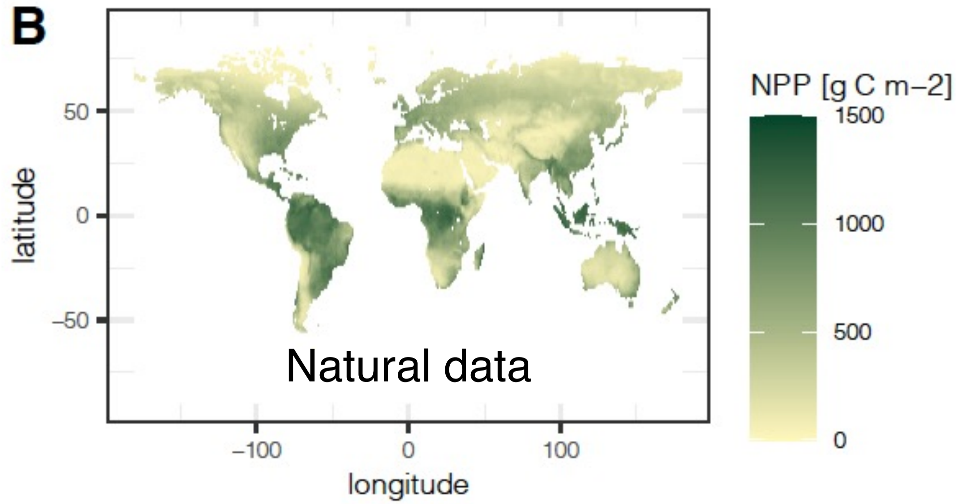
Look-up table of climate simulations with PlaSim (slab ocean or LSG ocean model) at different time steps at different CO_2 levels

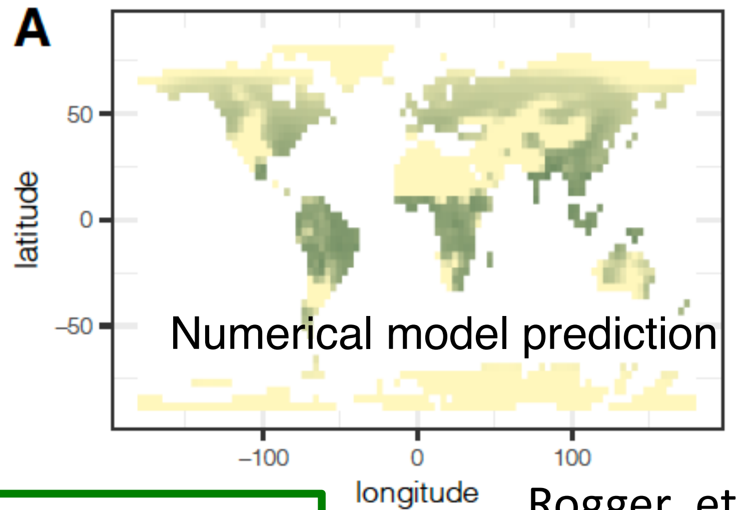


Carbon exchange between geologic reservoirs and atmosphere-ocean: models or reconstructions for degassing, silicate weathering

Eco-evolutionary vegetation model including trait evolution and ecological interactions (e.g., dispersal, competition) – based on gen3sis

Validation of net primary productivity (NPP)





Rogger et al. (2024, Science)

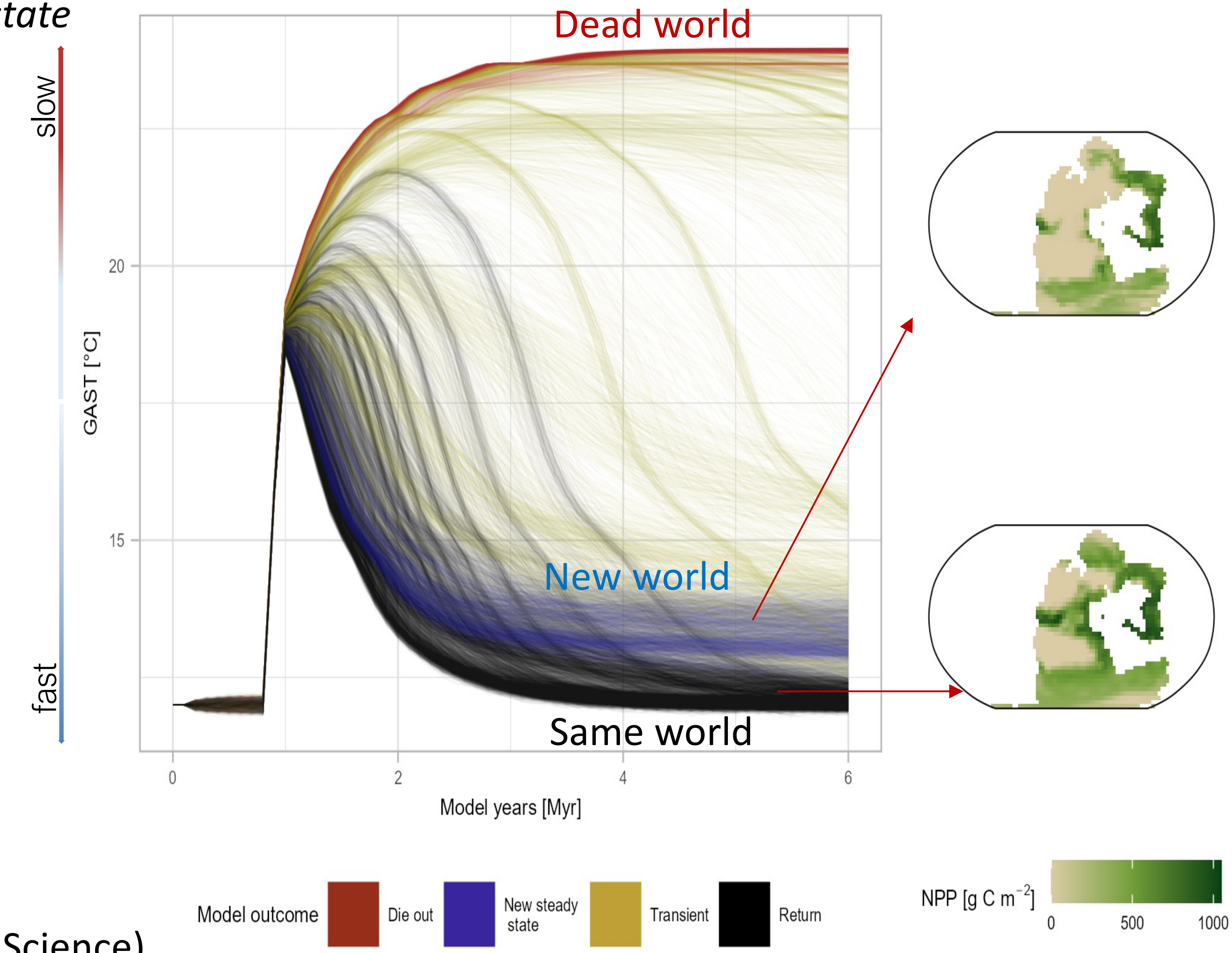
Rogger et al. (2024, Science Advances)

