Simulating the evolution of Earth's environment to understand complex life in the universe

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What drove ancient warm and cold climates on Earth?
Why did it take billions of years for atmospheric oxygen to accumulate?
What planets are most likely to host complex or intelligent life?

Over the last few decades, a detailed picture has been built of how Earth's surface environment has changed over the 4.5-billion-year history of the planet. For much of its lifetime, the Earth was truly an alien world, and one on which modern humans would not have been able to survive. When animals, and later mammals, evolved they faced a different world to the present, with different levels of oxygen and carbon dioxide in the atmosphere, much hotter or colder temperatures, and an environment punctuated by deadly extinction events.

While the picture of environmental change has become clearer thanks to geological evidence, we still know very little about why these changes occurred. Particularly, we do not yet understand the role of the biosphere in driving environmental change or the ways in which environmental change has driven biological evolution. This knowledge is essential for managing our planet as we chart our way into an unknown future, and understanding how our own planet works is essential if we are to know where to look for other complex or intelligent life in the universe.

Computer programs that we call Earth system models have been used to explore how our planet works, what it was like in the past, and what it might be like in the future. But despite their all-encompassing name, these models are only able to capture incomplete sets of the processes that are operating on our planet. Sometimes, they focus on the climate, the chemistry of the oceans, or the dynamics of the mantle and tectonic plates. Some models do aim to link all these parts of the Earth together, but our limited computing power means that to do so, they must use extremely simple versions of each process, or they must only run the model for a small number of model-years—not the billions of years that the planet has been in existence.

This all comes down to solving complex systems of equations in 3D, which is difficult and time-consuming, even with a supercomputer. We do not currently have the computational power to do everything we want to do. So, we must choose between having detailed representations of systems, large numbers of interacting systems or long model timeframes. We cannot have it all, but without all these pieces, we cannot understand the history of the Earth and figure out how we have come to inhabit it. The SIM-EARTH project aims to utilise new advancements in emulation, machine learning and biogeochemical theory to make a 'whole Earth' model possible for the first time.

Emulation

This process is at the heart of our new approach. An emulator is something that allows a computer to replicate something else—often in a simpler way. We have developed a 'climate emulator' to compute the results of 3D climate models far quicker than is usually possible. The emulator does not run the climate model—which would take weeks to produce a climate map—instead, it looks at a large database of previous climate model simulations and infers what the climate should look like based on this. For example, we can take runs of the climate model with high and low amounts of CO_2 in the atmosphere. Based on those end members, the emulator can then use this information to produce a climate map for

