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MODELING EARTH SYSTEM COMPLEXITY: THEORETICAL BIOLOGY APPROACHES TO THE GAIA HYPOTHESIS

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SUMMARY

The Gaia hypothesis is best presented as "*the hypothesis that supposed the Earth to be alive…as a living organism*"; therefore a necessary and sufficient characterization of "what is a living organism?" is required to address this hypothesis. The cell is the minimal organism that has been formally characterised as self-fabricating causal organization and constructive dynamics capable of active inference of its environment by the theoretical biology approaches of autopoiesis, the (M,R)-system, and the Free Energy Principle. Modelling the Earth complexity while taking the Gaia hypothesis at face value –the Earth is complex because it instantiates life at the planetary scale– can be, thus, addressed by the same the theoretical biology approaches. A first proof-of-concept based on Chemical Organization Theory and the Zero Deficiency Theorem applied to Earth's biotic and abiotic reaction networks shows that at molecular level there are Earth's reaction networks organized as an autopoietic system, i.e. able to self-fabricate. A second proof-of-concept based on the Free Energy Principle–here active inference, shows that a biosphere-climate dynamical system model can remain at non-equilibrium steady-state climate dynamics by active inference of net incoming solar radiation. Finally, considering that Earth system components and operational processes satisfies the formal entailments of the (M,R)-system would mean that its complexity has a formal equivalence to a self-referential (impredicative) system, which cannot, in principle, be completely surrogated by an algorithmic representation. Yet, it may indicate that potentially the Earth components could have multiple functions and that the Earth's climate dynamics could be context-dependent. These theoretical biology approaches open up the plausibility that the 4-billon years of Earth's habitability (climate homeorhesis) has occurred by autopoiesis and active inference at the planetary level and that the Earth system is likely to be akin to a living system, which must be borne in mind in future Earth's climate modelling.

NOTICE

Most of the chapters of this thesis are published or submitted to peer-reviewed journals. Technical terminology concepts that appear in bold are developed in the footnotes rather than in a glossary.

- ***Chapter 1.***

Introduction. Cartography of the multiple formal systems of molecular autopoiesis Rubin (2023) *Biosystems*, 230, 104955.

- ***Chapter 2.***

Taking the Gaia hypothesis at face value. Rubin & Crucifix (2022) *Ecological Complexity, 49, 100981*

- ***Chapter 3.***

Beyond planetary-scale feedback self-regulation: Gaia as an autopoietic system. Rubin, Veloz, Maldonado (2021) *Biosystems*, *5*(4), 791–806

- **Chapter 4.**

Future climates: Markov blankets and active inference in the biosphere. Rubin, Parr, Da Costa, Friston (2020) *Royal Interface*, *5*(4), 791–806

- **Chapter 5.**

Climate homeostasis by and for active inference in the biosphere. Rubin, Heins, Da Costa, Friston (2023). *Submitted*

- ***Chapter 6.***

Earth's Complexity Is Non-Computable: The Limits of Scaling Laws, Nonlinearity and Chaos. Rubin & Crucifix (2021). *Entropy 23(7), 915*.

- **Chapter 7.**

Coda: discussion and conclusion.

CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

GH	Gaia Hypothesis
GP	Gaia Phenomenon
GT	Gaia Theory
COT	Chemical Organization Theory
ZDT	Zero Deficiency Theorem
(M,R)-system	(Metabolism, Repair)-system
FEP	Free energy principle
NESS	Non-equilibrium steady state
GCM	General circulation models
DW	Daisyworld
LGM	Last Glacial Maximum
SRM	Solar Resources Management
OTU	Operational taxonomic unity

Chapter 1

Based on:

Rubin, S. (2023). Cartography of the multiple formal systems of molecular autopoiesis from the biology of cognition and enaction to anticipation and active inference. *Biosystems*, 230, 104955.

INTRODUCTION

1. Background

It is largely admitted that our predictions of Earth's climate dynamics are uncertain because the Earth system is 'complex'. However, what is meant by 'complexity' is not always made clear. There is an increased understanding that unpredictability is linked to the complexity of the system and that our predictions of Earth's climate dynamics are uncertain because the biosphere constitutes a major limiting factor in our ability to predict its dynamical evolution.

Geological observations and model based evidence suggests that Earth during most of the time since its full formation ~4 billon years ago has had surface temperatures not less than around 0^{O}C and not more than around 40^{O}C, in spite of a continuous solar fluctuation forcing (Catling and Zahnle, 2020; Sagan and Mullen, 1972; Goldblatt and Zahnle, 2011). This homeorhetic[1] trajectory of Earth's climate system seems to be one of the most fundamental phenomena maintaining habitability.

[1] Biologist C.H. Waddington preferred to distinguish between homeostasis and *homeorhesis,* because in a living system as opposed to a mechanical regulator what "*is being held constant* [uniform] *is not a single parameter but is a time-extended course of change, that is to say, a trajectory"* (Waddington, 1968, p.12). See also the introduction of Chapter 6.

Beyond the importance of the abiotic silicate-rock weathering negative feedback– such that it is very low at the inner edge of the habitable zone[2] and very high at the outer edge, the tightly interweaving of the biosphere with the oceans, atmosphere and lithosphere plays a central role for the Earth's homeorhetic climate dynamics (Margulis, 1998; Lovelock, 1988a; Kump et al., 2014; Lenton, 2016). It is therefore to be expected that to understand Earth complexity we will continue to gain knowledge from studying the Earth system as a unitary/whole system.

Currently two theoretical approaches can be categorized that attempt to model this interaction. The first comes basically from the hand of fluid dynamics and dynamical system theory. The way the biosphere is coupled in Earth climate system is the following: (a) Simulators of the climate system—called general circulation models—solve the equations of motion of the atmosphere and the ocean. They now routinely include parameterizations (semi-empirical equations) describing the response of the biosphere and carbon cycling processes. It is largely on this approach of understanding that official bodies are based to make public policy such as the Kyoto protocol and Paris agreement. (b) On the other hand, small dynamical systems are used to study climate-vegetation-biosphere interactions from a more qualitative prospective. They allow us to frame these interactions into the wider context of dynamical systems theory and thermodynamics, and these models raised the (remote) possibility that critical transitions could be detected in the very early stages of their development, the so-called “early warning signals” (Scheffer et al., 2009).

The second theoretical approach comes from cybernetics, control theory and information theory. The archetype of this type of modelling is Daisyworld (DW), which is a hypothetical planet composed of a simple biosphere of two species, black

[2]The habitable zone represents the range of distances around a star at which a terrestrial, rocky planet can support liquid water at its surface based on water and solar radiation properties. If a planet is too close to its parent star, then overheating and loss of water will occur, marking the inner edge of the habitable zone. If it is too far away, then overcooling and freezing out of water will occur, marking the outer edge of the habitable zone.

and white daisy, that regulates its own climate (temperature), despite a steady increase in solar radiation (Watson and Lovelock, 1983). It does this by varying the numbers of black and white daisies and so altering its albedo, and it accomplishes this by ordinary physical processes. Even though it is a simplified representation of the Earth system, it uses realistic parameters of the Earth system. From the DW point of view, a long-term stabilising effect of the climate due to biological activity is argued, thus pointing towards a biospheric explanation of Earth's homeorhetic surface temperature back in time.

Instead of focusing on the climate-biosphere interaction, in this thesis we take the climate-biosphere as a single whole unity interacting with its own external space solar weather. We approach the Earth system as a single unity organised as a living system (akin to a cell) including its abiotic and biotic components and capable of maintaining homeorhetic physiological ranges by active inference of its environment. Such key feature of living complex systems that we stand to study the Earth's complexity is called autopoiesis, which is a necessary and sufficient characterization of the self-fabricating organization of living organisms (Maturana and Varela 1980).

Lynn Margulis (1997) proposed autopoiesis as an alternative/parallel to mechanistic neo-Darwinian explanation of biological phenomena, which means that autopoiesis has profound implications in practically all fields of modern biology, from Synthetic Biology to the Cognitive Sciences, including Exobiology, Origin of Life and Eco-Evo-Devo. In this thesis I make the point that it also has profound implications for the Gaia hypothesis.

Autopoiesis is the causal organization of the living, so that when it stops, living stops too (Maturana, 1981). It occurs as a metabolic network of processes and constraints of molecular fabrication (catabolism and anabolism), which produce the processes and constraints that produce them through the fabrication of a semipermeable boundary that specify the topological domain of such a network (Fig. IA). This closed domain of operational relations between the metabolic network and semipermeable boundary is named *operational closure*, which defines the

organization of a biological unity in space coupled with its environment (Fig. IA). Thus, in observing a living being we can distinguish two domains of existence; that of the self-fabricating organization and that of its structural coupling with its environment where cognition occurs (Fig IB). The distinction of both domains is key for building a comprehensive theory of organisms as autopoietic systems, and thus of the Earth as a living system.

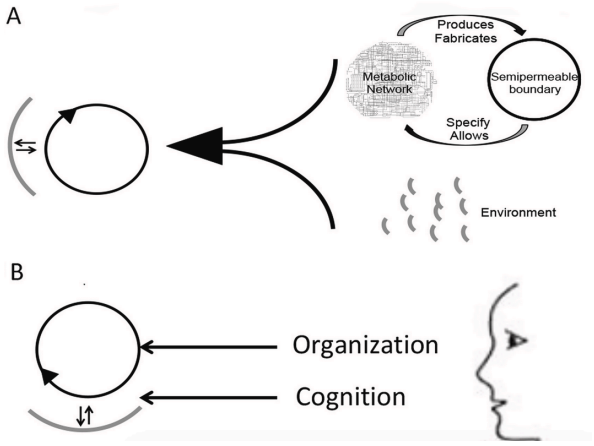

Figure I. Autopoiesis and its relational domains. A) Pictorial drawing of the constitution of autopoiesis as the living of a biological unity structurally coupled with its environment (on the left) arriving from operational closure (top right) and an enacted environment (bottom right). The operational closure and an environment are here drawn separated only for heuristic explanation. B) Distinction of two domains of existence of autopoietic systems; organization (self-fabrication) and cognition (structural coupling). The back and forth arrows indicate that both systems trigger structural changes in the other (Adapted from Rubin 2023).

A rich literature has grown up over the years that bears with autopoiesis, which tends to assume that it is a model, a theory, a principle, a definition of life, a property, refers to self-organization or even to hastily conclude that it is hylomorphic, hylozoist, in need of reformulation or to be overcome, making its status even more unclear. Maturana insists that autopoiesis is none of these and rather it is the causal organization of living systems as *natural systems* that self-fabricate such that when it stops, they die (Maturana 2011, Rubin 2023).

Like all-natural systems in the universe, autopoiesis is amenable to be defined in theoretical terms, i.e. encoded in mathematical models and/or formal systems, so different models of autopoiesis have been proposed (Rubin 2023). Models of autopoiesis can be made from its organizational domain or its relational (cognitive) domain, or models from both domains at the same time (Fig IB). A classification of them into analytical categories, reveals the models of autopoiesis as Turing machine (**algorithmic**) vs non-Turing machine (**non-algorithmic**) based,[3] and models with a purely reactive mathematical image as cybernetic systems, i.e. feedbacks based, or conversely, as anticipatory systems making active inferences. [4]

Among the multiple models of autopoiesis the Chemical Organization Theory (COT) (Dittrich & Fenizio, 2007), the (M,R)-system (Rosen, 1991) and the Free energy principle (FEP) (a.k.a., active inference) (Friston, 2013) seems to be suitable to address the Gaia hypothesis and thus Earth's complexity. COT is a characterization of self-fabricating organization while FEP characterizes cognition process of the system. The (M,R)-system covers both domains at the same time (Rubin 2023).

The idea that the Earth system, as a whole, could be organized as a self-fabricating system and behave as making active inference of its own external space weather has, to our knowledge, never been examined. In this thesis, we provide rigorous ground to the claim that Earth system is organized as a living system, that is, as a self-fabricating system able to perform active inference. We consider that this way of

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[3] The distinction between algorithmic and non-algorithmic mathematical models refers roughly to whether they are computable or not. This goes back to the foundational crisis of mathematics. In particular, what Gödel's incompleteness theorems implications about the syntactic logic of the Hilbert Program in close link with the Russel and Whitehead's Principia Mathematica. Following Hilbert's program is Church's thesis and the development of the Turing machine and Von Neumann's self-reproducing automata. In parallel, comes category theory and culminates with the non-algorithmic Rosen's (M,R)-system (for a detailed discussion see Rosen 1959, 1991, Louie 2005, 2007, 2020, Rubin 2023).

[4] There is a vast literature covering the details of these theories and how they relate to each other. The explanation of these theories is developed in most of the chapters of this thesis. For a recent comprehensive synthesis on this subject, please see Rubin (2023).

representing the Earth system could, to a great extent, widen our understanding of its complexity, but also make the Gaia hypothesis tractable and fathomable.

2. Research objective

The overall objective of this thesis is to addresses the Earth complexity from the Gaia hypothesis (GH) standpoint using clear-cut characterisations of living systems, such as autopoiesis, the (M,R)-system, and active inference, and in examining the implications of such modelling for the current state of the art.

The central hypothesis, to be documented, is thus;

Understanding the Earth system complexity as the instantiation of life at the planetary scale would mean that it could comprise self-fabricating organization and active inference.

3. Thesis outline

The thesis is organised in seven chapters including this introduction as Chapter I and a general conclusion as Chapter VII. Chapter I is based on a peer-review publication in *Biosystems* journal, while Chapter VII on a pre-print in *EarthArXiv*.

Chapter II focuses on setting the problem of how to understand and assess the Earth system complexity from the GH standpoint. This chapter is a peer-review publication in *Ecological Complexity* journal

Chapter III consists in a proof-of-concept based on Chemical Organization Theory and the Zero Deficiency Theorem applied on a simple but representative historical Earth's molecular biotic and abiotic reaction network showing that at molecular level the Earth system is organized as an autopoietic system. This chapter is a peer-review publication in *Biosystems* journal.

In *Chapter IV*, assuming that autopoietic organisation is plausible at the planetary level, we examine the Free Energy Principle (FEP) and its corollary active inference in the context of the GH. Starting from a synthesis of observations and models of

disparate natural sciences related to Earth system science we frame and justify how active inference at the planetary scale could be implemented. We put into perspective the active inference of the Earth system as comprising sensory and active states as a boundary (also known as a Markov blanket) that separates internal and external states. This chapter is a peer-review publication in *The Royal Interface* journal.

Chapter V consists in a proof-of-concept that shows a climate-biosphere dynamical system model capable of active inference behaviour and thus supports the possibility of autopoiesis at the planetary scale. This chapter is submitted and currently under review.

In *Chapter VI* we explore what could be the implications for current climate modelling if the Earth system were to satisfy the cellular model of the (M,R)-system. This chapter is a peer-review publication in *Entropy* journal.

Finally, in *Chapter VII* we draw conclusions about the implications of the theoretical biology approaches used throughout the thesis for modelling and understanding the Earth complexity. We also discuss the implications regarding these approaches in reference to tipping points, planetary boundaries, planetary feedback loops and the idea of Earth 'stewardship' opening perspectives that can establish a new research programme to understand the Earth system functioning towards a biologised renewed Gaia theory.