Climate evolution and biological dynamics after extreme CO_2 degassing

Adaptation capacity shapes climate trajectory and long-term climate state

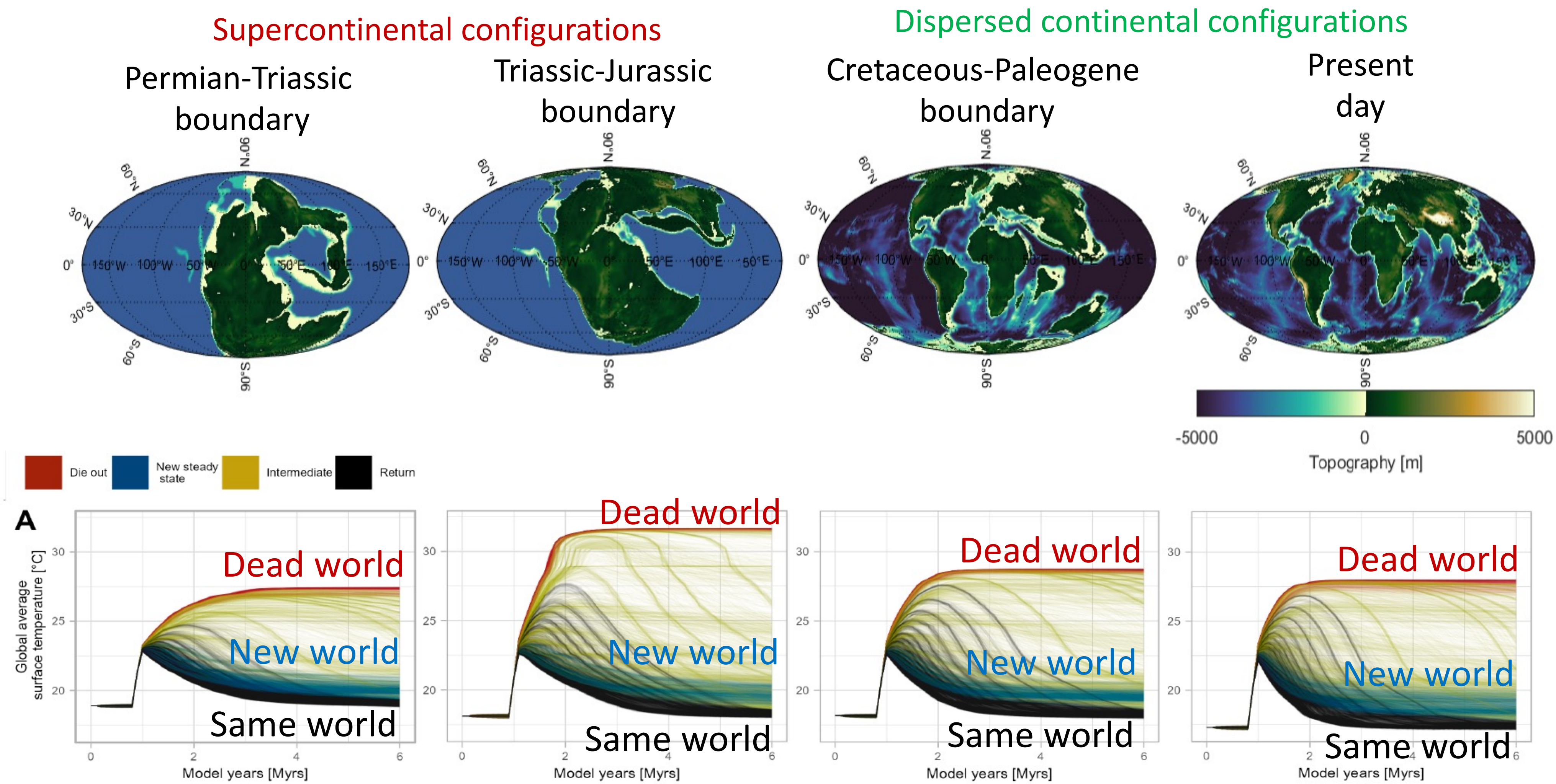
1.) Dispersal range: how far can the floras migrate?

2.) In situ adaptive evolution: how fast can it evolve and adapt to the local environment?



Rogger et al. (2024, Science)

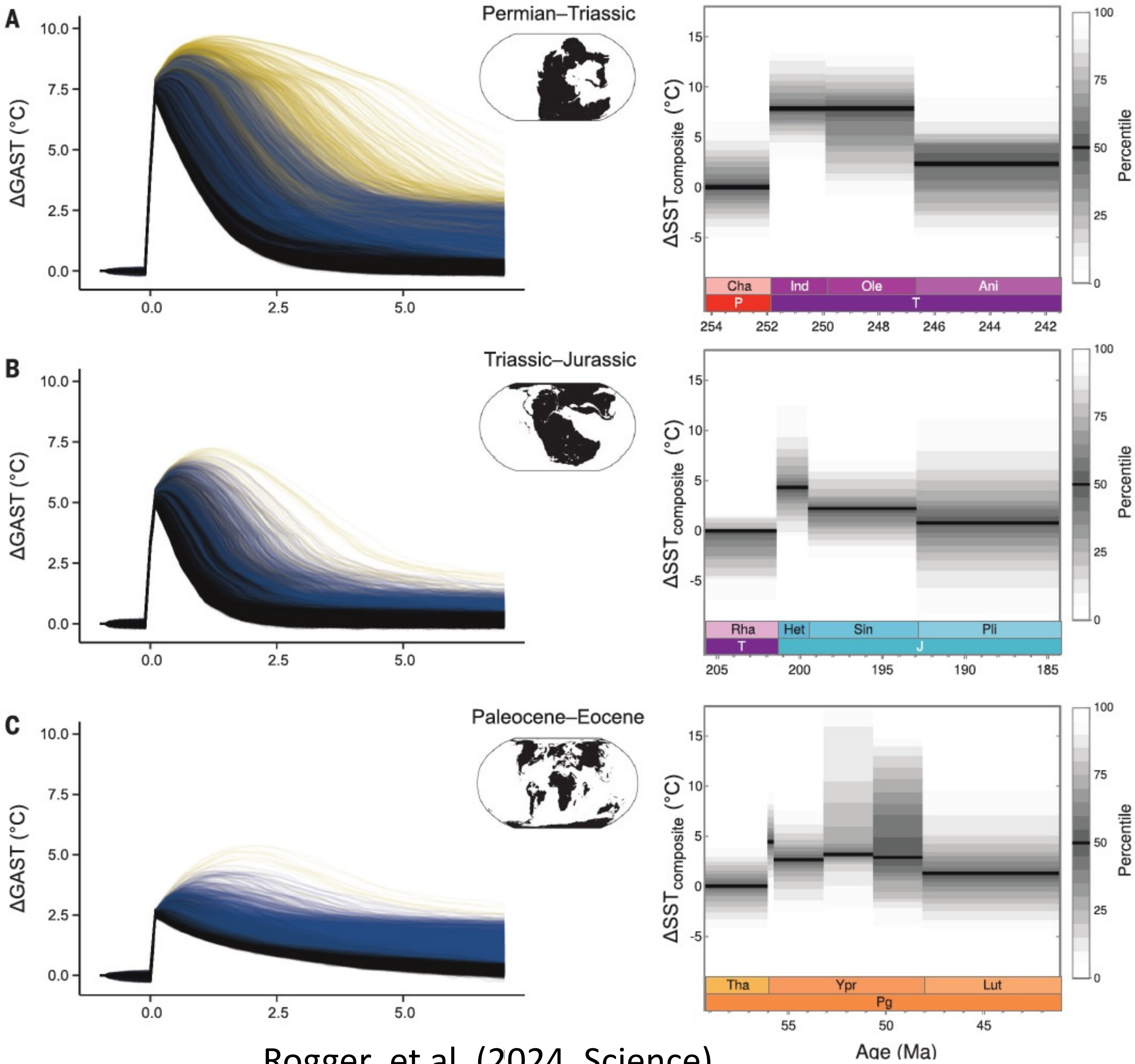
Configuration and vegetation of tectonic plates control longevity and severity of bio-climatic crisis caused by Large Igneous Province degassing



Rogger et al. (2024, Science)

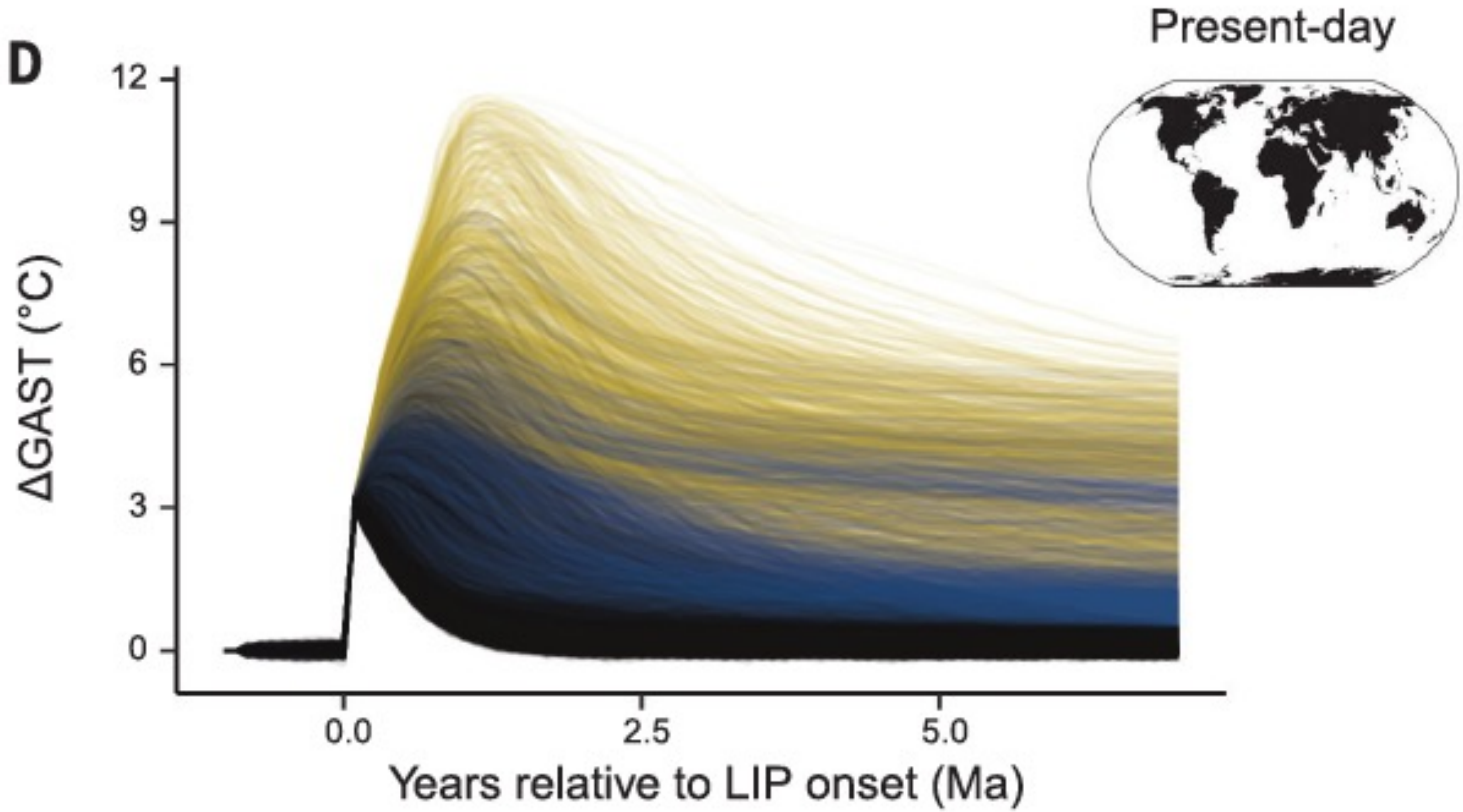
models

data



Rogger et al. (2024, Science)

Recovery is much slower than warming
Present day climate crisis can last for millions of years…



Rogger et al. (2024, Science)

What do we need?