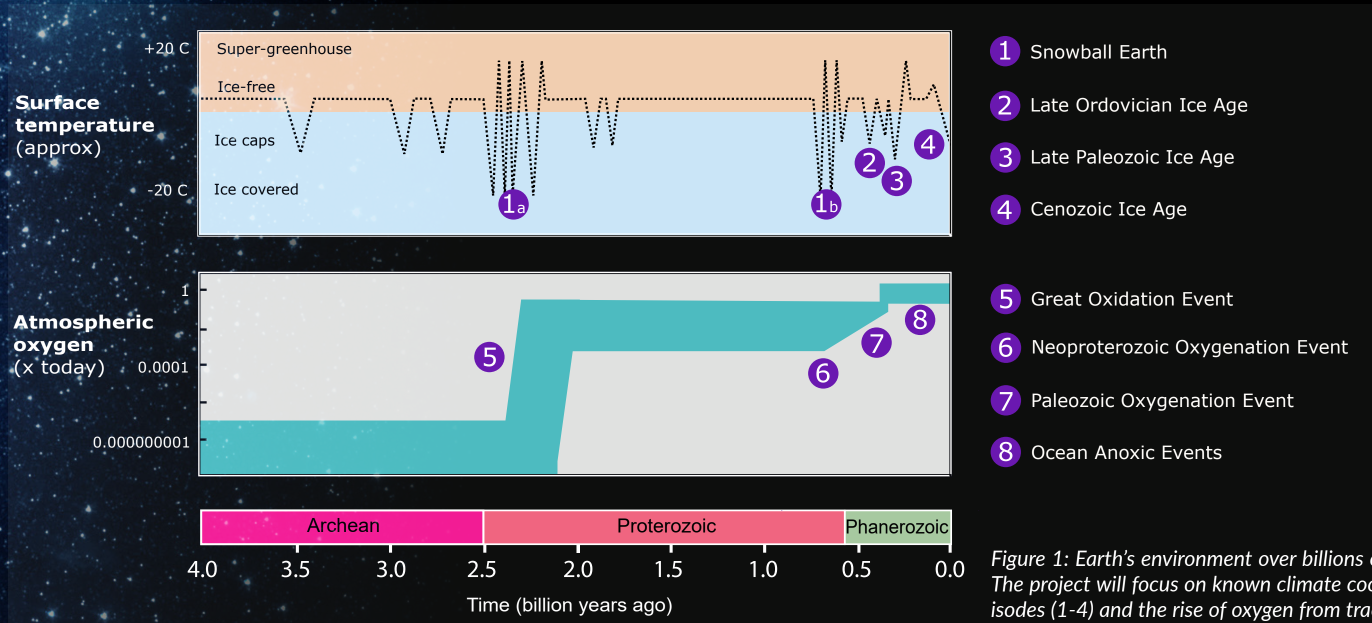

Figure 1: Earth's environment over billions of years. The project will focus on known climate cooling episodes (1-4) and the rise of oxygen from trace levels to 21% of the atmosphere (5-8).

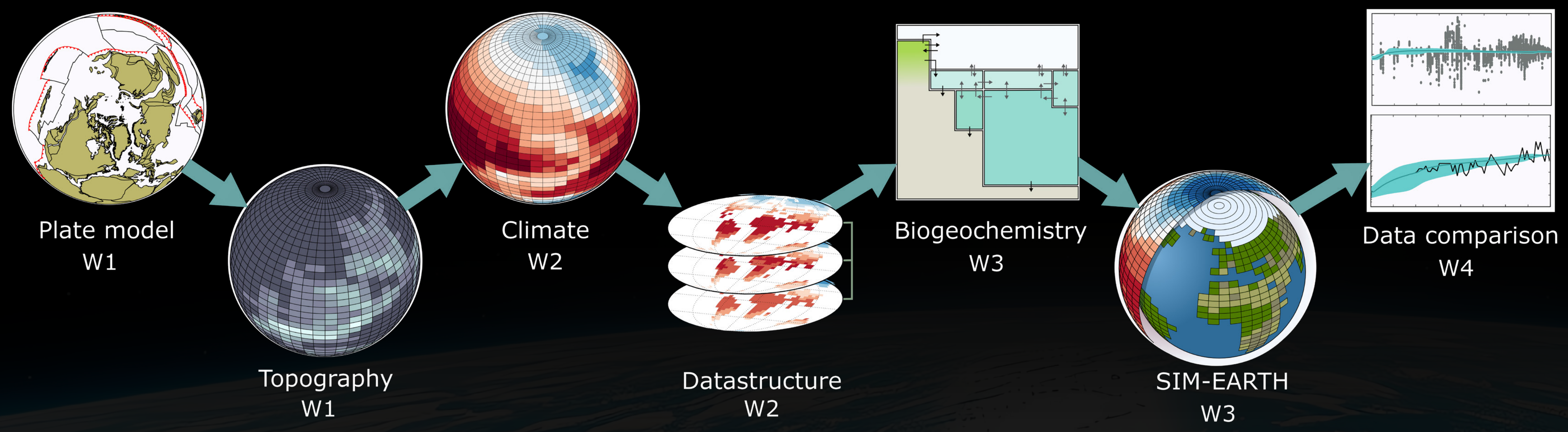

Figure 2: The SIM-EARTH workflow.

a medium amount of CO_2. We lose a little accuracy this way, but instead of waiting weeks for our result, we have it in less than a second. This dramatically speeds up our Earth system model.

Machine learning

Emulating changing CO_2 levels is relatively easy because the continents and oceans stay in the same place. But over the history of the Earth, this is not the case! The Earth's surface is constantly changing thanks to plate tectonics. Two hundred million years ago, the continents were clustered together in a 'supercontinent', and knowing the climate of the present day will not let us accurately guess what the climate of a supercontinent looked like.