Chapter 2

SETTING UP THE PROBLEM: TAKING THE EARTH COMPLEXITY AT FACE VALUE

Based on:

Rubin, S., & Crucifix, M. (2022). Taking the Gaia hypothesis at face value. *Ecological Complexity*, *49*, 100981.

ABSTRACT

The interest in understanding the climate-life system that has fostered the *Gaia hypothesis* (GH) has resulted in multiple explanatory theories, making its status unclear and controversial. This chapter seeks to set up the problem from a biological standpoint in terms of what makes a physical system be alive and then bring some clarity to the debates surrounding the GH with the aim to make it amenable to scientific scrutiny. We discuss what it means to take the GH at face value and its implications for modelling and understanding the Earth's complexity.

1. Introduction

The Gaia hypothesis (GH) has been fundamental in the development of what is now called Earth System Science (Rispoli, 2020), and key to the understanding of atmospheric carbon-based molecules as greenhouse gases that have a crucial effect on biosphere lifespan, long-term habitability and climate feedbacks (Lovelock and Watson, 1982). However, the GH remains much disputed and controversial. Some authors suggest that this is because it can be interpreted variously as a metaphor, an environmental philosophy, a worldview, or a research programme – or as all of these at the same time (Sagan, 1990; Kineman, 1991), and others consider that the hypothesis itself is merely pseudoscientific.

This proposal seeks to bring some clarity to the debates surrounding the GH by differentiating it from the Gaia phenomenon (GP) and the Gaia theory (GT). This dissection leads us to identify that GH involves Schrödinger's question **"what is life?"**[5] and that the controversy around the GH takes place at the level of explanatory theories to address it, i.e., the current GT. The development of the current GT obliterates Schrödinger's question, which still is greatly debated in biology (Margulis, 1997) and therefore does not take the GH at face value. We discuss theoretical advances that can make the GH amenable to scientific scrutiny, and their implications for a research programme that we call 'functional climatology'.

2. Schrödinger's negative entropy motivated planetary scale life observations

How might one detect life on another planet? NASA puts this question on Lovelock in the context of the Viking mission to Mars in the 1960s. This motivated Lovelock

[5] From here on we will refer to it only as Schrödinger's question, and to the term 'life' exclusively in reference to the existence of a concrete biological unity, organism or individual living system.

to explore a theory about what kind of physical system all living beings are, and hence to look at Schrödinger's book 'What is Life?'; "*the book that most influenced my own thinking"* (Lovelock, 1986, p.646).

One of the tenets of this book is that living systems remain organized because they *"feed upon negative entropy"* (Schrödinger, 1945, p.73). Negative entropy is used as shorthand for **free energy**[6]. Both classical thermodynamics and statistical mechanics imply that entropy monotonically increases in closed systems. The notion that life, according to Schrödinger, maintains itself out of this tendency was the starting point in Lovelock's proposal to NASA (Lovelock, 1965).

Schrödinger's free energy tenet allowed Lovelock to decide which planetary-scale **phenomenon**[7] to observe, and decide key experiments for the potential detection of 'Martian life'. His reasoning was that as life as 'feeding' upon free energy would maintain itself out of thermodynamic chemical equilibrium, the atmosphere of a planet with life would not be in equilibrium either. Arguably, this is the first Schrödinger-based prediction about what life is and how it can be detected: Mars's atmosphere is at thermodynamic chemical equilibrium; therefore, there is almost certainly no planetary life.

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6 Erwin Schrödinger in the second edition of 'What is Life?' states; "*if I had been catering for them [physicists] alone I should have let the discussion turn on free energy instead. It is the more familiar notion in this context. But this highly technical term seemed linguistically too near to energy for making the average reader alive to the contrast between the two things"*

7 Phenomenon comes from the Greek verb *phainein*, that has the same root as the word *phenotype*, a uniquely biological concept, which point out to an experience that is apparent to perception or observed feature(s) of living systems.

3. The Gaia phenomenon: observation of biological processes at the scale of planetary systems

The observation that Earth's atmosphere is distinct from Mars (and Venus) in being at thermodynamic chemical disequilibrium provided for the first time the recognition of planetary-scale biological processes, thereby suggesting that *"life has bulk properties and needs to be considered on a planetary scale"* (Lovelock, 1986, p.646) as "*a planetary phenomenon*" (Lovelock, 1991b). As Lovelock himself pointed out: "*At present most biologists can be convinced that a creature is alive by arguments drawn from phenomenological evidence*" (Lovelock, 1972, p.579).

The Gaia phenomenon (GP) is an all or nothing phenomenon that can be recognized in a multifaceted way, as living beings in general are. Several observations such as the often-referenced Lovelock's list (2003) support the existence of the GP on Earth, but not on other planets; i) the atmospheric thermodynamic chemical disequilibrium, ii) the long-term stability of marine pH and salinity, iii) the maintenance and possible origin of the hydrosphere, iv) the origin and rates of biogeochemical cycles, v) the biogenic methane of the Archaean atmosphere, vi) the metabolic production and balanced levels of oxygen in the atmosphere, vii) the impact of boreal forest and biodiversity on local and global climates, viii) the ocean-to-land transfer of elements by bioaerosols, ix) the biogenic cloud formation and the potential existence of a cloud albedo feedback to phytoplankton aerosols emission, x) the climate modulation by metabolic-enhanced rock weathering, and xi) the biogeochemical redox states. These and potentially others are the planetary-scale biological processes and constraints that constitute the way to recognize the GP.

Although not all the points on this list are proven as evidence of planetary life, and some of them are still under debate, the list provides a background that has prompted a search for an overarching explanation. As Margulis wrote: "*having recognized the Gaia phenomenon I would like to explain…how long this Gaia phenomenon persisted…*" (Margulis, 1996, p.54). This involved mobilizing an

ensemble of theories and conceptual frameworks for explaining the many facets of the GP, giving rise to the current GT (section 5 of this chapter).

4. The Gaia hypothesis includes Schrödinger's question 'What is Life?'

Moving from detecting the GP on Earth but not on Mars (or Venus), to the claim that 'Earth is alive', involves a statement linking together two descriptive statements: life and Earth. The statement that links them is the GH, which is best presented as "*the hypothesis that supposed the Earth to be alive*...[the Earth] *as a living organism*" (Lovelock, 1988b). This statement inherently involves a theory about what life is in the first place. Here is where Schrödinger's free energy was crucial to determine whether planets such as Mars conform in their operations the 'alive' class of systems. As Lovelock writes: "*it was by reading ...*"*What is Life? [...] that I first realized that planetary life was revealed by the contrast between [...] a dead planet and [...] the Earth*" (Lovelock, 1986, p.646). Consequently, the answer to Schrödinger's question is necessary, if not sufficient, for answering whether exoplanets are 'alive' and ultimately Schrödinger's question itself is similar to the 'What is Gaia?' question. Margulis and Sagan follow up with their own attempt to answer it, in a book which they say: "*reproduces not only Schrödinger's title but also ...his spirit*" (Margulis and Sagan, 1995, p.2).

Although how Schrödinger characterized the persistence of organization in biological systems as arising from negative entropy (free energy minimization) was a great insight in formulating the GH, the persistence of various facets of the GP diverted attention mainly towards the use of theoretical frameworks such as self-regulation by feedback loops, irreversible self-organized non-equilibrium thermodynamics, and neo-Darwinian adaptive evolution. These have been critical in establishing the current GT. However, concentration on these theoretical frameworks has displaced, if not obliterated, Schrödinger's question and thus the essence of the GH formulation. Next, we discuss briefly why none of these theoretical frameworks are sufficient to take the GH at face value.

5. The *status quo* of the current Gaia theory

Any theory aims to *explain why* and *how* a phenomenon can occur and persist i.e., the actual details of system operations. However, as Schrödinger's question has been obliterated from the GH formulation, the 'Earth is alive' hypothesis has been modified to the 'Earth is regulated' and much of the theoretical work has focused on explaining *why* and *how* this regulation occurs and persists, giving rise to the current GT (Rubin and Crucifix, 2022) (Fig.1).

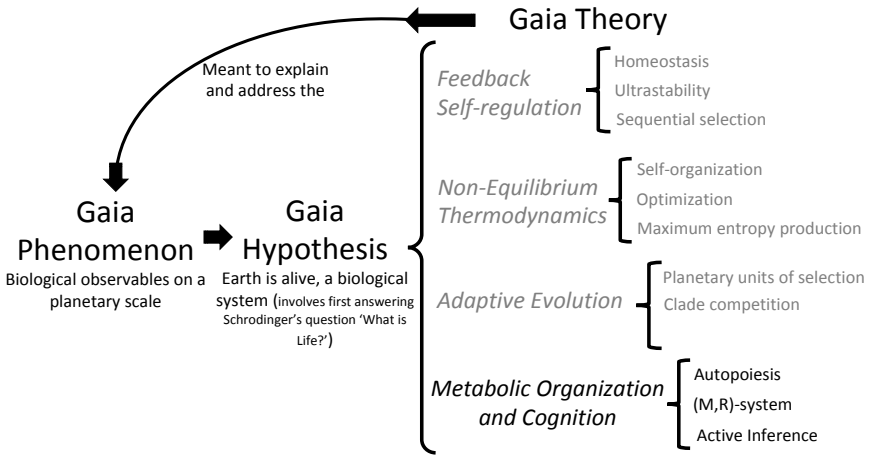

Figure 1. Explanatory genealogy of the current Gaia theory. The black arrows show the sequential loop among the Gaia phenomenon (GP), Gaia hypothesis (GH) and the explanatory genealogy of the current Gaia theory (GT) (grey font). Note that this loop departing from the GT is meant not only to explain the GP and address GH but depending on which of these theoretical explanations is used, it can potentially generate alternative observations of the GP, verifications of the GH, and therefore new research programmes and a renewed GT (black font).

5.1. CYBERNETIC CONTROL FEEDBACK SELF-REGULATION

Much of the theoretical work of current GT tends to focus on addressing to what extent the sum of living systems (microbes and plurimulticells like us) regulates (by

stabilizing or destabilizing **feedback loops**[8]) the Earth's chemistry, climate and habitability. This theoretical framework is the legacy of cybernetics and control theory (von Foerster, 1952) that mostly works under "*every good regulator of a system must be a model of that system*" theorem (Conant and Ashby, 1970), developed as a mathematical framework for what Walter Cannon, in reference to Claude Bernard's *milieu intérieur* concept, named "*the error-correcting theory of regulation or homeostasis*" (Cannon, 1929).

Under the 'Earth is regulated' assumption, Kirchner (1989) interpreted the GH as having a *weak* and a *strong* statement form. In the weak interpretation, biotic and physical processes are coupled regulators that operate through mutual feedback loops. In the latter, biotic activity is seen as the active regulator of the Earth chemistry and physical processes. That is, one deduces from Kirchner's own interpretation that the GH does not involve Schrödinger's question and that Gaia is a regulator, but not life itself on a planetary scale: "*Margulis and Lovelock* (1974) *propose that 'a test for Gaia is to consider what would happen if life were now deleted from the Earth.' This is of course, a test for life, not a test for Gaia*" (Kirchner, 1989, p.225).

Self-regulation by feedback loops is a reactive mechanism that is not confined to, nor is it a definitive feature of, living systems organization (Rosen, 1985c), and therefore may not be sufficient for addressing the GH. For example, a thermostat is not a living system, but regulates the room temperature through feedback loops. Mechanisms of feedback self-regulation have been described on so-far lifeless planets such as Mars (Chassefière, 1991; Ng and Zuber, 2003), and for the stabilisation of the surface temperature of a lifeless Earth (Walker et al., 1981).

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[8] Feedback occurs when outputs of a system are routed back as inputs as part of a chain of cause-and-effect that forms a circuit or loop. The system can then be said to feed back into itself (for a detailed introduction see Wiener 1948, Von Foerster 1952, Ashby 1952).

5.2. SELF-ORGANIZATION AND NONEQUILIBRIUM THERMODYNAMICS

Within the theoretical framework of non-equilibrium thermodynamics and self-organization, the GP may be i) a self-organized criticality system phenomenon (Bak, 1993) ii) a complex adaptive system (Lenton and van Oijen, 2002) and iii) a dissipative or planetary-gradient-reducer system (Sagan and Whiteside, 2004). These concepts refer directly or indirectly to irreversible non-equilibrium thermodynamic systems and the statistical theory of dissipative systems, self-organisation, symmetry breaking and pattern generation (Gregoire and Prigogine, 1977). When linked to Shannon (syntactic) information theory through the maximum entropy postulate (Jaynes, 1957), Earth does appear to maximize entropy production (Kleidon, 2009).

However, like cybernetic feedback loops, the phenomena of self-organized non-equilibrium thermodynamics are not specific to living systems. They are found in abiotic systems such as Bénard convection cells, the Belousov–Zhabotinsky reaction and so-called active matter. Chemical disequilibrium based on Gibbs free energy has been diagnosed in lifeless planets (Krissansen-Totton et al., 2016). Indeed, the bulk of irreversible thermodynamics is an attempt to understand the dynamic properties of open systems (a class to which living systems belong) by preserving the mathematical apparatus developed to deal with equilibrium in closed, isolated systems, i.e., to preserve the thermodynamic entropy appropriate to adiabatic systems (to which living systems do not belong) (Von Bertalanffy, 1950; Rosen, 1978, 1988). Thus, although a necessary theoretical tool, the statistical theory of self-organized non-equilibrium thermodynamic systems appears to fall short of characterising living systems (Rosen, 1979, 1985b; Martyushev, 2013), address Schrödinger's question and therefore to take the GH at face value.

5.3. NEO-DARWINIAN ADAPTIVE EVOLUTION

Several Neo-Darwinists have rejected the existence of the GP, arguing that organisms cannot reach a planetary 'common good' by natural selection and that natural selection cannot act on the whole planet (Doolittle, 1981; Dawkins, 1982). In response, Watson and Lovelock (1983) put forward a simulation they called Daisyworld, a hypothetical cybernetic planet which can regulate its temperature by feedback loops over a wide range of solar luminosities. These feedback loops are accomplished by ordinary physical processes rather than by natural selection. As Daisyworld refuted the objections, the critics have responded by developing Darwinian Daisyworlds that regulate their temperature simply through natural selection in terms of adaptation, competition, cheating and selfishness (Staley, 2002). However, the more Darwinian characteristics are added, the less well planetary temperature self-regulation is attained (Saunders, 1994; Roberston and Robinson, 1998; Rubin and de Castro Carranza, 2021).

Despite the results of these artificial life experiments based on the feedback self-regulation theory, efforts have continued to be made to show that the 'modern evolutionary synthesis' must explain or at least be compatible with the GP. They appear to be based mainly on two assumptions. The first one is that the GP is not the life phenomenon at planetary level, but i) an ensemble of planetary feedback loops, ii) an ensemble of biogeochemical cycles and/or iii) an adapted and differentially persisted *clade*. The second assumption is that these three notions of the GP should be consistent with how Darwinian natural selection works. In essence, this requires a form of selection at a higher level that may operate at multiple time scales (Lenton et al., 2018). That is, feedbacks, cycles or clades (hypothetically, different clades would have made several attempts, the surviving one is the one we belong to) must be seen as 'units of selection' (Doolittle, 2019, 2017). Yet, as they do not reproduce, which is essential for variation and therefore Darwinian selection, the hypothesis is that these self-perpetuating non-reproducing (Lenton et al., 2021) higher units of selection can acquire persistence-enhancing adaptations by chance which may

strength or maintain Earth's climatic feedbacks (Lenton et al., 2018). This is the so-called 'Darwinization' of Gaia (Doolittle 2017).