Future Dynamics.

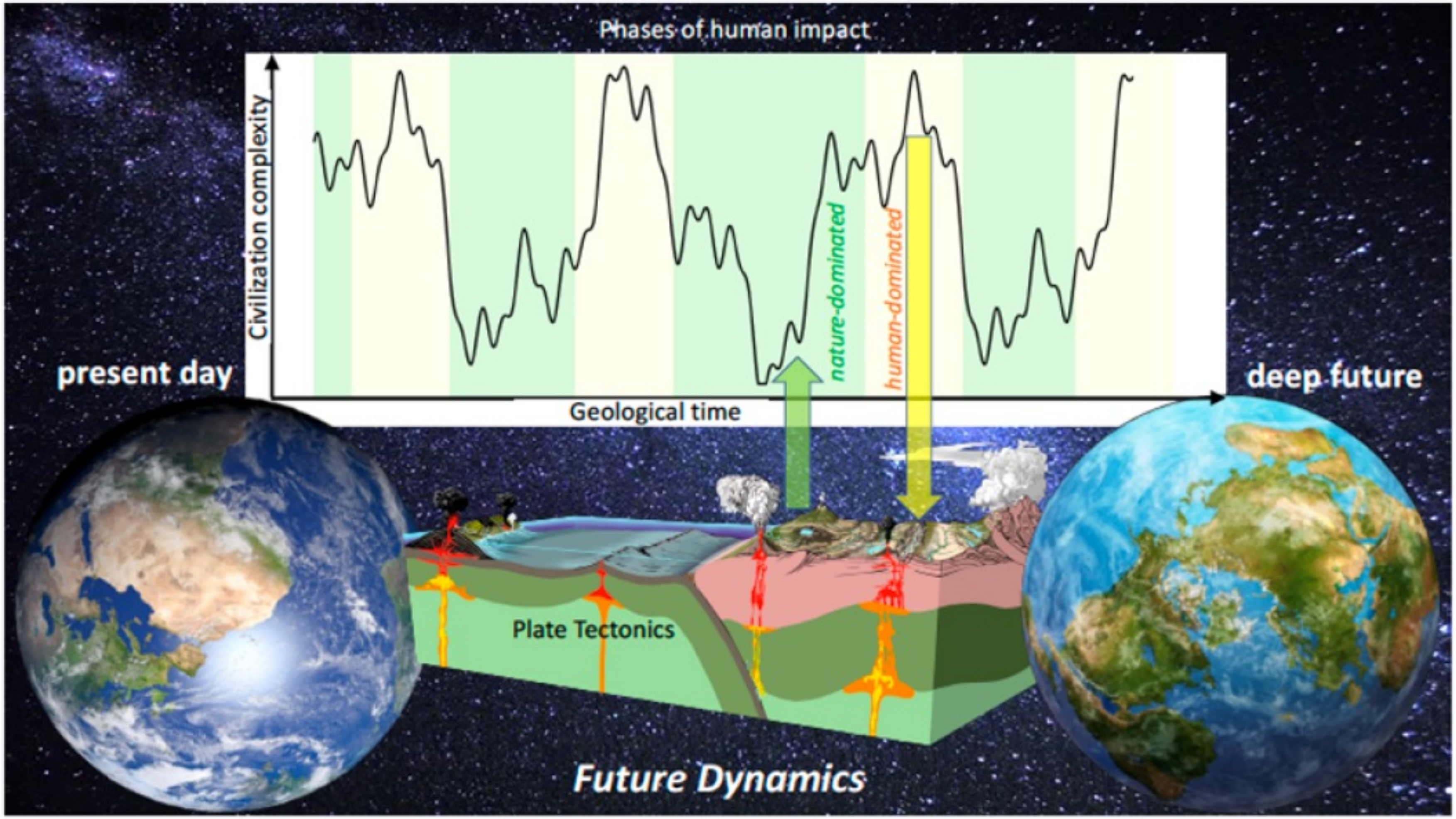
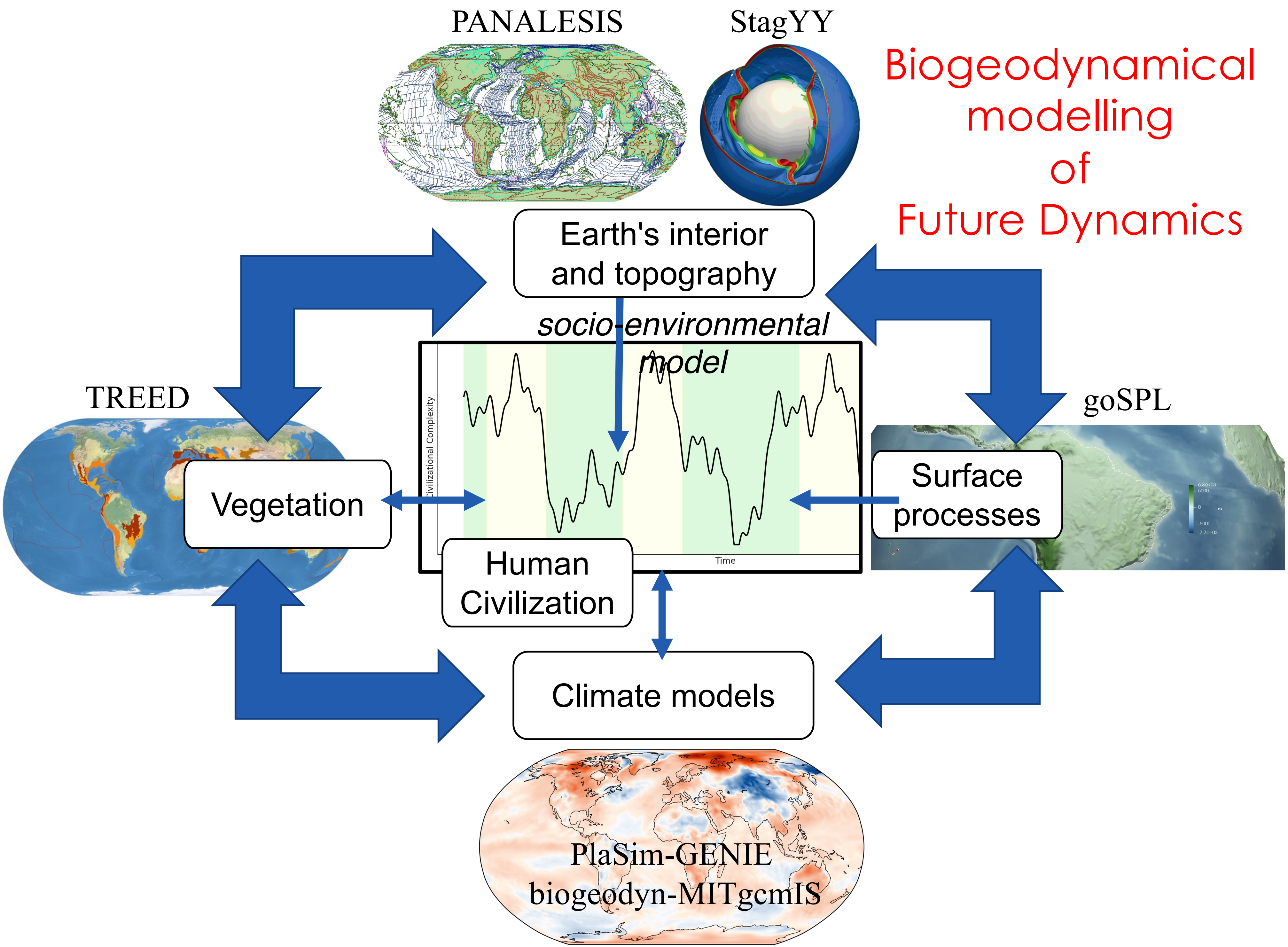
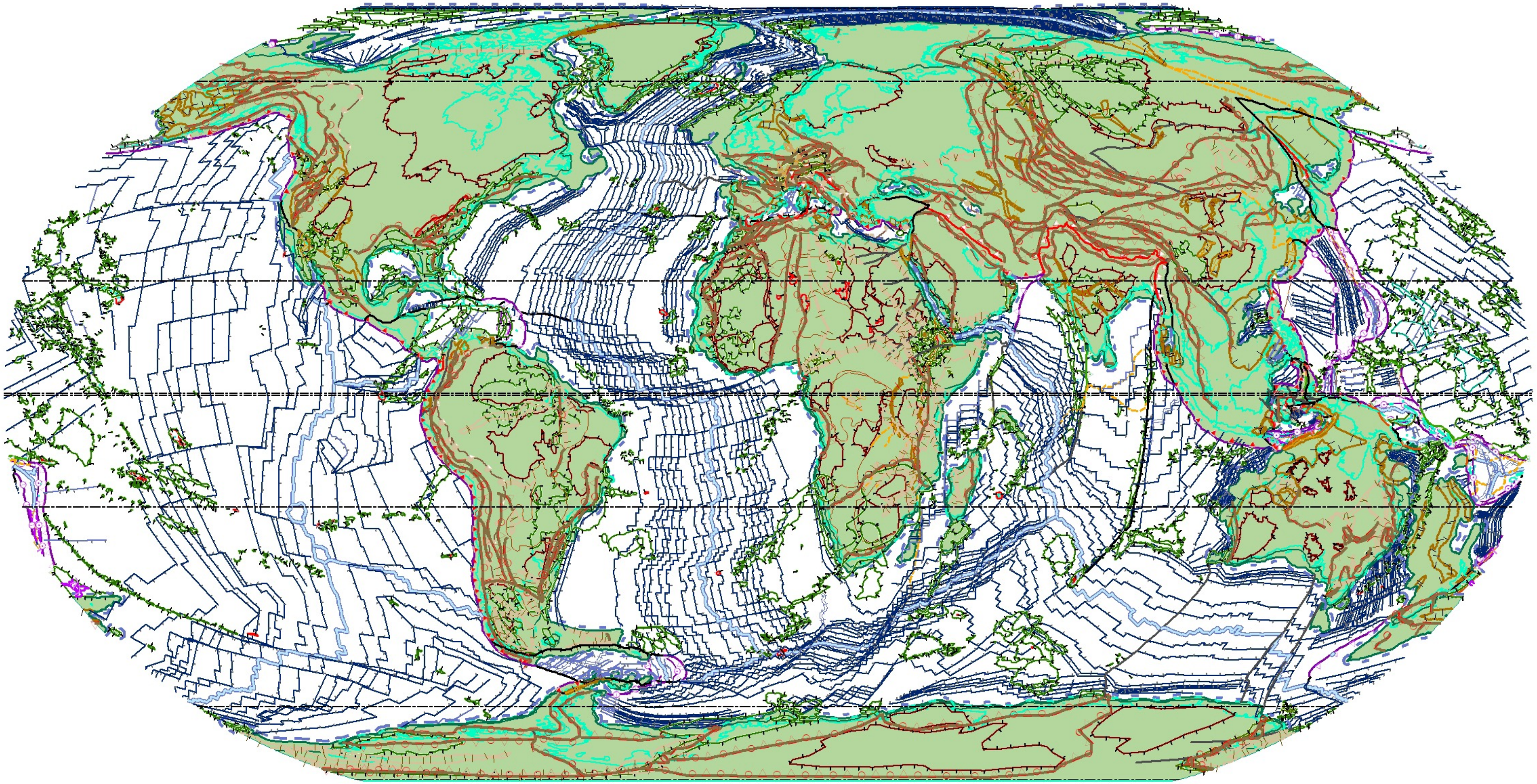