Fortunately, computers have recently become much better at understanding visual patterns thanks to machine learning algorithms using neural networks. With a neural network approach, we can use maps of climate for different continental configurations to infer how the climate would change as the continents move. This process is similar to how film studios 'up-sample' videos to a faster frame rate: we run our climate model at certain time points as the continents move and use a machine learning method to estimate what the in-between points should look like. Using this approach, our emulator can give us a reasonably accurate picture of global climate for a given time in Earth history and a given level of CO_2 in the atmosphere, and it can do so faster than you can blink. This lets us run our model for billions of years.

Biogeochemical theory

With emulation and machine learning, we can compute climate quickly, and we can do this as plate tectonics moves the Earth's crust. But the chemical make-up of the oceans and atmosphere is also time-consuming to calculate. We cannot simply track all the chemical species we are interested in (like oxygen and carbon) through every 'gridbox' (i.e. coordinate) of the climate emulator. Considering variation in latitude, longitude and ocean depth, this would result in tens of thousands of calculations for each chemical! What we must do here is reduce the ocean and atmosphere to a smaller number of boxes—few enough to be fast to compute, but not so few that we lose the level of detail we need: the ocean has different zones that behave differently, and we need to represent this. Getting this right requires us to understand how biology, geology and chemistry interact to cycle elements between the solid Earth, sediments, oceans, atmosphere and biosphere. This is called biogeochemistry and is the collection of processes controlling the surface conditions on Earth and other planets. By producing an efficient biogeochemical model with a minimal number of gridboxes and linking it to the tectonic-climate emulator, we can create a model of the world which is quite realistic and which can be run for billions of years to reconstruct the entire history of the Earth.

The SIM-EARTH workflow

Our project is broken up into four workflows, where we develop our model and then use it to better understand our planet. These are shown in Figure 2. In workflow 1 (W1), we use a representation of the movement of Earth's tectonic plates to establish the physical framework for the SIM-EARTH model. We look at where plates collide and build mountains, and where new crust is generated at mid-ocean ridges. From this, we build a global topography over time. This forms the structure in which we then run our climate model.

In W2, we use the physical constraints from W1 to drive a state-of-the-art climate model to build our emulator. This will take several years because we need to run the climate model for lots of different points over Earth history and for many different atmospheric CO_2 levels. But once we have finished this, the emulator can estimate climate almost instantaneously.

While we build the emulator, we will also develop our atmosphere-ocean biogeochemical scheme in W3 so that it is ready to couple towards the middle of the project. At this point, we have a working SIM-EARTH model. We can then do the exciting parts—recreating the history of our planet in the model and trying to understand why key events have happened. Broadly, we will do this by allowing the model to evolve over time just as our planet has done. Then, we will compare the model environment to the geological record to see if it matches, and if not, then why not?

What do we hope to learn?

Many hypotheses already exist as to why the Earth was warm or cool at certain times, or why oxygen levels have risen. These have not been easy to test with existing models, but we should be able to test them with the SIM-EARTH model. For example, were ancient cool periods the result of changes in tectonics, or were they actually driven by biological evolution (as microbes and plants take up CO_2)?

What's next?

Ultimately, we want to be able to reproduce the environmental evolution of the Earth in our model to test its accuracy, and then use this as a tool to explore how other planets might evolve.

For example,

What if the Earth had been smaller?

What if it was made of different compounds?

What if our Sun was a different type of star?

We can change these properties in our model and see what happens! We hope this can help us figure out what type of extra-solar planets we should observe with telescopes, and what types of stars we should aim these telescopes at to find potentially habitable planets.

PROJECT NAME

SIM-EARTH

PROJECT SUMMARY

SIM-EARTH is an ERC Consolidator Grant project. It aims to understand why Earth's surface environment has changed over time so we can better understand our past, how to manage our planet for the future, and where to look for complex life in the universe.

PROJECT PARTNERS

The project is led by the Earth Evolution Modelling Group in the School of Earth and Environment at the University of Leeds in the UK. It benefits from a strong collaboration network that includes universities in the UK, France, the USA, Canada and Australia.

PROJECT LEAD PROFILE

Professor Benjamin Mills is Chair in Earth System Evolution at the University of Leeds, UK. He leads the Earth Evolution Modelling Group and is chair of the Earth System Science Group of the Geological Society of London.

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The annual 'Life and Planet' conference runs in London every summer.

www.lifeandplanet.com

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