It is also assumed that these ensembles of higher units of selection can occur due to 'complex adaptability', 'progress by accumulation', selection by survival and even, hypothetically, Gaian reproduction (Gatti, 2018). In all cases, the objective appears to accommodate the 'modern evolutionary synthesis' tenets with planetary feedbacks and self-regulation.

At present, the literature lacks a formal discussion of how such evolutionary formulations of the current GT can incorporate recent advances in evolutionary theory such as the *extended evolutionary synthesis*, or evolutionary theory beyond natural selection, and the **adaptationist programme**[9] like the *evolutionary natural drift* (Maturana and Mpodozis, 1991; Varela et al., 1991; Mpodozis, 2022)[10]

Despite the efforts of 'Darwinizing Gaia', the evolutionary theory of natural selection, and indeed any evolutionary theory, appears to fall short of addressing Schrödinger's question, hence fundamentally sidesteps the GH. This does not imply that an evolutionary explanation is not useful; it merely indicates that evolution alone, although necessary to be consistent with the GP, is of secondary importance with respect to the GH, and therefore is not sufficient to address it at face value.

6. Is the Gaia hypothesis a tractable hypothesis?

The GH suggests that the GP on Earth is the manifestation of something more than feedback self-regulation, irreversible self-organized non-equilibrium

[9] The adaptationist program inherits from the early 20th century modern synthesis school of evolution by natural selection the assumption that all or most traits of organisms are evolved optimal adaptations, see (Gould and Lewontin, 1979). The prominent alternative to the adaptationist program is natural drift

[10] For a recent commentary of why the Gaia phenomenon and evolution by natural drift may involve anticipation see Rubin (2022).

thermodynamics or adaptive evolution alone. A parallel may be drawn with synthetic biology. To fabricate a living cell, we need more than the concatenation of biosynthetic cycles (Calvin cycle, tricarboxylic cycle, etc), feedback gene regulation (e.g. operon Lac, ribosomal operon, etc) and active matter. Likewise, bringing an inert non-equilibrium thermodynamic planet with feedbacks and a selection of higher units such as geochemical cycles would arguably not yield the GP. Therefore, Schrödinger's question remains central for posing the GH. In the current GT, the GP is reduced to an epiphenomenon, i.e., the instantiation of life does not occur on a planetary scale, but it is a simple *by-product effect* of cellular and multicellular activity occurring on a rocky planet. As Sagan (1990, p.188) quoting Harding, points out; *"we tend to think on this planet as a life-infested rock, which is as absurd as thinking of the body as a cell-infested skeleton"*.

We argue, however, that the controversy over the GH does not imply its intractability or a cryptic vitalism. Similar to other authors (Mikulecky, 2000; Kineman, 2019), we think that the best route to a successful approach to the GH and hence a renovated GT is through a clear-cut delineation of what life (living) is and what that implies. The GP should be considered primarily as *metabiotic* and not simply as the biosphere (as a clade or unit of selection). As Lovelock insisted; *"[i]t is not the biosphere alone but the whole Earth system"* (Lovelock, 2009a, p.166).

However, all major theories accounting for 'Schrödinger's question' are focused on the cellular scale (Letelier et al., 2011; Cornish-Bowden and Cárdenas, 2020) and this focus neglects precisely what the GH formulation has changed, i.e., Schrödinger's question could be answered by looking at the planets. Then, GT as a theory of living planets can also be a theory for cellular life (Lovelock, 1987), suggesting that Earth system science is properly studied as a *biological science* and that biological models can be applied meaningfully at the scale of the entire Earth (Lerdau, 2014). Therefore, there should be some attempt to show how the theories that account for Schrödinger's question at one level also apply at the other, and to what extent understanding Gaia could illuminate the nature of life itself.

Current evaluations of 'what is life?' follow a diversity of approaches (Letelier et al., 2011; Cornish-Bowden and Cárdenas, 2020). Most of them are associated with cybernetic systems and feedback loops. In contrast, others reject these approaches and instead explicitly recognize biological self-production/self-fabrication organization (Maturana and Varela 1980; Rosen 1991; Friston 2013). Specifically, given the limitations of characterizing life as a mere cybernetic regulator (Rosen, 1985c), autopoiesis (self-production), a clear-cut characterization of living systems organization, was suggested before the early criticisms of Doolittle (1981) and Dawkins (1982) as a way of taking the GH at face value (von Foerster, 1975). According to Margulis, '*[w]hereas the smallest recognizable autopoietic entity… is a tiny bacterial cell the largest is Gaia*' (Margulis, 1990, p.861); "*planetary physiology… is the autopoiesis of the cell write large*" (Margulis and Sagan, 1995, p.54), while Lovelock argued that: "*[t]he tightly coupled evolution of the physical environment and the autopoietic entities …led to a new order of stability: the state associated with Gaia*" (Lovelock, 1988a, p.219–220). Addressing Schrödinger's question – and specifically the idea that it involves autopoiesis – suggests that explaining Gaia as an autopoietic system could be a promising way forward (Fig. 1).

Several authors consider that autopoiesis is a plausible scenario for the instantiation of life organization on a planetary scale[11]. In the next chapter we will show that this is plausible using a proof-of-concept based on the chemical organization theory and the zero deficiency theorem applied on an Earth's molecular reaction network.

The central idea is that the Earth should self-fabricate its own components and boundary conditions through metabolic closure, also called operational closure or closure to efficient causation[12]. This **metabolic closure**[13] refers to how biological

[11] See Clarke (2020) and Rubin & Crucifix (2022) for a detailed review of more references.

[12] Formal treatments of autopoiesis has been shown to have an equivalence to the (M,R)-system (Nomura, 1997; Zaretzky and Letelier, 2002; Letelier et al., 2003), and thus of operational closure to closure to efficient causation respectively. See also Chapter 6.

systems are causally the result of their own operations, such that a geo-metabolic network produces a boundary (an atmosphere) that enables it to continue producing itself, in dynamical and non-equilibrium thermodynamically open conditions. Closure, thus, does not refer to closed thermodynamic systems, but rather, to a circular organization of *efficient causes* (operators, constraints or boundary conditions) generated continually and internally within the system, an organization that fundamentally differs from biochemical or biogeochemical cycles in which circular organization refers to *material causes.*

As the self-fabricating organization occurs at different scales (Maturana, 1980), Mikulecky (2000) previously suggested that the theory of the (M,R)-system may provide the formal basis for mathematically proving the GH.

In Chapter 4 we will show how the (M,R)-system attributes can affect deeply our understanding and modelling of the Earth's climate-system complexity (Rubin and Crucifix, 2021). This implies that as long as the components of a system satisfy the conditions of self-fabricating organization, they may accomplish a set of relations, which can be distinguished, heuristically, as structures having 'functions' (Rosen, 1972; Varela and Maturana, 1972). For example, the heart has a certain form (structure) that is 'adequate' to 'pump' blood. Although this may not be the only constitutive relation with the body, this has an effect on the whole organism that at the same time maintains the heart pumping blood. At the cellular level, to take another example, the folded enzyme affects its cytoplasmic environment by

[13] Metabolic closure is distinct from thermodynamic closedness (material closure), feedback loops or material cycles. To exemplify metabolic closure, consider a closed glass bottle, half full of water but open to solar radiation. The radiation evaporates the water that is condensed in the walls of the bottle. Condensed water falls as liquid, to be again subject to evaporation. The evaporation-condensation cycle is analogous to a material cycle, with the glass bottle and sun acting as boundary condition (efficient cause) in the sense that they constrain the internal flow of water. But this is not a biological system doing metabolic closure, as the glass bottle is not self-produced: an external agent produces it. If the glass bottle were itself produced by the evaporation-condensation cycle fuelled by solar energy, then one would say that the glass bottle self-produces, achieves metabolic closure and hence is organized as a living system (Hofmeyr, 2007).

catalysing components, which also maintains the conditions for the right folding to occurs and hence its catalytic function. Similarly, we also consider that the Earth's climate-system and its biosphere may accomplish a same sort of metabolic closure set of relations (Rubin and Crucifix 2021).

A crucial point is that this distinctive organization of biological systems allows them to develop anticipative models of themselves and their environment to self-repair and persist (Rosen, 1985a; Louie, 2012). In dynamic terms this has been framed as free energy minimization (a.k.a., active inference) (Friston 2013). Framing the Earth as an autopoietic system could indeed allow the system to persist over a nontrivial time-scale through active inference (Rubin et al., 2020). This part will be extensively developed in chapters 4 and 5.

So far, we think that the problem is set; understanding the Earth complexity is taking the GH at face value and this means that organization and cognition (active inference) are fundamental features of it. This will suggest that the idea of spatial and temporal climate dynamics is not anecdotal and that the Earth instantiate self-fabrication, hence active inference on a planetary scale. In fact, we consider that from these advances in theoretical biology, the GH can be formally tractable, as initially oriented, opening the possibility to understand the Earth complexity from an organizational theoretical biology standpoint. In the following chapters this proposal will be developed in full detail.

Chapter 3

EARTH, AUTOPOIESIS AND CHEMICAL ORGANIZATION THEORY

Based on:

Rubin, S., Veloz, T., & Maldonado, P. (2021). Beyond planetary-scale feedback self-regulation: Gaia as an autopoietic system. Biosystems, 199, 104314.

ABSTRACT

The Gaia hypothesis states that the Earth is an instance of life. However, appraisals of it tend to focus on the claim that life is a feedback self-regulator that controls Earth's chemistry and climate dynamics, yet, self-regulation by feedbacks is not a definitive characteristic of living systems. Here, we consider the characterization of biological systems as autopoietic systems (causally organized to self-produce through metabolic –efficient– closure) and then ask whether the Gaia hypothesis is a tractable question from this standpoint. A proof-of-concept based on Chemical Organization Theory (COT) and the Zero Deficiency Theorem (ZDT) applied on a simple but representative Earth's molecular reaction network supports the thesis of Gaia as an autopoietic system. We identify the formation of self-producing organizations within the reaction network, corresponding to recognizable scenarios of Earth's history. These results provide further opportunities to discuss how the instantiation of autopoiesis at the planetary scale could manifests central features of biological phenomenon, such as autonomy and anticipation, and what this implies for the further development of the Gaia theory, Earth's climate modelling and geoengineering.

1. Introduction

In the attempt to detect life on Mars (Lovelock, 1965), the observation that Earth's atmosphere is a far-from-chemical-equilibrium product of metabolic activity led to the formulation of the Gaia hypothesis (GH) (Lovelock, 1972, 1979; Lovelock and Margulis, 1974; Margulis and Lovelock, 1975). The GH states that the Earth is an instance of **life**[14] (Lovelock, 1988, Lovelock, 2003).

The pre-Gaian seminal contributions of Lovelock-Margulis's precursors Hutton, Vernadsky and Bogdanov, the father of geology, founder of the concept of biosphere and of systems theory (tektology) respectively, are quite important towards the Earth System thinking, but also towards the unifying ideas of geology and biology (Rispoli, 2020). While Hutton described the Earth as "*not just a machine but also an organized body as it has regenerative power*", it was suggested that "*life is not a form of energy and is not merely a geological force, rather it is the geological force*" (Vernadsky, 1945). Bogdanov saw that life and Earth constitute one complex system (Rispoli, 2020). Although these ideas are precursors towards a living Earth standpoint, it is nevertheless unclear whether they were key to the Gaia hypothesis formulation.

What is known is that the formulation of the GH followed one of the key concepts that Schrödinger (1945) developed as an answer to the 'What is Life?' question: *negative entropy* (see footnote 6). In Schrödinger's words, through this *"marvellous faculty, […] a living organism […] 'feeds upon negative entropy' […] to compensate the entropy increase it produces by living and thus […] maintain[s] itself on a stationary and fairly low entropy level"* (Schrödinger, 1945, p. 73). The

[14] Here we refer to the term 'life' in reference to the following notion: *"life is not a property of living beings, the word life only evokes or names an invented abstract entity that we claim that must be there to sustain the living of a concrete singular living being"* (Maturana, 2011, p.147). That is, we consider lifeas a natural system, as a living unity/system, an individual organism (see Rubin 2023).

GH seizes on this explanatory framework to extend Schrödinger's characterization of living systems, hitherto pertaining solely to cellular or multicellular organisms, up to the planetary scale (Lovelock, 1987; Margulis, 1990). Thus, its formulation involves fundamentally the Schrödinger's question "*What is Life?*" (Schrödinger, 1945), as reviewed in Chapter 2. In this respect the GH formulation is different from the idea of unifying geology and biology from pre-Gaian precursors. As we have seen previously, the question 'What is Gaia?' amounts or it is equivalent to Schrödinger's question, 'What is Life?'. Hence, answer what Gaia is requires going beyond the notions of organism-environment, biotic-abiotic, biosphere-geosphere and/or biology-geology coupling. In a planetary context it is metabiotic (Clarke, 2020). As Lovelock usually refers to it; "*a single living entity capable of* [self] *maintaining* […] *and endowed with faculties and powers far beyond those of its constituent parts"* (Lovelock, 1979). Therefore, an operational explanation of what life is, hence, the distinction between the living and the non-living is critical to taking the GH, hence Earth complexity at face value.

However, although biological systems in general can be recognized phenomenologically by empirical means and Schrödinger's free energy (negative entropy) is a fundamental piece of the puzzle, there is still no generally agreed answer to 'What is Life?' (Cornish-Bowden and Cárdenas, 2020). This indicates why the GH, while always controversial and much disputed, has also grown unclear (see Chapter 2). This is not a problem that was born with GH, but rather a problem inherited from biology (Margulis, 1997). Moreover, as we have seen in chapter 2, the explanatory scope of current Gaia theory as purveyed by Earth scientists or Darwinists confines the Gaia hypothesis to its *Darwinization* (as expressed within the tenets of the modern synthesis's adaptationist programme of evolution with or without natural selection) or its *mechanization* (expressed with the tenets of the cybernetics, dynamical systems theory and self-organized far-from thermodynamics equilibrium) to fit the notion that Gaia phenomenon is not a living phenomenon per-se, but an epiphenomenon of the effect of the sum of living systems on planetary

feedbacks self-regulation. Please see Rubin and Crucifix (2019) for previous discussion.

The *Darwinization* and *mechanization* of the GT have diverted attention and finally omitted the use of a generic characterization common to all living systems such as offered by autopoiesis, the (M,R)-system and the Free Energy Principle. This chapter shows that GH is tractable from the clear-cut and operationalizable autopoietic characterization of biological systems. In Section 2 of this chapter, we outline the autopoietic characterization of living systems as refined by recent advances in metabolic theory. In section 3, we develop the thesis of Gaia as an autopoietic system and in section 4, we test it by applying chemical organization theory (COT) and the zero deficiency theorem (ZDT) in a simple but representative Earth system reaction network. Finally, section 5 discusses some key concluding remarks of the central feature of the autopoietic organization–autonomy–as inherent in Gaian behaviours and the implications of it for the Earth's climate modelling, geoengineering and the future of Gaia theory.