Figure 4. The concept of Future Dynamics bridging Earth's and human civilization's present day with their deep future by considering human civilization dynamics (top) under conditions of plate tectonics (bottom). The curve shows oscillations in civilizational complexity over time highlighting the alternating pattern of environmental impact across history. Yellow (human-dominated) regions mark periods of heightened human influence on Earth's systems, while green (nature-dominated) regions represent lower-impact phases.

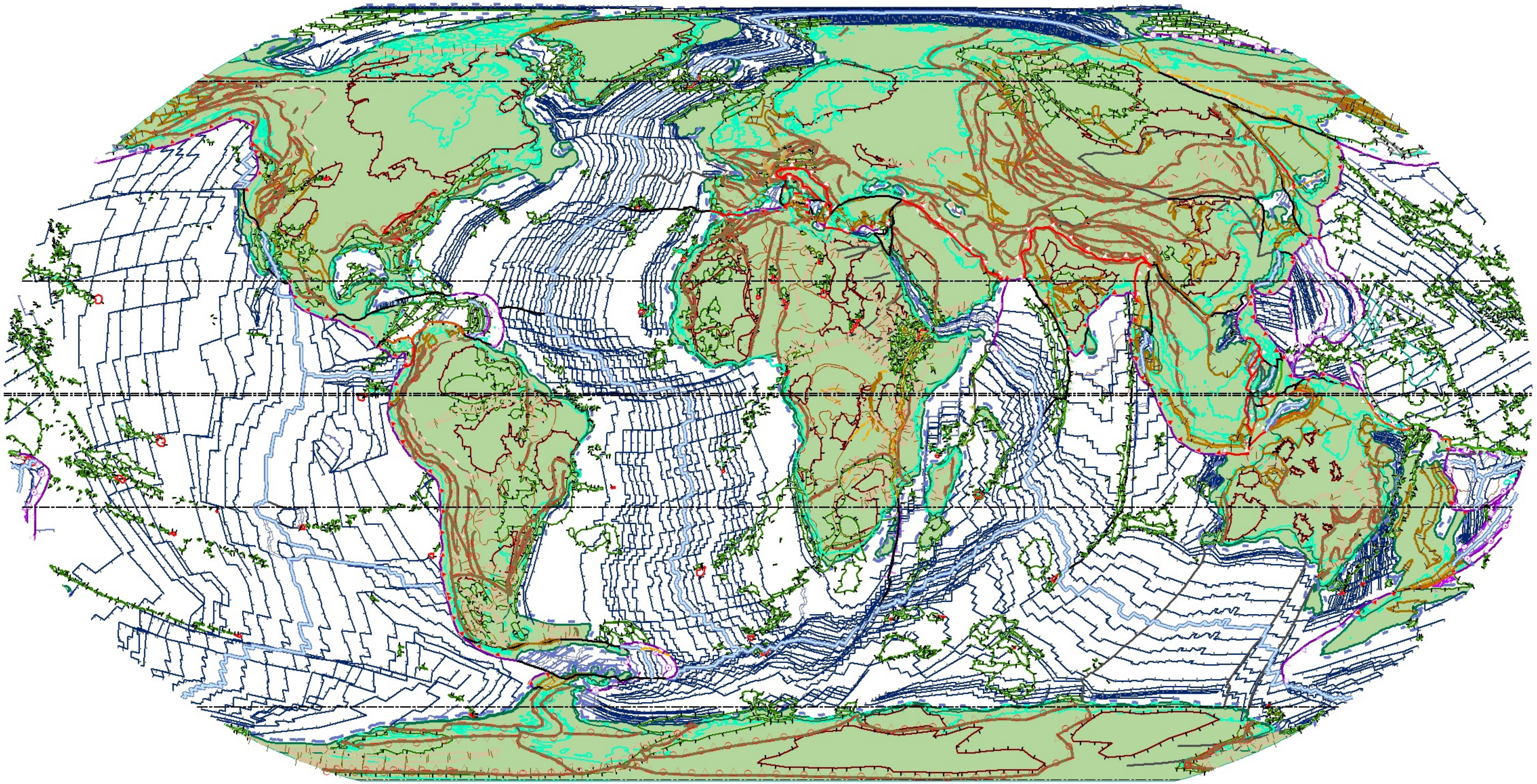

PANALESIS
StagYY
Biogeodynamical modelling of Future Dynamics
Earth's interior and topography
socio-environmental model
TREED
Vegetation
Civilizational Complexity
Time
Human Civilization
goSPL
Surface processes
Climate models
PlaSim-GENIE
biogeodyn-MITgcmIS

Future Earth's geographical configuration and landscape



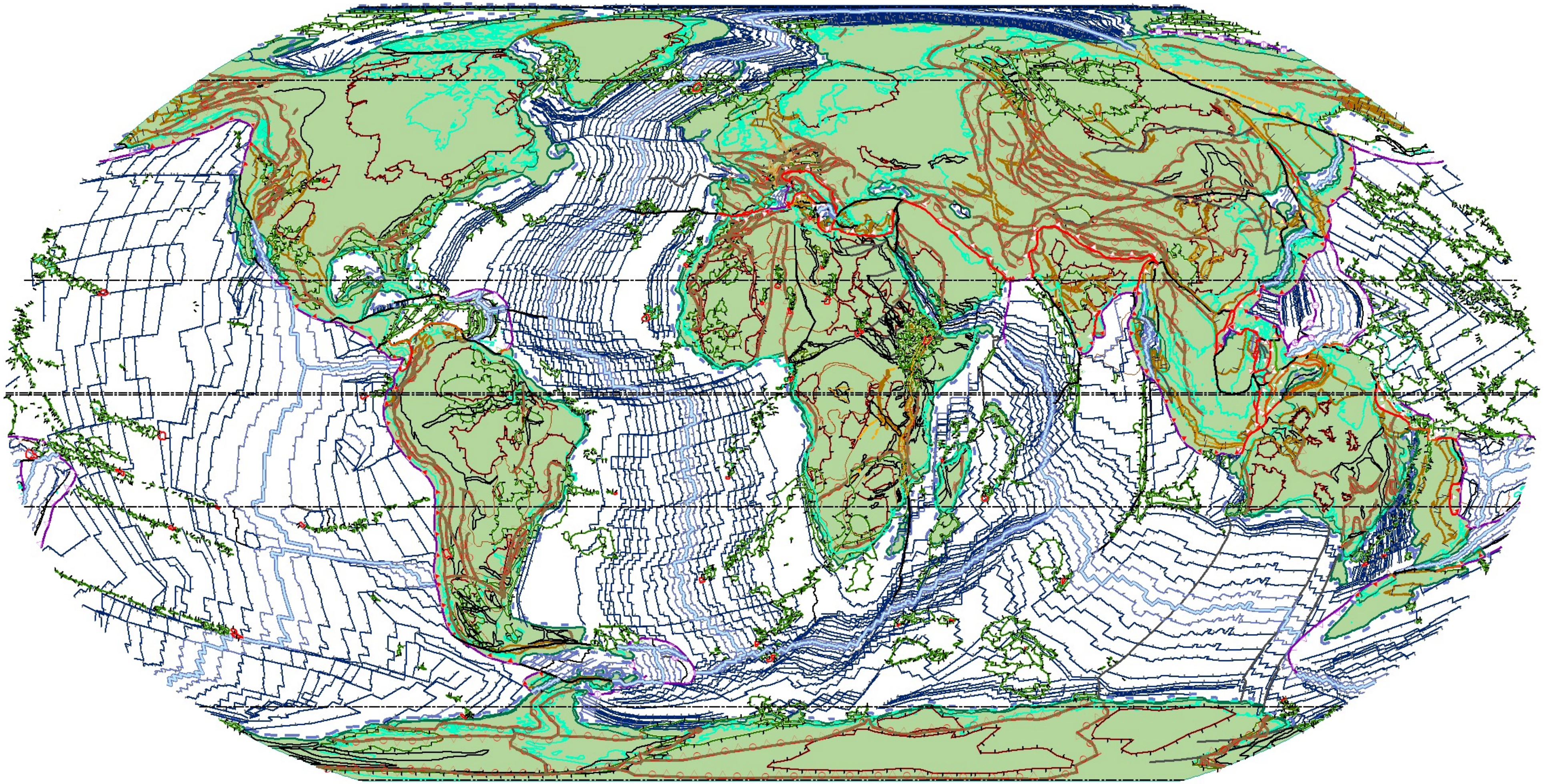
present day (Christian Verard, personal communication)

Work Package 1. Future Earth's geographical configuration and landscape



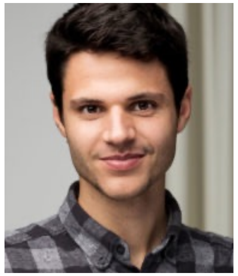
5 Myr after present day (Christian Verard, personal communication)

Future Earth's geographical configuration and landscape

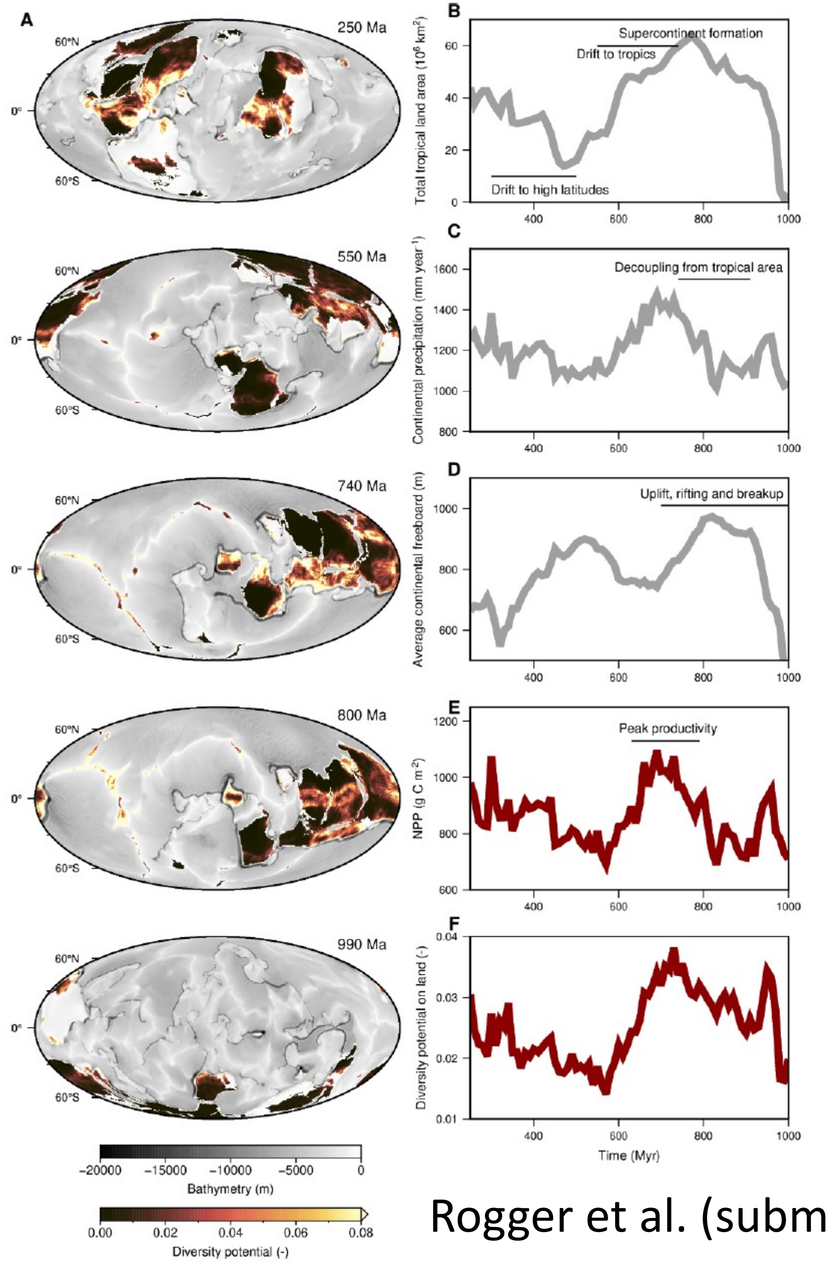


10 Myr after present day (Christian Verard, personal communication)

Future plants- and humans-mediated carbon cycle.



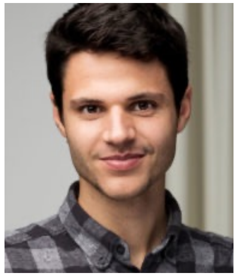
Julian Rogger



Rogger et al. (submitted to Science Advances)

Figure 1: Overview of the planetary simulation. A) Continental arrangement and vegetation diversity potential through time. B) Changes in total tropical land area, C) area-weighted average precipitation on continents, D) average elevation of land above sea level (continental freeboard), E) the average vegetation net primary productivity (NPP), and F) modelled vegetation diversity potential over the course of the 750 Myr simulation of the Earth-like planetary system. The simulation period starts at 250 Myr, following a spin-up of the geodynamic mantle convection model.

Future plants- and humans-mediated carbon cycle.