2. Living systems, autopoiesis and metabolic closure

The father of physiology, Claude Bernard, noted that "*all the vital processes, varied as they are, have only one object, to conserve the uniformity of ... the internal milieu"* (Bernard, 1878a, p.84). Since then, one of the common features broadly accepted as important to recognize living systems is how, despite forcing by environmental fluctuations and energic dissipation, they precisely conserve the uniformity of their internal milieu (their physiological boundaries) through the maintenance of their organization. Upon this notion of organization, later thinkers constructed the idea of the uniformity of the internal milieu primarily as fixing internal parameters at a 'set point' and using feedbacks to 'regulate' the values of these set-point parameters against deviation-*errors*. Walter Cannon named his *error-correcting theory* of regulation *'homeostasis'* – stability through constancy (Cannon, 1929). Therefore, biological organization was thought to be captured by the concept

of homeostasis, and its mathematical formulation was consolidated with the development of cybernetic systems and control theory. The core of these early cybernetic notions was *stability through self-regulation by feedback mechanisms* in which a system's behaviours seem, but are not, to be internally produced and automatically goal-oriented (von Foerster, 1952).

However, for an alternative recognition of biological organization framed in terms of self-production by metabolic closure (autopoiesis and the (M,R)-system) (Letelier et al., 2003, 2011, Maturana and Varela, 1980, Rosen, 1991), the feedback is a *reactive response* (Louie, 2017; Nadin, 2010; Rosen and Kineman, 2005; Rosen, 1985c, a). The feedback is an error-counteracting response, which takes place only when there is external perturbation sufficient to make the system's parameters deviate from externally pre-defined 'set points'. The feedback reactive response, thus, cannot accommodate constitutive anticipative and autonomous biological behaviour proper to biological systems (Maturana, 2011). When we consider the biological organization framed in terms of self-production by metabolic closure the conservation of physiological boundaries and maintenance of stability does not take place by error-correcting feedback responses, but instead, through cognition, autonomy, anticipation and/or active inference (Friston, 2013; Maturana, 2011; Rosen, 1985a). These central features of living systems, which are inherent to their constructive dynamics given by metabolic closure and self-producing organization are the means by which they maintain stable operations in face of fluctuations, dissipation and the second law of thermodynamics.

While the (M,R)-system outlines a *formal system* of self-producing organization of biological systems through metabolic efficient/operational closure, autopoiesis outlines the *causal realization* of it as a natural system. That is, autopoiesis is "*not a philosophical proposition of a formalization of the phenomenon of life"* (Maturana, 2011, p. 144). Nor is it a theory, model, or principle of biological organization. Rather, it "*describes the molecular* ... [dynamics] … *taking place in the realization of the living of living systems* [such that] *the molecular autopoiesis of a cell is its*

living in the continuous realization of their self-production without the participation of any organizing principle" (Maturana, 2011, p. 144, brackets are ours). Autopoiesis is characterized by a) self-production as *"a network of processes of production (transformation and destruction) of components which: (i) through their interactions* [openness to the flux of matter and energy] *and transformations continuously regenerate and realize the network of processes (relations) that produced them; and (ii) constitute it (the system) as a concrete unity in space in which they (the components) exist by specifying the topological domain of its realization as such a network"* (Maturana and Varela, 198, p. 78, brackets are ours) (Fig. 2A), and by b) metabolic (operational) closure: *"a closed domain of operational relations specified only with respect to the system organization that these relations constitute, and thus it defines a space whose dimensions are the relations of production of the components that realize it as a concrete biological unity*" (Maturana and Varela, 1980, p. 97)(Fig. 2A).

One of the ways to computationally track autopoiesis has been through chemical reaction networks. The relationship both dates back to the algorithmic implementation of what is known as computational autopoiesis (Varela et al., 1974; McMullin, 2004). This implementation shows that a dynamical system based on simple rules can spontaneously develop a self-produced boundary. Around the same time, the foundational work of Feinberg and Horn (1974) formulated the zero deficiency theorem (ZDT), which links the structure of a reaction network to its ability to reach an asymptotically stable state. *Deficiency zero* basically means that such a network can regenerate autonomously all the complexes used up by its reactions from complexes produced by other reactions (see appendix A at the end of this chapter). ZDT also introduces the notion of *complexes*, which represent the collections of molecular species required to trigger (or produced by the occurrence of) reactions. If a reaction network is *weakly reversible*, it is possible to ensure that the differential equations that capture the reaction network's time evolution exhibit a dynamically stable regime for any choice of the kinetic parameters. ZDT is striking because it links two structural conditions (weak reversibility and zero deficiency),

which are extremely simple to check for even large reaction networks, to a dynamical property (asymptotic stability) that is extremely difficult to check for even reaction networks of moderate size. For our purposes, the interest here is that the fundamental idea behind ZDT is similar to the self-production condition of autopoietic systems (Contreras et al., 2011; Kreyssig et al., 2012). A tremendous number of explorations linking structure and stability of a similar kind have followed since the introduction of ZDT, resulting in the well-established deficiency theory of chemical reaction networks (Feinberg, 2019).

A related but different approach to deficiency theory starts from the idea that instead of focusing on the general structural properties of the reaction network (which approach neglects dynamic properties such as the values of the kinetic constants), one can focus on the possible *reaction pathways* that are dynamically feasible, and impose conditions on them that can be linked not only to stability, but to any desired behaviour of the network, such as increased production of biomass, degradation of toxic molecules, resilience under kinetic perturbations, etc. This area of study is called Pathway Modelling (Rajvanshi and Venkatesh, 2013), which can be applied to large-scale phenomena, and some recent efforts along this line have recently been proposed for biogeochemistry (Zerkle and Mikhail, 2017).

Chemical organization theory (COT) (Dittrich and Di Fenizio, 2007), stemming from the seminal work of (Fontana and Buss, 1994) who first used the untyped−calculus as a formalization of autopoietic systems, is one of the approaches that links the structure of reaction networks to their dynamics. COT has developed directly from pathway modelling and deficiency theory, and establishes a formal criterion for determining a reaction network to be *operationally closed* and stoichiometrically *self-maintaining* (see appendix A at the end of this chapter). The parts of the reaction network that fulfil these two conditions, called *organizations*, contain all stable states that the reaction network can reach in the long term: For any long-term steady state that the reaction network reaches, the molecular species whose concentration is larger than zero—that is, the *active* part of the network—will

be a chemical organization unit (Dittrich and Di Fenizio, 2007). However, depending on the kinetic constraints such as reaction rates or boundary conditions, some organizations become feasible but others not (Peter et al., 2010). Organizations can hence be characterized in terms of the possible ways, given particular kinetic constraints, that the consumed species (molecular components) are produced by reaction pathways. When comparing COT and ZDT, we observe that ZDT provides a more solid, but more stringent, criterion for identifying whether a reaction network reaches self-maintenance by metabolic closure-like. COT has been compared to frameworks such as the (M,R)-system and autocatalytic networks as a suitable method to explore the internal structures within networks that generate autopoietic operations, as represented both analytically and algorithmically by self-maintenance (Centler et al., 2008).

Given the limitations of characterizing living systems as cybernetic or dissipative systems (Chapter 2), it has been suggested that the autopoietic organization presents the proper biological ground to address the GH (von Foerster, 1975). Margulis stated: "*Whereas the smallest recognizable autopoietic entity ... is a tiny bacterial cell the largest is Gaia*' (Margulis, 1990, p. 861); *'planetary physiology ... is the autopoiesis of the cell write large"* (Margulis and Sagan, 1995, p. 54). However, some authors downplayed Margulis' notion of an "*autopoietic Gaia*" as an "*Aquarian poetic vision*" (Doolittle, 2017) rather than a scientific research programme. Thus, a serious examination of the question whether or not a rigorous relation exists between Gaia phenomenon and autopoiesis is called for. This thesis represents this attempt. In the next section, we develop arguments for the autopoietic, thus metabolic-closure, approach to the GH hence to Earth complexity.

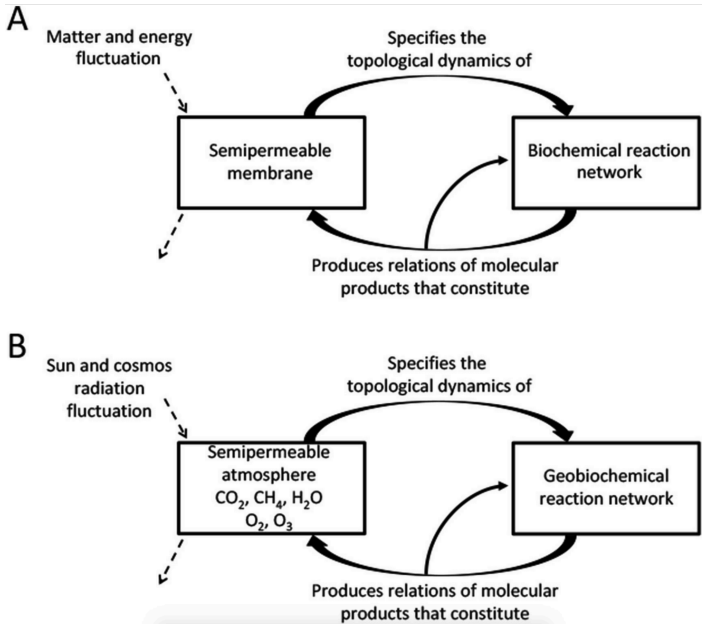


Figure 2. A) Representation of Autopoietic organization. Autopoiesis (self-production or self-fabrication) occurs when a molecular reaction network produces itself (thin central arrow) and a semipermeable boundary, which specifies the topological dynamics of the metabolic reaction network (arrows in both directions). Metabolic closure results from the interrelation between the metabolic network and the boundary. Metabolic closure renders an autopoietic system capable of selecting the matter and energy that enters and exits the system (dotted arrows). In this sense an autopoietic system is also an open system in relation to its environment. B) A schematic representation of Gaia as an autopoietic system organized on a planetary scale. The interdependence between the geo-hydro-biospheric metabolic network and atmosphere (arrows in both directions), in the sense that the geo-hydro-biospheric metabolic reaction network produces itself (thin central arrow) and the main components of the atmosphere (the Earth system's semipermeable boundary), and the atmosphere reciprocally specifies and allows the dynamics of the geo-hydro-biospheric metabolic reaction network, describes how Earth's autopoietic organization takes place on a planetary-scale.

3. Autopoiesis, Earth system and the Gaia hypothesis

The *reactive* paradigm of cybernetic control systems (Rosen, 1985a, 1985c) grew in popularity in the scientific thinking of the 1960s and 1970s and, quite naturally, Lovelock and Margulis (1974) provided the cybernetic homeostatic standpoint of the GP. Later, both acknowledged that Gaia returns to a *homeorhetic trajectory*, not to a homeostatic state In this sense, "*Gaia ... like the physiology of an embryo, is more*

homeorhetic, than homeostatic" (Margulis, 1990, p. 866), and instead of homeostasis, "*Gaia's history is characterized by homeorhesis with periods of constancy punctuated by shifts to new, different states of constancy"* (Lovelock, 1991a, p.141).

Lovelock and Margulis also recognized the asymmetry between internal and external conditions as crucial to explain GP from a biologically grounded standpoint: "*Different from a physicist, biochemist and neo-Darwinist's view ...* [Gaia is] … *a bounded system that is open to a flux of energy and matter, and that is able to keep its internal conditions constant, despite changing external conditions"* (Lovelock, 1991, p. 29, brackets are ours); *"Cells and Gaia display a general property of autopoietic entities: as their surroundings change unpredictably, they maintain their structural integrity and internal organization"* (Margulis, 1997, p. 267).

One of the conditions for the existence of the asymmetry between internal and external conditions in an autopoietic system is a self-produced boundary (Maturana, 1980), which formulation resonates with Schrodinger's query, '*how can the events in space and time which take place within the spatial boundary of a living organism be accounted for by physics and chemistry?* (Schrödinger, 1945, p. 2), which has also been one of the bases for formulating the GH (Margulis and Lovelock, 1975). Thus, addressing the GH from the biological-organizational standpoint amounts to recognizing a system that "*specifies its own boundaries ... that defines the limits of the system in the same domain in which it specifies them through relations of production of components that generate these relations and define it as a unity"* (Maturana and Varela, 1980, pp. 108–109). Therefore, to determine whether Gaia is an autopoietic system, it is necessary to determine to what extent the Earth's atmosphere (the boundary) is self-produced by relations of molecular production of Earth's biotic and abiotic components (a planetary reaction network), and whether the latter specifies the dynamics of the former.

Today, it is generally accepted that the production of the principal components of the troposphere (the habitable boundary of the atmosphere), mainly, the cloud-forming aerosols, greenhouse gases and oxygen are immediately related to metabolic activities (Lenton et al., 2018; Catling and Zahnle, 2020). Stratospheric ozone, which blocks mutagenic UV rays from reaching the Earth surface, also is metabolically derived from oxygen released by photosynthesis (Falkowski, 2006). Most notably, methanogens, sulphate-reducing bacteria and subsurface cyanobacteria, which are the main producers of the main components governing Earth's climate dynamics, are involved in the self-production of the life-supporting and life-supported boundary layers of the atmosphere. Furthermore the chemical elements of the atmosphere derive from the modification, mobilization, and microbial transportation and deposition of geochemical elements of the lithosphere (McGenity, 2018). These productions also involve the life-dependent hydrosphere and rely upon the entire integration of Earth dynamics through biogeochemical cycles (Falkowski et al., 2008). That is, there is evidence that the Gaia's boundary (the atmosphere) has been produced continuously by a sort of geo-biosphere metabolism that at the same time has changed its structure specified by type of atmosphere (reductive or oxidative) (Sagan, 1990; Falkowski, 2006). This aligns with Morowitz's argument: "*the metabolic character of life is a planetary phenomenon, no less than the atmosphere, hydrosphere, or geosphere"* (Morowitz et al., 2008, p.8). In other words, the continuous metabolic fabrication of the atmosphere (troposphere and stratosphere) in the same domain in which it continuously allows the metabolic reaction network (relations of production of components) amounts to recognizing the existence of a self-producing organization of the planetary domain, and hence, the recognition of Gaia as an autopoietic system (Fig. 2B). In the next section, we shall prove this, on formal theoretical grounds, by applying COT and the ZDT to a representative Earth's molecular reaction network.

Stoichiometric equations	Process of molecular production
r_1: $S+H_2 \rightarrow H_2S$	Abiotic or Biotic hydrogen sufide synthesis
r_2:$12H_2S + 6CO_2 \rightarrow C_6H_{12}O_6 + 6H_2O + 12S$	Biotic anoxic hydrogen sulphide chemosynthesis
r_3:$2FeO + 3CO_2+H_2O \rightarrow Fe_2(CO_3)_3+H_2$	Abiotic geochemical ferrous iron carbonate synthesis
r_4:$CO_2+2H_2 \rightarrow CH_2O+H_2O$	Biotic anaerobic chemoautotrophic respiration
r_5:$HCO_3+ 4Fe(II)+10H_2O \rightarrow CH_2O+4Fe(OH)_3+7H^+$	Biotic anaerobic phototrophic ferrous iron oxidation
r_6:$CO+H_2O \rightarrow CO_2+H_2$	Biotic carboxydotrophogenesis
r_7:$3CH_2O+H_2O \rightarrow CH_3COO^-+CO_2+2H_2+H^+$	Biotic fermentation
r_8:$2CO_2+4H_2 \rightarrow CH_3COOH+2H_2O$	Biotic anaerobic acetogenesis
r_9:$CH_3COOH \rightarrow CH_4+CO_2$	Biotic anaerobic heterotrophic methanogenesis
r_{10}:$CO_2+4H_2 \rightarrow CH_4+2H_2O$	Biotic anaerobic chemoautotrophic methanogenesis
r_{11}:$CH_4+ SO_4^{2-} \rightarrow HCO_3^-+HS^-+H_2O$	Biotic reverse methanogenesis
r_{12}:$CO_2+H_2O \rightarrow CH_2O+O_2$	Biotic photosynthesis
r_{13}:$2H_2+O_2 \rightarrow 2H_2O$	Abiotic atmospheric water synthesis
r_{14}:$3H_2+O_2+S \rightarrow 2H_2O+H_2S$	Biotic aerobic sulfate reduction
r_{15}:$2H_2S+O_2 \rightarrow 2S+2H_2O$	Biotic aerobic chemoautotrophic respiration
r_{16}:$C_6H_{12}O_6+6O_2 \rightarrow 6CO_2+6H_2O$	Biotic aerobic heterotrophic respiration

Table 1. A reaction network of molecular production of the Earth system's molecular components. In the left of the table are the stoichiometric equations and in the right the corresponding process of molecular production (synthesis and catalysis). This small but representative Earth's reaction network involves biotic and abiotic reactions that are known, by the geological record, to be present from the Hadean-Archean eon up to the Anthropocene epoch. The stoichiometric equations have been selected according to i) the geological records (around 4 billions of years ago), ii) the recapitulation of microbial metabolic evolution and diversification, and iii) the main greenhouses of the atmosphere (H_2O, CH_4, CO_2) and the reactions taking place at the interface between the lithosphere and hydrosphere. Some of the biotic reactions can happen abiotically, but only with high amounts of activation energy. For example, the reaction r_1 requires more than 150 °C, which is plausible abiotically around volcanic and vents activity.

4. Gaia, COT and ZDT

The seminal paper by Feinberg and Horn (1974) first presenting the Zero Deficiency Theorem (ZDT) discussed the possibility of applying the ZDT far beyond cellular reaction networks, to ecological or other kinds of systems, and suggested that some

ZDT systems are stable because they "*have their roots in ecological considerations"* (Feinberg and Horn, 1974, p. 785). For its part, COT has been applied to the characterization of self-producing behaviours not only in biochemical but also in ecological systems. Our interest in ZDT and COT for an autopoietic account of the GH lies here.

However, for a preliminary inference applying COT and ZDT with regard to Gaia as an autopoietic system, we should consider that the physical embodiment of autopoiesis, in any cellular, metacellular or planetary domain, must always be *molecular*. Maturana has indicated the molecular nature of operational closure regardless the scale it happens: "*There are autopoietic systems of higher order, integrated by* [populated by] *lower order autopoietic unities that may not be the components realizing them as autopoietic systems ... there are higher order autopoietic systems whose components are molecular entities produced through the autopoiesis of lower autopoietic unities"* (Maturana, 1980, p. 53, brackets and underline are ours). This molecularity of living systems organization has been also pointed out as intrinsic of the GP (Williams, 1996; Volk, 2004). Yet, it does not mean that GP may be reduced altogether to the molecular phenomena of chemical reaction networks. Rather, it simply points out that metabolic closure given by autopoietic organization take place at the molecular level and is an all-or-nothing phenomenon (Maturana, 1980). That is, life happens or not; Gaia occurs or not.

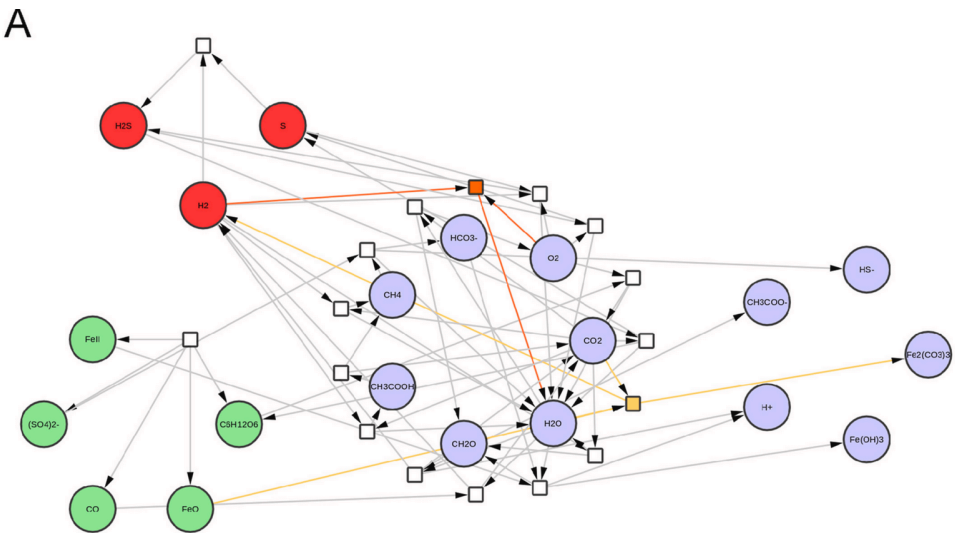
COT and ZDT is a constructive method with the potential to identify whether a reaction network can be organized as an autopoietic system, and thus provide a fundamental approach for exploring whether computational representation of molecular autopoiesis may occurs in planetary systems in the context of the GH. To explore it, we selected—according to the geological history of the Earth (around 4.5 billion years) and of the evolution of microbial metabolisms (more than 3.8 billion years)—some critical molecular components of the Earth system and their geochemical (abiotic) and biochemical (biotic) reactions (Table 1). To study the potential autopoiesis of such reactions, the inflow of molecular component resources

contains elements that are known, by the geological record, to be present from the Hadean-Archean Earth up to the Anthropocene epoch. Our aim is to show a proof-of-concept of the GH through a COT and ZDT approach, that it is possible to identify reaction networks that plausibly describe Gaia as an autopoietic system, and thus the organization as a key feature of Earth complexity.

Our analysis consists of identifying the organizations of the Earth system's reaction network shown in Table 1, and of computing the deficiency of such organizations, with the aim of determining whether or not their stability is certain in any dynamical setting (zero deficiency), or only under particular kinetic constrains (not zero deficiency).

Fig. 3 shows the COT analysis of the Earth system reaction network described in Table 1. It possesses four closed sets, of which three are self-maintained organizations. These may represent three structural scenarios of Gaia's ontogeny. The entire network (in cyan) could represent the Phanerozoic period during which the CH_4, CO_2, H_2O, O_2 components, those largely involved in the dynamics of the atmosphere and hydrosphere, hence in the Earth's climate system, are self-produced. Other components such as CH_3COOH (acetic acid), also fundamental to all forms of life due to its relationship with coenzyme A and with the metabolism of carbohydrates and fats, and HCO_3, the key component for the ocean pH, are also self-produced. This network includes not only the other cyan and the green reaction networks, but also part of the red reaction network (Fig. 3). Interestingly, the red reaction network is closed but not self-maintaining, thus not an organization. However, the larger cyan network (whole network in Fig. 3B) seems to have gained the property of the red scenario through the incorporation of H_2 into its organization. Indeed, most of the reactions of the whole network organization produce H_2S directly and indirectly. This component is highly abundant since the late Archean Earth (Abramov and Mojzsis, 2009) and key in the current sulphur cycle. It is often produced from the microbial breakdown of organic matter in anaerobic conditions by sulphate-reducing bacteria, but also by volcanic activity. That is, the presence of

H_2S is indicative of volcanic activity, and thus of tectonic, continental drift and geomorphological changes, which took place from the Proterozoic to the current phase of the Phanerozoic period. It has been proposed that the hydrological cycle itself is life-dependent, a Gaian contrivance established to prevent the escape of H_2 into space and thus out of the Earth system (Harding and Margulis, 2009). Additionally, the structure of the inner and outer layers of the continental plates appears to have been dominated by water-dependent continental drift (Lowman and Lowman, 2002). In short, the whole network, although very simple, has key self-produced elements and may also represent current evolutionary changes in the Earth's climate system. So far, this reaction network can be considered as a toy model to represent Gaian autopoiesis and thus Earth complexity.



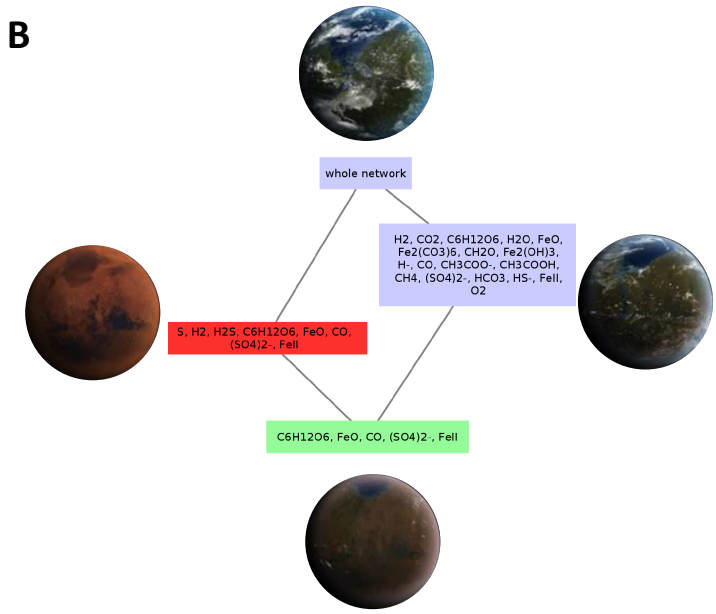


Fig. 3. A) The self-producing organization of the Earth system's molecular reaction network depicted by COT in the scenario in which $\emptyset \rightarrow C_6H_{12}O_6$ (glucose) is a necessary part of inflow. Circular nodes represent the component or chemical species (resources), while white square nodes represent the reactions. The yellow squares correspond to reactions associated with biotic activity, and the orange ones, with abiotic activity. Arrows go from reactants to products. Colours differentiate the dynamic properties of the resources. Green represents the inflow, red represents the set of species that, together with the inflow (green), form a closed sub-net that is not self-maintained. Cyan represents the species that together with the inflow (green) form the closed sub-network that is an organization. B) Structurally relevant sub-reaction networks of the COT analysis. The green sub-network corresponds to the inflow. The red sub-network corresponds to a closed but not self-maintaining system, thus not an organization. The two cyan sub-networks correspond to two increasingly complex organizations. The one below is an intermediate scenario of the whole network, which represents today's Earth system.

The self-producing organization shown in cyan (Fig. 3B) shows a previous and intermediate scenario, which may correspond to the Proterozoic eon, and hence to a plausible structure in this geological time-scale. Specially, the presence of CH_4 and O_2 and more sugars and acids can be explained by the transition from the Archean to the Proterozoic eons (from 4 to 2.5 billion years ago). In this transition, solar radiation alone was too weak to maintain liquid water and ice-free conditions on

Earth, and one plausible explanation is the warming produced by higher greenhouse gas concentrations in the atmosphere (see Chapter 5,6 for references and explanations). The greenhouse effect precisely involves CH_4, which has stronger radiative forcing than CO_2 and is almost entirely metabolically produced (Conrad, 2009). The occurrence of O_2 in the self-sustained organization of the represented Earth system reaction network can be related to the shift from reductive to oxidative atmospheres—due to the advent of photosynthesis in the middle to late Archean period. The effective elimination of the CH_4 greenhouse resulted in occasional glaciations and thus in the increase of planetary albedo related to climatic compensation against the increment of solar radiation. Moreover, the oxidative atmosphere and photosynthesis correspond to heterotrophic metabolism, and hence to the self-production of sugars and acids.

The smallest self-producing organization is formed by the inflow FeO, CO, SO_4^{-2} FeII and glucose (in green), suggests a planetary semi-chemoautotrophic scenario dominated by iron-sulphur and carbon, and hence a plausible structure of Gaian autopoiesis. The role of iron-sulphur minerals in catalysing prebiotic reactions has been recognized as a potential pathway to form simple organic molecules, the first metabolic cycles, and hence on carbon fixation (Fuchs, 2011). It is possible that this organization was a precursor to Gaia, since there is reasonable paleontological evidence of iron-sulphur availability in the early Archean Earth (Hazen, 2013) related to short peptide folds in primitive amino acids sequences. Indeed, the contemporary planetary-scale electron-transfer reactions (Falkowski et al., 2008) employs no more than 400 oxidoreductase genes (evolved from deeply branching Precambrian lineages of methanogens) (Fuchs, 2011) of which approximately 60% contain Fe in the active site (Harel et al., 2012). This development is crucial for the evolution of the primitive pathways of carbon fixation (Russell and Martin, 2004), and thus to the future Gaian aspects of Earth's climate dynamics.

For the ZDT test, we first notice that none of the three parts of the network that form an organization are weakly-reversible. Hence the ZDT does not apply to any of

them. For a more detailed analysis, in Table 2, we show the values required to compute the deficiency of the organizations (see Appendix A of this chapter). The only organization with zero deficiency is the inflow. If we had assumed outflow reactions for the inflow species, then the inflow would have been (trivially) weakly reversible and thus the zero deficiency theorem would have applied to it. The other two organizations (the cyan sets in Fig. 3B) have non-zero deficiency. Indeed, for the intermediate organization we have deficiency 2, and for the whole network the deficiency is 5. Hence, the most remarkable result here is that the non-trivial organizations are neither weakly reversible nor have zero deficiency. Even in case we add outflow reactions to the inflow, deficiency will remain different to zero for the cyan organizations in Fig. 3. This can be observed by simple inspection of the reactions in Table 1, and moreover, for the largest organization, the deficiency is greater than for the intermediate case.

Organization	# reactions	# species	deficiency	# complexes	# of linkage clases	stoichiometric subspace
Whole net	21	20	5	38	17	16
Intermediate	17	18	2	30	13	15
Inflow	5	5	0	6	1	5

Table 2. Deficiency analysis of organizations found for the organizations of our sample reaction network.

Further research should concentrate on a more extended reaction network for the Earth system and on quantitative aspects with regard to climate dynamics and the self-producing constraints that allow stability at the level of molecular species in the absence of zero deficiency. However, for the aim of this paper, this proof-of-concept is sufficient to show how Gaia is the realization of self-production–autopoiesis– across the Earth system.

5. Discussion: From calculation to the living, a challenge of understanding Earth complexity from biological organization

This chapter outlines the key explanatory scope of autopoiesis in relation to the GH, thus Earth complexity. This approach rests upon self-producing organization as more fundamental than self-regulation by feedback mechanisms (Maturana 2011; Rosen 1985a,c). Equipped with COT and ZDT as a workable operational formalization of autopoiesis—self-production (Contreras et al., 2011; Kreyssig et al., 2012), we presented a proof-of-concept by which Earth's molecular reaction network, composed by biotic and abiotic reactions, satisfies the self-producing organization. This suggests that autopoiesis may quite plausibly be the case at the planetary scale, and hence can establish a research program of the GH, and thus the understanding of Earth complexity beyond the feedbacks self-regulation.