Julian Rogger

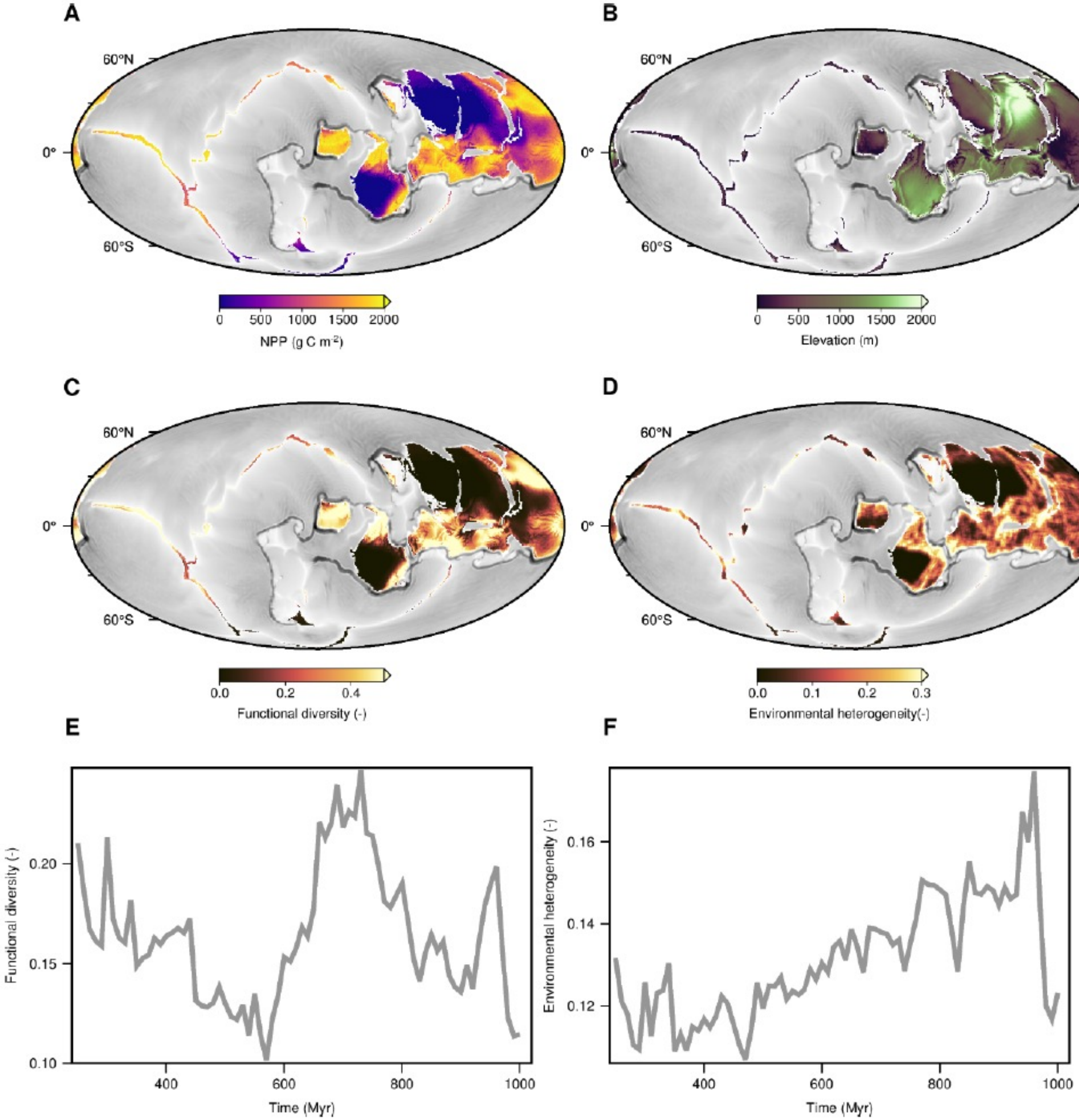


Figure 2: Decomposition of the plant diversity potential through time. Spatial distribution of A) vegetation net primary productivity (NPP), B) topography, C) the modelled functional diversity potential, B) environmental heterogeneity during the supercontinent period (740 Myr). Temporal trajectories of D) the functional diversity potential, E) environmental heterogeneity throughout the planetary simulation. A high functional diversity index in the model represents a large number of plant trait combinations that are evaluated as viable in a given climatic environment. Environmental heterogeneity describes the arrangement of vegetation habitats at a large landscape scale (300 km × 300 km).

Rogger et al. (submitted to Science Advances)

Work Package 3. Future climate multi-stability and tipping points.

1. MITgcmIS

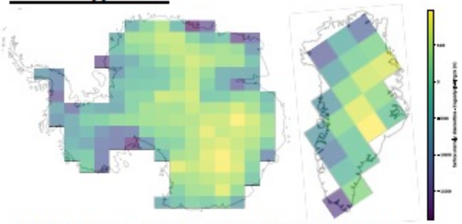


Figure 2: Height anomaly map of BedMachine observations - MITgcmIS

Newly developed **global-scale ice sheet model**, based on the shallow-ice approximation (SIA) and an improved positive degree-day (PDD) method that includes a **percolation layer** for a delayed melting at T= 0°C [6]. It is directly implemented in **the MITgcm cubed-sphere** grid to avoid interpolation errors. **Isostasy** and **lapse-rate** corrections are also included in the *MITgcmIS* python code.

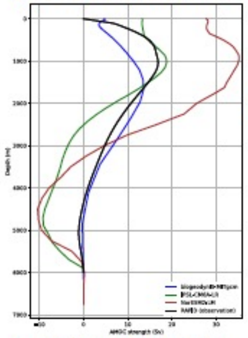


Figure 3: AMOC depth profile at 26.5 °N

Good agreement with the observations with a volume of 28×10^6 km^3(MITgcmIS) against 31×10^6 km^3 (observations).

Correct representation of related climatic components, such as the **Atlantic Meridional Overturning Circulation** (AMOC).

2. PANALESIS

biogeodynIS-MITgcm can run starting from **different boundary conditions.** This allows us to **investigate paleoclimates.**

Figure 4: PANALESIS palaeogeographical reconstructions at selected time frames [5]

Energy is **well conserved**, and the **heat transport is well described** at the top of the atmosphere and at the ocean surface.

	F_s (Wm^{-2})	R_t (Wm^{-2})
biogeodynIS -MITgcm	0.0 ± 0.6	0 ± 2
IPSL-CM6A-LR	1.4 ± 0.2	0.8 ± 0.3
NorESM2-LM	0.8 ± 0.6	0.1 ± 0.6

Table 1: Global average of the energy budget at the surface (F_s) and at the top of the atmosphere (R_t)

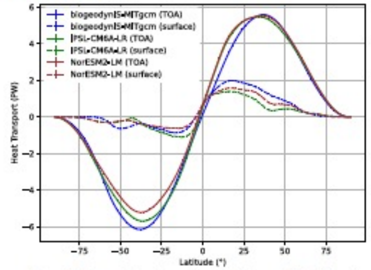
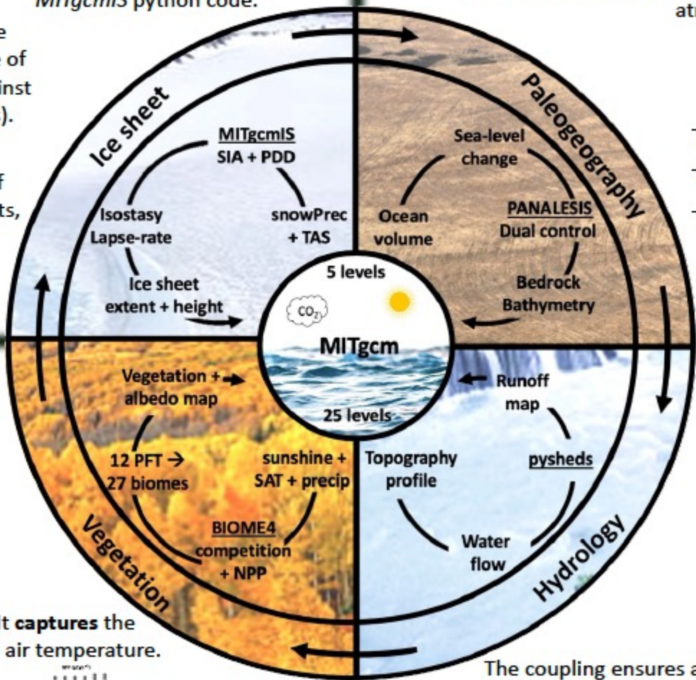


Figure 5: Climatological annual mean of the total (solid) and oceanic (dashed) northward heat transport



4. BIOME4

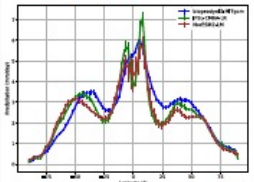


Figure 7: Zonal average of the climatological annual mean precipitation

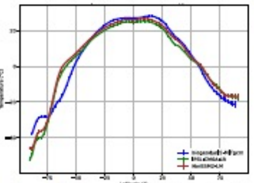


Figure 8: Zonal average of the climatological annual mean surface air temperature

The offline coupling is repeated until convergence. It **captures** the **general zonal distribution** of precipitation and surface air temperature.

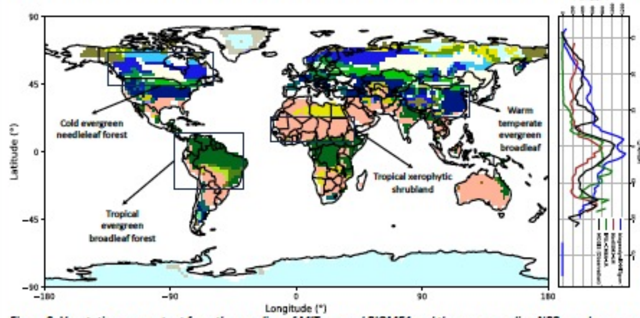


Figure 9: Vegetation map output from the coupling of MITgcm and BIOME4,and the corresponding NPP zonal average

Our coupled setup provides a **good** representation of the **overall** pattern of Net Primary Productivity (**NPP**) and the biomes distribution, in particular the **Amazonian** and the **Boreal forests** and the **desert.**

3. pysheds

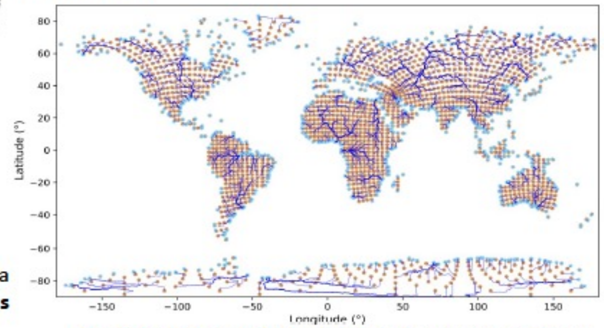


Figure 6: Map of the hydrological flow from the land points (brown) to the corresponding ocean points (light blue)

The coupling ensures a **consistent water-mass transport.**

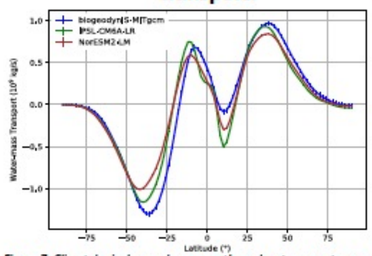


Figure 7: Climatological annual mean northward water-mass transport

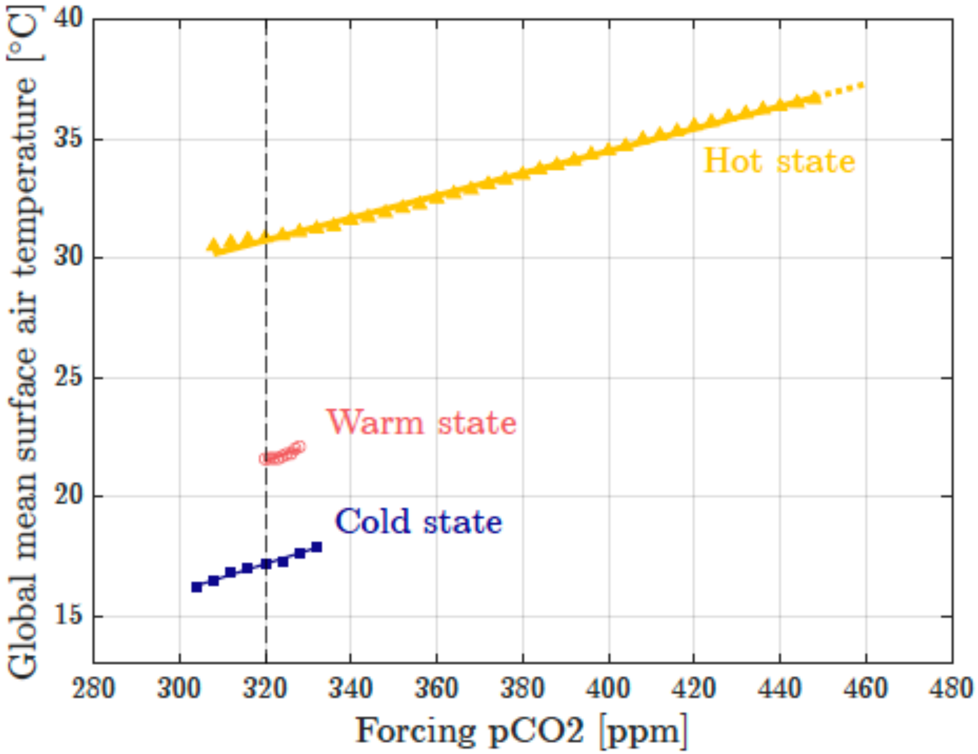
Our coupled setup provides a **good conservation of the water mass** and a sufficiently **good** representation of the **sea ice extent.**

	E - P (10^{-9}kgm^{-2}s^{-1})	NH sea ice extent (10^6 km^2)	SH sea ice extent (10^6 km^2)
biogeodynIS- MITgcm	-2 ± 1	9.7 ± 0.1	16 ± 1
IPSL-CM6A - LR	-8 ± 9	13 ± 7	12 ± 3
NorESM2 - LM	-3 ± 1	11 ± 3	6 ± 3

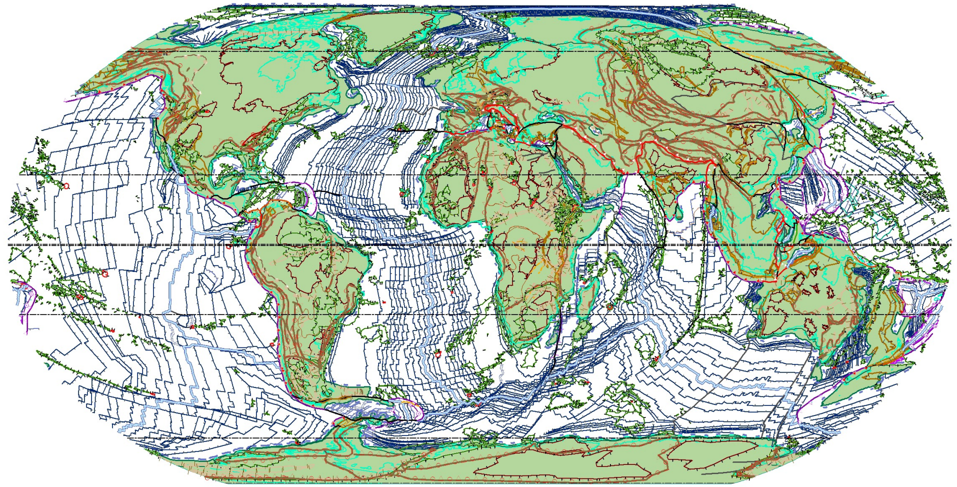
Table 2: Global average water budget and the hemisphere sea-ice extent

biogeodyn-MITgcmIS (Moinat et al., 2025; Moinat et al., in preparation)

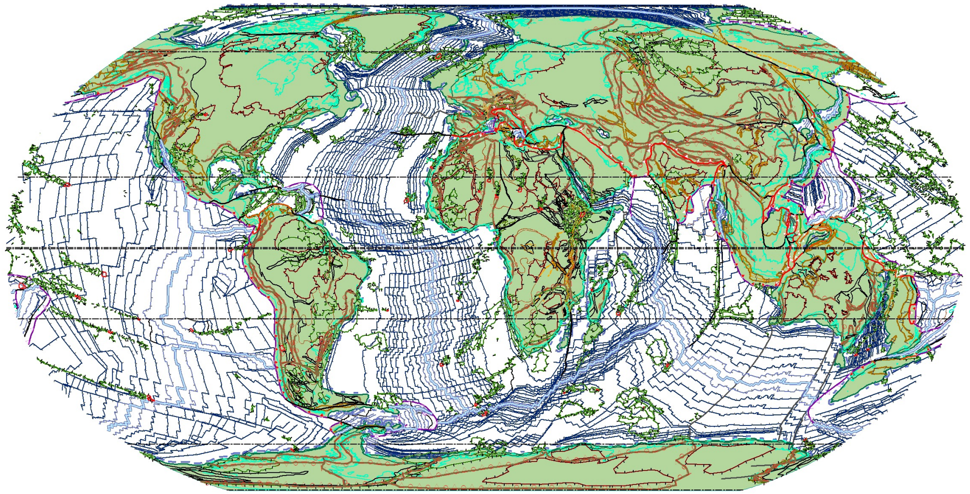
Future climate multi-stability and tipping points.



Alternative climatic steady states (attractors) for the Permian-Triassic paleogeography (Ragon et al., 2023)



5 Myr after present day



10 Myr after present day (Christian Verard, personal communication)

Evolution and longevity of human technological civilization

Model specification

We propose the following model:

$$\begin{aligned}\dot{x} &= \left(b\frac{z}{x+\epsilon} - dx\right)\left(1 - e^{-z/\epsilon}\right) \\ \dot{y} &= ry\left(1 - \frac{y}{K}\right) - \alpha x^2 y \\ \dot{z} &= \alpha x^2 y - cz\end{aligned} \quad (1)$$

for a society with population x, natural resources y and wealth (or capital) z. More generally, the model can be interpreted as follows: x represents a bulk measure of capacity, such as extraction capacity, technological capability, state power, or working population. y represents available resources, which are assumed to be regenerative, while z represents returns. x grows in proportion to returns per unit capacity and decays at a rate proportional to its size. y grows logistically and decreases via extraction, in proportion to its current value times the square of the capacity (a measure of interactions within the social system). The extraction of resources leads to an increase in z. Table 1 provides details on the parameters of the model and their interpretations.