Based on the COT analysis of the Earth's molecular reaction network, we conclude that it is possible to establish a link between autopoiesis, identified self-maintained reaction networks and the different scenarios that resemble the ontogeny (history) of the Earth system. That is to say, since organizations as defined by COT entail structures integrated by autopoiesis, the links between these structures and Earth's evolutionary scenarios may resemble a kind of ontogenetic process of the Earth altogether.

Based on the ZDT analysis, we conclude that the stability of the organizations of Earth's molecular reaction networks is due to the self-production of species by reaction processes, and not by self-production of complexes in the sense of ZDT. The inapplicability of the zero deficiency theorem to the reactions of the Table 1 occurs because the self-production of these networks does not occur at the level of complexes but at the level of molecular species, in a distributed manner across reaction pathways. The latter is an indication that the dynamical stability of Gaia persisted over geological periods due to appropriately well-linked, but not trivial, reaction pathways that self-produce the system.

Let us note that COT and ZDT are computable tools to study the self-producing organization of large-scale reaction networks and the work presented here is just a proof-of-concept. A wider program of research Earth complexity from biological organization would involve exploring the multiple approaches to metabolic pathway analyses in order to link the structure of Earth's molecular reaction network pathways to its dynamical properties at the various evolutionary scenarios. On the one hand, the latter involves identifying how to describe relevant systemic properties in the framework of pathway analysis such as autocatalysis (Hordijk et al., 2018). On the other hand, these methods could help us to understand the structure of planetary scale biogeochemical networks (Kim et al., 2019), whose fast development needs to be complemented by appropriate and scalable inferential rules to apply metabolic pathway methods.

Our results of this chapter suggest that the GP may be associated to the conservation of the Earth system self-producing-autopoietic organization by different scenarios of structural change. In other words, the system can go through different structural changes (smooth, extreme, abrupt, catastrophic) but preserve its organization, hence its living-like character—these events can be, so to speak, not fatal if we understand them as structural changes (see full discussion in the chapter 6). Indeed, Earth's history has been punctuated by several structural changes associated with massive biodiversity losses, planetesimal impacts, geomorphological and atmospheric composition changes (Falkowski, 2006). However, the GP has persisted, thus the living, and hence the complex character of the Earth system. Although the range of COT and ZDT is limited to identifying an autopoietic organization of a representative reaction network of the Earth system, nevertheless, it reaffirms the biological bases from which to address the Earth complexity from a theoretical biology perspective.

Appendix A.

5.1. REACTION NETWORKS BASICS

A reaction network is defined by a set of *components* $M = \{m_1, \ldots, m_n\}$ and a set of *reactions* $R = \{r_1, \ldots, r_n\}$, where each reaction r_i is a transformation of a subset $A \subseteq M$ to another subset $B \subseteq M$:

$$r_i: A \rightarrow B = \{a_1, a_2, \ldots | a_i \in M\} \rightarrow \{b_1, b_2, \ldots | b_j \in M\}$$

The subset $A = \text{supp}(r_i)$ in known as the *support* or *reactants* of r_i and $B = \text{prod}(r_i)$ as its *product.* All element of A are in conjunction via the "+" symbol. Which represents that the reaction can take place (*triggered*) if and only if all the elements of A are simultaneously present. When the reaction occurs, the reactants of r_i are *consumed* to form the *products B* that emerge from *the reaction.* Moreover, A and B can be multisets, *i.e.* each element m_i participating in a reaction r_j can be consumed or produced in a different amount (say c_{ij}). Hence, we describe a reaction as of:

$$r_i = c_{i1}m_1 + \cdots + c_{in}m_n \rightarrow p_{i1}m_1 + \cdots + p_{in}m_n$$

With c_{ij} and $p_{ij} \in N_0$. These coefficients define the stoichiometry of the reactions, which encapsulates the structural dynamics of the reaction network.

From here, we are able to define the *stoichiometry matrix* $\mathbf{S} = (s_{ij})$, a matrix with $(n \times m)$ dimensions, where $m = |M|$ and $n = |R|$. Here the $s_{ij} = p_{ij} - c_{ij}$ coefficients denote the number of components of type i is produced ($s_{ij} > 0$), consumed ($s_{ij} < 0$), or unchanged ($s_{ij} = 0$) in reaction j. In this way, the dynamics of a reaction network in a specific time-interval can be specified by the occurrence v_i of each chemical reaction r_i during such time-interval Moreover, it is possible to obtain a dynamical equation for the concentration of the components $\mathbf{x} = (x_1, \ldots, x_n)$ of a reaction network described as follows:

$$\frac{dx}{dt} = S \cdot v, \tag{1}$$

Where v is a vector specifying the rate of occurrence of each reaction.

To fix ideas, let's consider an example where M = {*a,b*} and R:

r_1:$\emptyset \rightarrow a$
r_2:$a + b \rightarrow 2b$

We can see that $s_{11} = 1 - 0$, $s_{21} = 0 - 0$, $s_{12} = 0–1$ and $s_{22} = 2 - 1$. which results in

$S = [(1,-1),(0,1)]$.

5.2. ZERO DEFICIENCY THEOREM

Note that each a specific collection of reactants is needed for each reaction to trigger. And the reaction also produces another specific collection of products. These specific collections are called *complexes*.

For example, the complexes for r_2 are $a + b$ and $2b$, acting as reactants and products respectively. The ZDT basically states that if complexes acting as reactants act as well as products then the network is going to reach equilibrium.

Let *C* be set of complexes of a reaction network, and *G* be the directed graph with nodes given by the complexes and directed edges given by the reactions

$r_i = \upsilon_k \rightarrow \upsilon_k'$, with $\upsilon_k, \upsilon'_k \in C$.

Let $G_1,\ldots, G_l$ denote the connected components of *G*. {G_j} are the *linkage classes* of the reaction network. Let l = # of linkage classes.

A chemical reaction network (M,R) with a set of complexes *C* is called *weakly reversible* if for any reaction $\upsilon_k \rightarrow \upsilon_k'$, there is a sequence of directed reactions υ_k' beginning with as a source complex and ending with υ_k as a product complex.

Let *s = dim (S)* be the dimension of the stoichiometric subspace of *S*.

The **deficiency** of a chemical reaction network (M,R) is $\delta = |C| - l - s$, where $|C|$ is the number of complexes, l is the number of linkage classes of the network graph, and s is the dimension of the stoichiometric subspace of the network.

The Deficiency Zero Theorem of Feinberg (Feinberg, 1979) states that for a (M,R), chemical reaction network with deterministic mass-action kinetics that.

1.Is weakly reversible,

2.Its deficiency is equal to zero.

We have that, for any choice of rate constants $\boldsymbol{k}$, within each positive stoichiometric compatibility class c there is precisely one equilibrium value, x_c, satisfying $S_c \cdot v_c(x_c) = 0$, where S_c, v_c and x_c are the stoichiometric matrix, the flux vector and the state of the system restricted to the compatibility class c, and that such equilibrium is locally asymptotically stable (relative to its compatibility class).

We make use the CrnPy library for the calculation of the deficiency, number of linkage classes, number of complexes and stoichiometric subspace of the subnets that satisfy the organization property.

5.3. ORGANIZATION

We would like to describe subsystems of our reaction networks in terms of their ability to persist in the long-term. An *organization* can be understood as a subsystem of a reaction network such that all its components are able to persist in the long-term. Under the COT framework, it is necessary for a reaction network to satisfy certain conditions to fulfil that property:

•We say a set $C \subseteq$ M is *closed* if for all $r \in$ R such that supp(r) $\subseteq C$, then prod(r) $\subseteq C$. This can be understood as that *no novel components* can be generated. In other words, the components produced are already present in the reactive part.

We can also define the *closure* $C = G_{CL}(S)$ of a set S as the smallest closed set that contains S. This operation can be performed by adding products of *the* reactions that can be triggered from the set S. Formally, these products are defined by $P = \cup_i \text{prod}(r_i)$ such that $\text{supp}(r_i) \subseteq S$, and the discovery of which possible new reactions can be triggered is formally specified by determining which r_i not considered already are such that $\text{supp}(r_i) \subseteq S \cup P$. The latter process can be repeated recursively until no new reactions can be triggered (this process safely terminates as the reaction set is finite).

•A set $C \subseteq$ M is *semi-self-maintained* if $\forall x \in C$ such that $\exists r \in$ R with $x \in \text{supp}(r)$ then must $\exists r^0 \in$ R such that $x \in \text{prod}(r^0)$. This property realizes that any component that is consumed by some reaction, must be produced by some other (self-produced).

•Let's consider $C \subseteq$ M semi-self-maintained, and $R_C \subseteq$ R to all reaction $r \in$ R such that $\text{supp}(r) \subseteq C$. Considering C and R_C we can construct the stoichiometric matrix S of this sub-network. In this way we define C is *self-maintained* if condition $S \cdot v \geq 0$ with $v > 0$. Considering the latter condition and equation (1), the concentration of the components will either increase or remain zero, and therefore we ensure that no component will be depleted in the long-term. The latter is equivalent to say that the amount of components produced by triggering the reactions at the rates specified by v is greater or equal than what is necessary to trigger v. The computation to test if a closed set is an organization, can be solved using linear programming (Dantzig, 1998).

Therefore, an organization is such when a subset C satisfies the property of self-maintenance and closure. So, it does not consume something that is not produced enough, and its components persist under long-term dynamics.

5.4. METHODS

We already mentioned the feasibility of a reaction network being an organization was calculated by means of linear programming (LP). The proposed LP

methodology consists in finding which creation and destruction components reactions are necessary to add to the network, so it achieves a stable dynamic (also known as flux balance analysis). If S is our stoichiometric matrix, we consider the following *E* matrix as:

$E = [\text{diag}(1), \text{diag}(-1)]$

Where diag(*x*) is a diagonal matrix with *x* values in his diagonal and with dimension ($n \times n$) such that $n = |M|$. For this new stoichiometric matrix E we wish to analyse which components are necessary required as inflow and outflow in such a way that E is considered stable i.e.:

$$Ev^e = 0 \qquad (2)$$

Here v^e is the related flow vector. This process can be understood as which of these components are added to the inflow or outflow, by means of v^e. If a flux vector component $v^e_i = 0$ is turned off in such way that condition (2) holds, those components are not considered as inflow or outflow of the stable network E. Our imposition on v^e for LP is such that the components associated with the original stoichiometric matrix *S* are greater than zero. Thus, the original reaction network is always present. We arbitrarily impose that they should be greater that one. This can be done without loss of generality given the linearity of equation $S \cdot v \geq 0$. If v is solution then λv is also solution for any $\lambda \in R^+$. Therefore, the optimization problem to find the feasibility of being an organization relay on minimizing: $\min(C \cdot v^e)$.

By holding,

$Ev^e = 0$
$v^e \geq h$

h is such that the $S \cdot v \geq 0$ condition is satisfied:

$$h_i = \begin{cases} 0 \; if \; 1 \leq i \leq 2|M| \\ 1 \; else \end{cases}$$

The *C* vector associated to the cost function is:

$$C_i = \begin{cases} 1 \; if \; 1 \leq i \leq |\mathrm{M}| \\ 0 \; else \end{cases}$$

Therefore, the only consideration cost for this minimization problem, is to require components in the inflow reaction. The R code of this program and for the respective Earth system reaction networks (*sbml* folder) can be found in the following *GitHub* repository https://github.com/pmaldona/Gaia_RN.

Chapter 4

AUTOPOIESIS, PLANETARY BOUNDARY, AND ACTIVE INFERENCE IN THE BIOSPHERE

Based on:

Rubin, S., Parr, T., Da Costa, L., & Friston, K. (2020). Future climates: Markov blankets and active inference in the biosphere. Journal of the Royal Society Interface, 17(172), 20200503.

ABSTRACT

In this chapter we formalize the Gaia hypothesis about the Earth climate system using advances in theoretical biology based on the minimization of variational free energy. This amounts to the claim that non-equilibrium steady-state dynamics—that underwrite our climate—depend on the Earth system possessing a Markov blanket boundary. Our formalization rests on how the metabolic rates of the biosphere (understood as Markov blanket's internal states) change with respect to solar radiation at the Earth's surface (i.e. external states), through the changes in greenhouse and albedo effects (i.e. active states) and ocean-driven global temperature changes (i.e. sensory states). Describing the interaction between the metabolic rates and solar radiation as climatic states—in a Markov blanket—amounts to describing the dynamics of the internal states as actively inferring external states. If this formalization is correct, this would guarantee climatic non-equilibrium steady-state through free energy minimization and thus a form of planetary autopoiesis.

1. Introduction

The standard models of the Sun's evolution show an increase in its radiation and brightness over time (Gough, 1981; Bahcall et al., 2001). Yet, there is empirical and model evidence that, despite exposure to increasing radiation, the temperature of Earth's climate has remained bounded at habitable levels ≈0–40°C since the Archean (4 billion years before present) (Catling and Zahnle, 2020; Lovelock and Kump, 1994). By contrast, Earth's climate dynamics would not be possible for its planetary lifeless neighbours—such as Mars and Venus—whose dynamics are non-life-like (Lammer et al., 2018).

It has been noted since the inception of physiology that biological systems maintain their organization and bounded internal conditions in the face of external fluctuations (Bernard, 1878b). By contrast, the entropy of inert (and closed) systems is unbounded and increases indefinitely. This asymmetry between external and internal conditions is thus broadly recognized as an important characteristic of biological systems (Maturana and Varela, 1980; Rosen, 1991). Schrödinger asked about such internal conditions, "*how can the events in space and time which take place within the spatial boundary of a living organism be accounted for by physics and chemistry?"* (Schrödinger, 1945, p.2).

Recent advances in theoretical biology suggest that biological systems can resist dissipation and external fluctuations through predictive behaviour (Rosen, 1985a; Sterling, 2012; Friston, 2013). That is, biological systems preserve their organization and bounded internal conditions by anticipation and active inference, or at least behave as if they had these predictive faculties. The underlying observation is that the time evolution of all systems, whether they are biological or not, depends on the past. However, the time evolution of living systems looks as if it depends not only on the past and present but also on the future (Rosen, 1985a; Sterling, 2012; Friston, 2013). The reason for this is that living systems act on the basis of a predictive

model of their ambiance: they appear to model their ambiance to preserve their organization and bounded internal conditions (Rosen, 1985a; Sterling, 2012; Friston, 2013). Such predictive behaviour is named anticipation (Rosen, 1985a; Nadin, 2010; Louie, 2012; Rosen and Kineman, 2005; Poli, 2014), allostasis (Sterling, 2012, 1988; Schulkin and Sterling, 2019) and recently, active inference (Friston, 2013; Ramstead et al., 2018; Kirchhoff et al., 2018; Karl, 2012). Active inference is a corollary of the free energy principle that describes the organization of systems that can be distinguished from their external milieu, in virtue of possessing a Markov blanket (Friston, 2012, 2013).