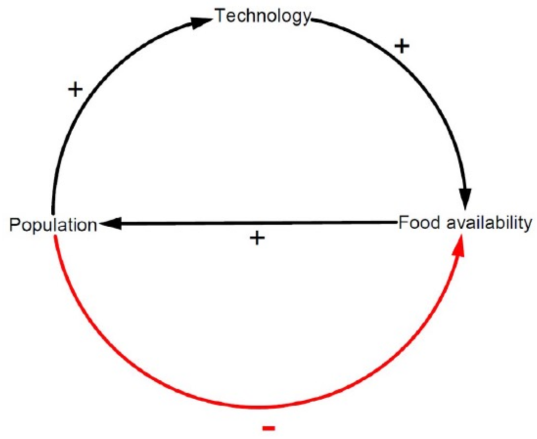
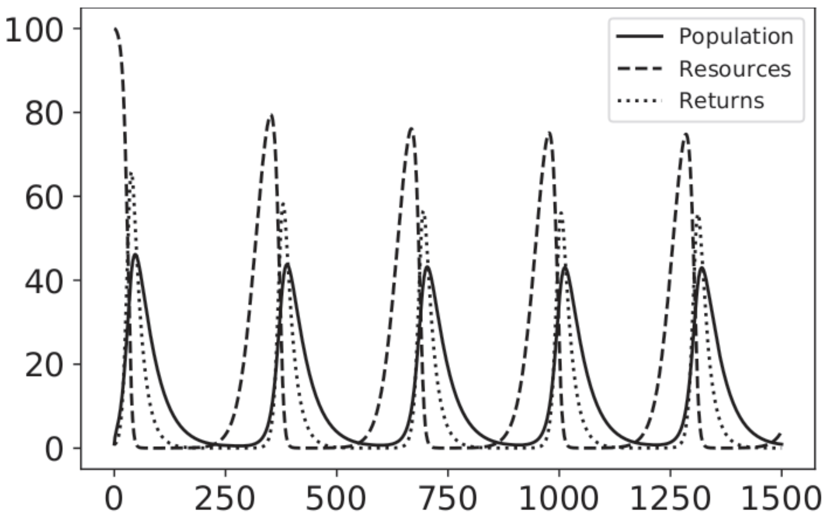
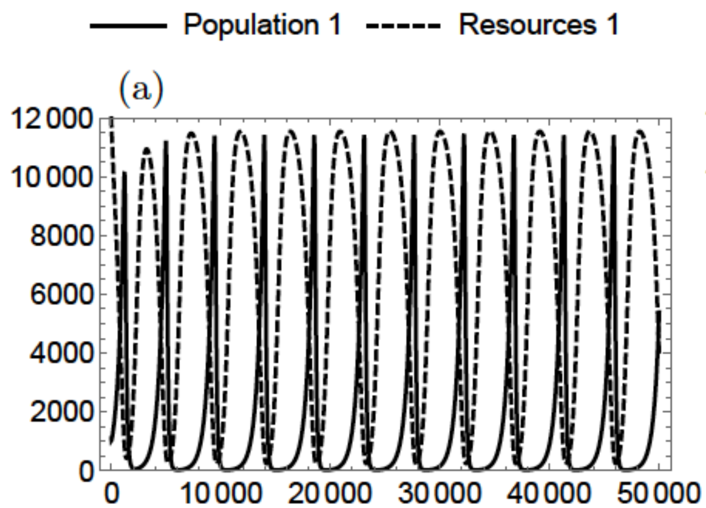


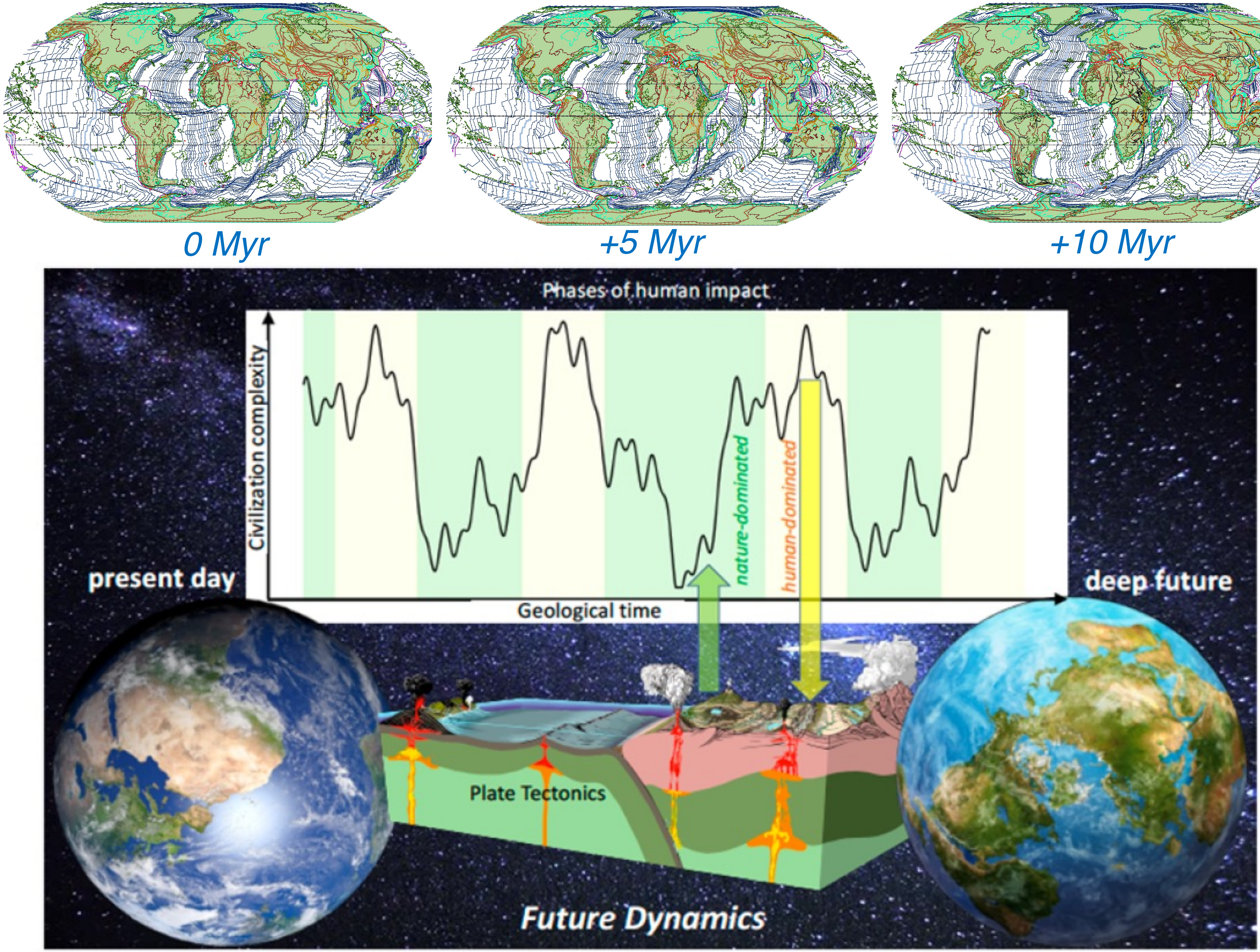
Fig. 1. A causal loop diagram (CLD) illustrating the relationship between population and food availability posited by Malthusian theory (lower half). An increase in population leads to a decrease in availability of food due to larger consumption. An increase in available food spurs an increase in population due to the higher amount of resources. The feedback tends to stabilise: any increase in population comes with a decrease in available food, which leads to a lower population. Boserup considers technology as adding a positive feedback loop (upper half), wherein a greater population leads to more technological innovation which allows more food production.[42]





socio-environmental models (Roman, 2018; Roman and Bertolotti, 2023)

Evolution and longevity of human technological civilization



Habitable Planet, 2026, 2(1), 1–13
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Article

The Long-Term Survival of Human Civilization: A Science-Based Paradigm

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Research Highlights

- Human technological civilization is likely unique in the galaxy
- The long-term survival of our civilization is a prime scientific and moral priority
- Civilization's activities should be aligned with solid Earth tempos and cycles
- We propose "Future Dynamics"—a new scientific frontier focused on civilization's long-term survival

BIOGEODYNAMICS
cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY
International Lithosphere Program
ETH zürich
Schweizerischer Nationalfonds

Conclusions

1. Computational Geodynamics is an expanding young science with strong HPC-AI potential.

2. New research frontiers in computational geodynamics are defined by its expansion to other fields:

Geodynamics + Seismology

Geodynamics + Landscape Science

Geodynamics + Geochemistry

Geodynamics + Climatology

Geodynamics + Planetology + Astronomy

Geodynamics + Biology + … = **Biogeodynamics**

including (hopefully) emergence of

Biogeodynamics + Social Sciences = **Future Dynamics**

BIOGEODYNAMICS

3. **The exciting new fields of Computational Biogeodynamics emerged, which explores connections between deep Earth processes, surface processes, and evolution of life and human civilization on Earth and other planets.**

Cross-disciplinary HPC-AI community effort is required for future progress.

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