Since the asymmetry between the Earth's internal and external conditions implies some sort of action to maintain the bounded temperatures at habitable levels, we, therefore, offer the following hypothesis: can the Earth's climate system be interpreted as an anticipatory system that minimizes variational free energy? (Rubin and Crucifix, 2017). This hypothesis provides an interesting connection with the GH which argues for Earth's planetary bounded internal conditions *by* and *for* the biosphere (Lovelock, 1979; Lovelock and Margulis, 1974; Margulis and Lovelock, 1974). Here, we formalize the Gaia hypothesis by providing key organizational relationships among the atmosphere, hydrosphere, lithosphere and biosphere that allow a mathematical formulation of a Markov blanket for the Earth's climate system. This should be considered as a precondition for interpreting and proving (elsewhere) that the temperature of the Earth's climate—bounded within habitable ranges—has arisen due to an anticipatory or active (Bayesian) inference. In the following section, we briefly review the relationship between Markov blankets, free-energy minimization and active inference. We then propose, based on empirical evidence and prior model-based theoretical work, the existence of a Markov blanket for the Earth's climate system. Finally, we point out some implications of this formal treatment for studying the Earth's climate dynamics.

2. Free energy, Markov blankets and active inference

Although the principle of free energy minimization arose in neuroscience, it turned out to be sufficiently generic to ascribe cognitive processes to all living systems (Friston, 2013). Thus, the minimization of free energy (a.k.a., active inference or a generalized prediction error) can be regarded as a dynamical formalization of the embodied cognition implicit in the autopoiesis (self-production) of living systems (Maturana and Varela, 1980; Friston, 2013; Allen and Friston, 2018; Friston et al., 2015; Bateson, 1979; Von Foerster, 1984). One of the conditions for the existence of an autopoietic system is a boundary (Maturana, 1980), which resonates with Schrödinger's question above. A Markov blanket defines the boundary between a system of interest and its environment in a statistical sense. More specifically, it provides a statistical partitioning of a system into states internal and states external to the system. In this context, a Markov blanket is a set of variables through which things internal and external to a system interact.

Important examples of Markov blankets arise in multiple fields. One of the most commonly encountered is the present—which is the Markov blanket separating the past from the future and underwrites the notion of a Markov process. Markov processes (Gagniuc, 2017) are stochastic (random) processes whose dynamics may be characterized without reference to their distant past. In other words, if we know the present state of a system, knowing about the past tells us nothing new about the likely future. In biology, Markov blankets have been associated with the physical boundaries through which all influence between the internal milieu and extra milieu spaces are mediated. This concept has been extended to a number of spatial scales within the context of the Schrodinger's 'what is life?' question (Ramstead et al., 2018). What is common in all these examples is that the Markov blanket boundary separate the world into two sets of states, the internal and external which interact only via their Markov blanket (Clark, 2017).

Pearl (Pearl, 1998) introduced the term 'Markov blanket' to describe the set of variables that mediate relationships to and from a variable of interest. More precisely, for a given variable *X* and its known blanket states *b*, no more information about *X* is gained when knowing the state of variables outside *b*. This does not imply that knowing the blanket states allows one to fully predict the evolution of the target variable. This is because there may be some intrinsic properties in the system that renders *X* stochastic. Markov blankets segregate 'directed graphs' known as Bayesian networks such that one side of the blanket is conditionally independent of the other, given the blanket. This conditional independence clearly has important implications.

The Markov blankets that one considers in active inference, comprise sensory and active states, that feature specific coupling or causality relationships with internal and external states (Karl, 2012; Friston, 2013) (Fig. 4). Here, the term 'states' stands for any variable of the system. A stipulative condition for the existence of a Markov blanket is that internal states must be conditionally independent of external states, given blanket states and vice versa. This formalizes the idea that there are no direct interactions between internal and external states, only via the blanket states. In other words, internal and external states can only influence one another via sensory and active states and the internal states only 'see' the external states through the 'veil' of the Markov blanket (Friston 2012, 2013). Specifically, active states mediate the influence of internal states on external states, and sensory states mediate the reciprocal influences. In other words, internal states cannot influence sensory states, while external states cannot influence active states (Fig. 4). The conditional independence between internal and external states—provided by blanket states—enables interactions between the inside and outside of the system, but only via the blanket. It is worth noting that the terms 'active' and 'sensory' derive from applications of this formalism to biology. However, the same mathematical relations exist in Hamiltonian dynamics, where these may be replaced with the labels 'position' and 'momentum'.

Active inference is, thus, an account of autopoiesis in dynamic terms, provided that such systems are (i) at non-equilibrium steady state (NESS) and (ii) that can be statistically segregated from their environment as in figure 4. The first NESS condition simply means that a system persists over a non-trivial timescale and does not dissipate. This implies the existence of a NESS density to which the system self-organizes that can be thought of as a probabilistic description of the system's **pullback attractors**[15] (Crauel, 1999; Crauel and Flandoli, 1994). The second (statistical segregation) condition implies the presence of a Markov blanket (Pearl, 1998; Kirchhoff et al., 2018). The NESS dynamics of the system—and the presence of the conditional independencies implied by a Markov blanket—means that the average internal state effectively parameterize a probability distribution over the external states (Friston, 2013; Kirchhoff et al., 2018; Friston, 2019; Parr et al., 2020). In other words, for any given blanket state, the average internal state represents the causes (i.e. hidden, or external) of sensory impressions. It is fairly straightforward to show that the dynamics of the (average) internal state constitute a gradient flow on a variational free energy functional of this parameterized density. The minimization of free energy (and implicit minimization of sensory entropy) enables biological systems to maintain their sensory states within physiological bounds, and undertake predictive behaviour about the causes of their sensation necessary to sustain their existence (Karl, 2012; Friston, 2013; Da Costa et al., 2020).

In this context, minimization of free energy means resisting entropic fluctuation and maintenance of a bounded set of physiological states. As free energy is a functional of a probabilistic model (the parameterized density over external states above), this

15 In mathematics, the attractor of a random dynamical system may be loosely thought of as a set to which the system evolves after a long enough time. The basic idea is the same as for a deterministic dynamical system, but requires careful treatment because random dynamical systems are necessarily non-autonomous. This requires one to consider the notion of a pullback attractor or attractor in the pullback sense. In the FEP actually roughly designates a stationary probabilistic distribution.

means a system must instantiate an implicit model of its ambient space. Minimizing free energy fits such a model to sensory states, thereby ensuring good predictive behaviour. In Bayesian statistics, the quality for such a model is known as the 'model' evidence or marginal likelihood: namely, the probability of observing some data, given a model of how those data were generated. Variational free energy upper bounds the negative log model evidence, which is a ubiquitous quantity in statistical physics, Bayesian statistics and machine learning (Friston, 2010). In predictive coding, the evidence is taken as the (precision weighted) prediction error. Crucially, in the free energy framework these are all the same thing: the probability distribution encoded by the internal states that quantifies the dynamics of the external states and evolves towards the variational free energy minimum (Friston, 2018)—an upper bound on surprise or negative log evidence (i.e. the negative log probability of finding the system in a particular state) (Friston, 2013).

The surprise is a function of the states of the Markov blanket itself (Friston, 2018). Free energy is a function of probabilistic beliefs, encoded by internal states about external states (i.e. expectations about the probable causes of sensory interaction), given any blanket state.[1] When these beliefs are equal to the posterior probability over external states, free energy becomes equivalent to surprise. Otherwise, it is always greater than (i.e. constitutes an upper bound on) surprise (Friston, 2018). Vicarious interaction through a Markov blanket lends an interpretation to the dynamics of such systems, as if internal states were inferring external states based upon the blanket states. This implies that the kind of organization of Markov blankets we consider results in processes that work to seek out evidence (active inference), namely self-evidencing dynamics underlying the autopoietic—thus autonomous—organization of life (Varela, 1979; Rosen, 1991).

In brief, this means we can characterize living systems as minimizing variational free energy, and therefore surprise, where the minimization of variational free energy entails the optimization of beliefs about things beyond the Markov blanket (i.e. external states). Thus, external fluctuations can therefore (or must therefore) be

modelled to maintain a bounded set of physiological states. This formalism has been applied to a range of problems in biology (Friston, 2013; Friston et al., 2015; Calvo and Friston, 2017; Ramstead et al., 2018) and physics (Friston, 2019; Parr et al., 2020). On the basis of the ensuing Bayesian process of active inference, we turn next to defining and evidence-based Markov blanket for the Earth's climate system.

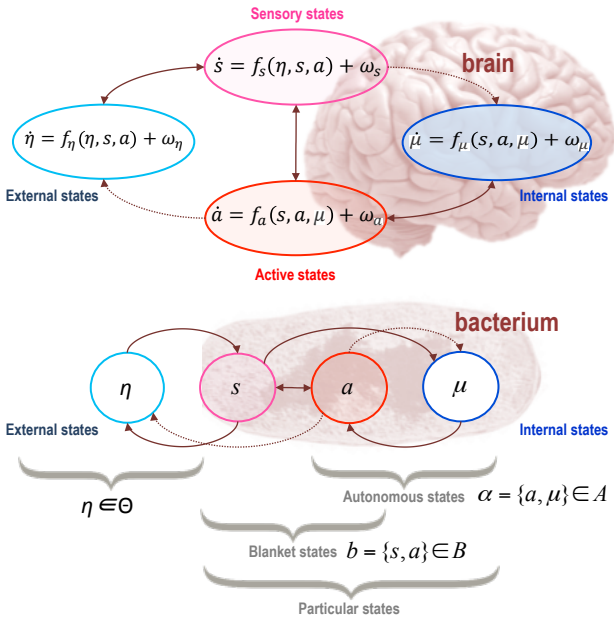


Figure 4. Markov blankets and active inference. A,B) The partition of states into internal states and hidden or external states that are separated by a Markov blanket—comprising sensory and active states in the brain and in a cell, respectively. A) For the assignment of states in the brain, see (Friston, 2010). (B) The internal states can be associated with the intracellular states of a cell, while sensory states become the surface states of the cell membrane overlying active states (e.g. the actin-like MreB filaments that mediate cell mobility). The intracellular state dynamics of a cell correspond to perception, while action mediates coupling from internal states to external states. Importantly, once such a Markov blanket is established for a system of interest, along with the necessary condition of non-equilibrium steady state (NESS), one can formally show that the internal states predict external states and thereby self-maintain the system, via a minimization of variational free energy. This, in turn, implies that the expected entropy of sensory states remains bounded, thereby ensuring resistance to dissipation by external fluctuations. Note that s here is assumed to be given by a static function of *x*. The underlying reason for this is that most software implementations use g to specify a likelihood of sensations given external states, under an adiabatic approximation to the underlying dynamics.

3. Markov blankets and the Earth's climate system

Several authors suggest that autopoiesis happens at the planetary scale (von Foerster, 1975; Jantsch, 1980; Margulis and Sagan, 1986, 1995; Onori and Visconti, 2012; Sahtouris, 1996; Capra and Luisi, 2014; Levchenko et al., 2012; Rubin and Crucifix, 2019; Clarke, 2020). The implication of this view is that minimization of variational free energy must also occur at the planetary level. The challenge for this perspective is to identify the Markov blanket of a climate system (here, the Earth) such that we can think about how internal states of the system may appear to infer and act upon external states. Delineating this blanket is essential in finding the generative model that determines climate dynamics. To do so, we need to define variables (i.e. states) internal and external to the Earth's climate system—those states that constitute or are intrinsic to the system and those that are not. In so doing, we regard empirical, and model-evidence based interactions between the Earth's climate components and identifies a set of variables that satisfy the conditional independencies allowed by the Markov blankets that underwrite active inference (Fig. 5).

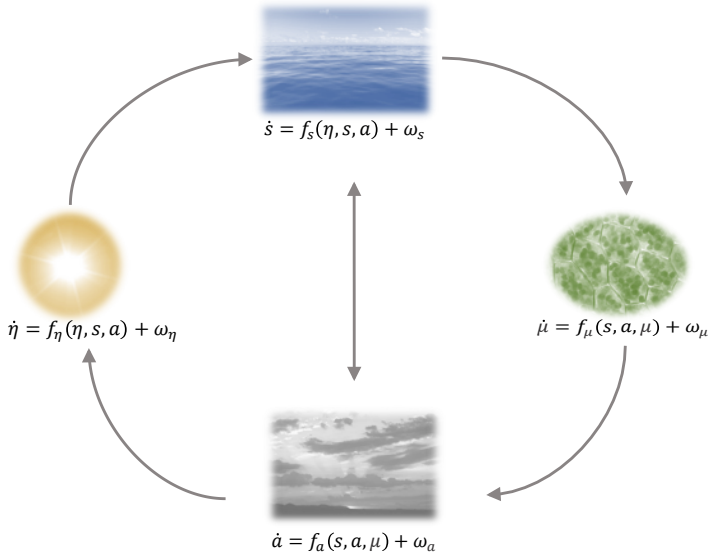


Figure 5. Earth's climate and Markov blankets. This figure illustrates the conditional dependencies between four key variables in the Earth's climate system. These

conditional dependencies imply a Markov blanket comprising active (*a*) and sensory (*s*) states (in analogy with perception–action loops in cognitive science) that mediate the interactions between internal (*μ*) and external (*η*) states. The internal states are the metabolic rate changes of atmospheric greenhouses and aerosols turnover (see §3.2 for the full explanation). These influence active states (changes in greenhouse and albedo effects) (see §3.3) and vicariously the external states (solar radiation changes at the Earth's surface) (see §3.1). The external states cause changes in the sensory states (ocean-driven global temperature changes) (see §3.4), which leads to changes in the internal states. External (and sensory) states exhibit dynamics prescribed by stochastic differential equations (or a static stochastic mapping) with Gaussian white noise uncorrelated in time (*ω*). Internal and active states perform a gradient descent on variational free energy (*F*), defined in relation to a (characteristic) NESS density for the external and sensory states. As a consequence, the internal states appear to model and act upon the external and sensory states.

Figure 5 illustrates the conditional dependencies between variables forming the Earth's climate system and Markov blanket, highlighting that the metabolic rates of the biosphere (internal states) only influences solar radiation at the Earth's surface (external states) via changes in greenhouses and albedo effects (active states), while reciprocal interactions are mediated by the ocean-driven global temperature changes (sensory states). We turn next to defining each of these variables that constitute this climatic partition of states.

3.1. EXTERNAL STATES (*η*): INCOMING SOLAR RADIATION CHANGES AT THE EARTH'S SURFACE

The **space weather**[16] and external environment of the Earth system, such as the electromagnetic solar radiation and galactic cosmic shortwave radiation and energetic electron precipitation, are the source of energy, but also of external forcing and perturbation, respectively (Mironova et al., 2015). In many mainstream climate models (radiative energy balance models, earth system models of intermediate 'complexity' and general circulation models) cosmic rays are not a source of forcing fluctuation in the climate system. Indeed, the study of the impact of cosmic rays on Earth, in general, does not fall within climate science, but rather with astrophysics

16 'Space weather refers to dynamic conditions on the Sun and in the space environment of the Earth, which are often driven by solar eruptions and their subsequent interplanetary disturbances' (Liu et al., 2014).

and planetary science. In line with the interdisciplinary perspective offered here, we mention these possibilities—which could be incorporated into the external states of a Markov blanket for the Earth's climate system. However, the key construct of the Markov blanket does not depend upon this, and the external states stand in for anything outside of the system of interest that causes changes to the blanket states.

According to the standard model of stellar evolution, the incoming solar radiation during the Archean to the Proterozoic eon (3.8 billion to 542 Ma) was 20–30% lower than at present (Gough, 1981; Sagan and Mullen, 1972). The faint young Sun was only 76–83% as intense as its current value (Goldblatt and Zahnle, 2011). Also, the Sun often displays extreme and severe coronal mass ejections, solar flares and storms, making the Earth's space weather difficult to predict (Liu et al., 2014). Sunspots and low solar activity (solar Maunder minimum) correspond with historically documented cold periods on Earth—and is often related to little ice ages, in the form of frost fairs (Lockwood et al., 2017). Diverse reconstructions of past climate records, in cosmogenic isotope archives, have revealed associations between the Earth's climatic response to solar radiation changes and cosmic ray variations (Kirkby, 2007).

Despite changing space weather, such as solar radiation fluctuation, the Earth is close to being in *radiative equilibrium*. The incoming energy (mainly of the Sun) is balanced by an equal flow of heat that the Earth radiates back to outer space. Under the condition of the Earth's so-called energy flux balance (Stephens et al., 2012), Earth's temperature is bounded at habitable levels (Lovelock and Kump, 1994). How the energy flows into—and away from—the Earth is key to understanding climate dynamics (Stocker et al., 2013). This also indicates that although the solar radiation at the Earth's surface is necessary, it is not the only factor affecting global temperatures on Earth. There are different constraints and processes that account for the Earth's energy flux balance. These depend on the timescale. At very short times scales, among other phenomena, the incoming Sun radiation leads to evaporation of seawater and sea surface temperature changes (Liang and Wu, 2013). At millennial time scales (the last 3 Myr) changes of solar radiation at the Earth's surface due to

variations in the Earth's orbit *triggered* climatic changes such as glacial-interglacial oscillations (variations in ice volume and ice-sheet extent) (Milankovitch, 1941), the so-called Milankovic effect of orbital (astronomical) forcing. At long timescales (from 2 to 4 billion years), different constraints on the Earth system offset the weak forcing and radiation of the faint young Sun. Thus, the solar radiation exerts different forcings at different time-scales. Our proposal is that changes in solar radiation at the Earth's surface account for the external states of the Earth's Markov blanket (η) (Fig. 5).

For the Earth's Markov blanket proposed here, volcanoes—a source of carbon and abiogenic aerosols—may not be external to the Earth's climate system as it is in mainstream climate models. This follows from the next argument: the structure of inner and outer layers of the continental plates appears to have been dominated by water-dependent continental drift changes (Lowman and Lowman, 2002). The hydrological cycle, which allows continental drift and geomorphological changes, is life-dependent (Harding and Margulis, 2009). Together with the shift from the reductive to oxidative atmosphere—from the advent of photosynthesis and the shifting balance between seafloor and terrestrial weathering (Mills et al., 2014) in the middle Archean to the Proterozoic period—resulted in the strength of the hydrological cycle, continental drift, continent growth, plate spreading, volcanic activity (Rosing et al., 2006; Hawkesworth and Kemp, 2006; Falkowski, 2006; Kump, 2008). Tectonic and volcanic activity and their products, therefore, are ultimately internal to the Earth system functioning, and thus to its Markov blanket.

Under free energy minimization, the forcing by the external sates may affect Earth's climate only through its Markov blanket's sensory states ($\eta \rightarrow s$) (ocean-driven global temperature changes) (Fig. 5). At first glance, one might think this to be only partially true, because the solar irradiance impacts on the Earth's upper atmosphere. However, the insolation on the upper atmosphere is quite different to the insolation reaching the Earth's surface after passing through the atmosphere, most of which is metabolically derived (see next sections). Hence, changes of atmospheric states such as changes in green houses concentration triggered by the solar irradiance and

cosmic ray particle ionization—such as large-scale electric current dynamic changes in the troposphere (Lam and Tinsley, 2016), or enhanced cloud formation—are ultimately determined by the internal states through active states (e.g. cosmic rays do not produce cloud condensation nuclei, but may trigger its biogenic production (Kirkby et al., 2016)). In short, the changes in solar radiation at the Earth's surface may be selected by the internal states through active inference.

3.2 INTERNAL STATES (μ): METABOLIC RATE CHANGES

Internal states must be conditionally independent of external states provided blanket states and vice versa. This formalizes the idea that there are no direct interactions between internal and external states, only via the blanket states. Here, we propose that the metabolic rate changes fulfil this condition, and thus are the Earth's Markov blanket internal states (μ). We base this proposition on the following arguments.

The metabolic rate reactions directly depend on habitable bounded temperatures and only indirectly on the incoming solar radiation (external states). This means that the external states of Earth's Markov blanket can only affect the metabolic rate changes through bounded sensory states ($\eta \rightarrow s \rightarrow \mu$) (Fig. 5). One may argue that this is not true, because the photosynthesis depends on solar radiation. However, at low temperatures, between 0 and 10°C or above 20°C the enzymes that carry out photosynthesis do not catalyse at the optimum photosynthetic rate, which is obtained between 10 and 20°C (Grimaud et al., 2017; Schaum et al., 2017). Indeed, all the metabolic rate reactions on the Earth system depend directly on the physiological temperatures between ≈0–40°C (Gillooly et al., 2001) at which the Earth has remained since the Archean (Catling and Zahnle, 2020).

The metabolic rate changes affect the incoming solar radiation (external states) only through its active states ($\mu \rightarrow a \rightarrow \eta$) (Fig. 5). While the biosphere captures no more than 1% of solar radiation, and thus can be considered insignificant on the Earth's energy flux balance, from the Archean to the present the atmospheric and lithospheric chemical elements have been continuously metabolically transformed, produced (Margulis and Lovelock, 1975, 1974; Izon et al., 2017; Atekwana and

Slater, 2009; Jelen et al., 2016; Jansson and Hofmockel, 2019), mobilized (McGenity, 2018), localized (Tornos et al., 2018) and integrated into biogeochemical cycles (Falkowski et al., 2008).

The biogeochemical cycles have emerged on a planetary scale to form a set of nested abiotically driven acid–base and (mostly) microbially driven redox reactions that set lower limits on external energy required to sustain the cycles. These reactions altered and created, on a planetary scale, the average redox condition of the Earth's surface state. The metabolic oxidation of Earth is driven by photosynthesis, which is the only known energy transduction biochemical pathway that is not directly dependent on preformed bond energy (Falkowski et al., 2008). In this manner, the metabolic rate changes are in part linked to the rate of net primary productivity (NPP). Indeed, through biogeochemical cycles (specially carbon cycle) global NPP had contributed three times more energy to the geochemical cycles than Earth's internal heat (Hawkesworth and Kemp, 2006). While the contribution of the marine ecosystems (mostly microbial and unicellular) is longer over geological timescales, the continental ecosystems per unit area contributes much more and faster due to availability of key nutrients and solar energy. However, due to the extension of the ocean and the accelerated rates of continental weathering in the continents both have equivalent contribution to the global NPP (Schwartzman, 2017).

The biogeochemical carbon cycle, upon which most of the current climate change depends (Stocker et al., 2013), involves carbon dioxide (CO_2) and methane (CH_4) in the troposphere due respectively to metabolic enhancement of rock weathering (Schwartzman and Volk, 1989; Schwartzman, 2017) and methanogenesis rates (Bardgett et al., 2008). On Earth 99.9% of CH_4 is due to methanogenesis (Conrad, 2009). The biogeochemical carbon cycle also is linked to the O_2 levels (availability of useful energy) and the formation of ozone (O_3) in the stratosphere which intercepts, absorbs and converts more than 97% of the sun's mutagenic ultraviolet radiation into heat (Falkowski, 2006). The biogeochemical sulphur cycle involves the production and release into the troposphere of biogenic cloud-forming aerosols,

such as dimethyl sulphide (DMS). On average, the aerosols of ocean microorganisms boost the number of cloud droplets by about 60% annually (McCoy et al., 2015). DMS is produced not just on the sea (Sanchez et al., 2018), but also on continents (Carrión et al., 2015; Jardine et al., 2015). Ion-induced nucleation of pure biogenic particles (Kirkby et al., 2016) and the microbes suspended in the atmosphere also induce cloud formation (Bryan et al., 2019; Hamilton and Lenton, 1998). A biogenic aerosol–climate linkage has been postulated, through the albedo effect of clouds affecting the incoming solar radiation, hence the Earth's energy flux balance and temperature (Charlson et al., 1987). Model-based evidence shows this is highly plausible (Gunson et al., 2006; Gabric et al., 2013; Wang et al., 2018). What is crucial is that the existence of glaciers and ice sheets, which translates effectively into changes in albedo effects (active states), depends on the accumulation of snow and therefore on a great part of global cloud cover derived from metabolism. Thus, the metabolic rate changes have resulted, among other things, in changes in greenhouse and albedo effects (active states) (Fig. 5), and hence in the Earth's energy flux balance and habitable temperatures.

Planetary life-like phenomenon is an organizing and self-organizing critical phenomenon (Bak, 1993; Levin, 2005; Lenton and van Oijen, 2002; Schwartzman, 2002; Levin, 1998) involving not just the biospheric biogeochemical cycles, but the atmosphere, hydrosphere and geosphere (Morowitz, 1993; Morowitz et al., 2008; Goldford and Segrè, 2018; Kim et al., 2019). On geological timescales, resupply of C, S and P is dependent on tectonics, especially volcanism and rock weathering. Although, the internal states proposed here focuses only on carbon cycling, biogenic aerosols and (oxygenic) photosynthesis, whereas the metabolic network of the biosphere is much more complicated (Falkowski et al., 2008; Jelen et al., 2016) and rates may be limited by other components such as nitrogen availability (also biologically constrained), an extensive overview of the Earth's metabolism should be considered in the future for a more detailed account of internal states. Here, we simply acknowledge that the system cannot respond with infinite capacity to appropriate temperature ranges when it also depends on biological cycling of

essential nutrients. In this regard, the dynamics of internal states' response may be critical.

Some explanations have associated the metabolic responses at the planetary level with biological evolution at the 'species' level (Lenton et al., 2018). This proposal suggested that the persistence of the biosphere increased its likelihood of acquiring further persistence-enhancing traits and that species that destabilize their environment are short-lived and result in extinctions until a stable state is found. While it is reasonable to say that metabolic rate changes plays out on the diversity, richness, abundance and connectivity (trophic and symbiotic relations) of eukaryotic systems and prokaryotic microorganisms in the ocean, continents, deep subsurface and atmosphere (Margulis and Sagan, 1986; Medini et al., 2005; Stolz, 2016; Magnabosco et al., 2018), diversity depends on 'speciation' that requires the arising of new lineages, which may take longer timescales than metabolic timescales. At least, so far, there is no experimental evidence of speciation (i.e. identification of functionally distinct microbial strains which are only distinguishable at the operational taxonomic unity (OTU) or sub-OTU level based on common marker sequences (Eren et al., 2013)) under controlled conditions at metabolic timescales. Thus, although the biospheric diversity encodes the metabolic capacity, contributes to the stability and perhaps contributes significantly to speed up or slow down the metabolism of the system, it is more congenial that the dynamics of the internal states' responses are firstly associated with metabolic rate changes based on a relatively stable microbial set of a key core enzymes[17] (e.g. Rubisco) scattered in a single rhizome network of the biosphere (Raoult, 2010; zu Castell et al., 2019; Margulis, 1998; Hermida, 2016) despite enormous genetic diversity[18] (Falkowski et

17 Enzymes that are involved in major redox reactions and electron transfer of Earth's chemistry (Williams, 1996; Falkowski et al., 2008)

18 Paleontological evidence (Barnosky et al., 2011) shows that the Earth system had several mass extinctions (reduced diversity in the sense that it loses more than three-quarters of its species in a geologically short interval) and did not lose its habitability condition. A parallel example would be the

al., 2008; Jelen et al., 2016). Enzymes are fast-acting, demand low energy and of activation and thermodynamically constrain the redox reactions (Wolfenden and Snider, 2001), which continuously and directly ensures the changes in greenhouse and albedo effects that constitute the active states (Fig. 5), and thus instantiate the internal states (μ) beneath the Earth's Markov blanket.

3.3 ACTIVE STATES (a): CHANGES IN GREENHOUSE AND ALBEDO EFFECTS

From the Archean to the Proterozoic eons (from 4 to 2.5 billion years ago), solar radiation alone was too weak (Gough, 1981; Bahcall et al., 2001), to maintain liquid water and ice-free conditions on Earth (Sagan and Mullen, 1972) (see §3.1). Indeed, if all other global parameters are held constant, and if the Archean–Proterozoic Earth's greenhouse gas concentration in the atmosphere were the same as now (405 ppm/0.0405% and 722 ppb/0.007% and of the air of CO_2 and CH_4 respectively) (Goldblatt and Zahnle, 2011; Goody and Yung, 1995), the Earth's mean temperature would have been below the freezing point of seawater (−4°C to 18°C) (Goldblatt and Zahnle, 2011; Goody and Yung, 1995). Earth would have been in continual deep freeze, with glaciers reaching the Equator, at until one billion years ago, when the solar radiation had increased enough to melt the ice (Goldblatt and Zahnle, 2011; Goody and Yung, 1995). In this case, the internal states of the Earth system, which rely on liquid water and physiological temperatures, would have been very limited or perhaps non-existent. And yet, there is ample geologic, palaeontological and model-based evidence regarding this geological period showing the existence of extensive bodies of liquid water at the surface and continuous habitable Earth's temperatures (≈0–40°C) (Sagan and Mullen, 1972; Goldblatt and Zahnle, 2011; Catling and Zahnle, 2020; Feulner, 2012; Waltham, 2019). This puzzle is called the faint young Sun paradox.

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development of a metacellular whose homeorhetic identity remains the same from the embryo (low cellular diversity) to the adult (high cellular diversity), regardless of the cellular diversity.

Earth's climate responses compensated for the young Sun's lower radiation at the Archean Earth's surface through the warming produced by higher greenhouse gas concentrations (increase of greenhouse effect) and reduced albedo (reduced radiation reflection) (Sagan and Mullen, 1972; Goldblatt and Zahnle, 2011; Catling and Zahnle, 2020; Feulner, 2012; Waltham, 2019; Owen et al., 1979). Precisely, the CH_4, which has stronger radiative forcing than CO_2 and is almost entirely metabolically produced (see §3.2), could have provided 10–12°C of surface warming (Haqq-Misra et al., 2008)with levels ranging 10^2 to 10^4 times higher than modern amounts (Catling and Zahnle, 2020). A high amount of atmospheric nitrogen (increasing atmospheric pressure), dependent on the biogeochemical nitrogen cycle, would have given 4.5°C extra warming (Goldblatt et al., 2009). Thus, the increment of greenhouse gas fluxes and abundance was *necessary* to offset a fainter Sun (Feulner, 2012; Catling and Zahnle, 2020), if the habitable conditions of the Earth system were to be maintained.

The solar radiation has steadily increased by 20–30% from the Mesoarchean, to the Proterozoic, to the present (Gough, 1981; Bahcall et al., 2001). That is, the faint young Sun became a bright mature Sun. Yet, the Earth's liquid water did not evaporate as with Venus or dissipate as with Mars (Lammer et al., 2018). Increasing solar forcing through time is roughly cancelled by decreasing greenhouse and increasing albedo effects by atmospheric clouds and lithospheric ice–snow cover, which reflect the Sun's radiation back into space (Mitchell et al., 1995; Feichter et al., 2004). Evidence shows that over that period, the CH_4 and CO_2 greenhouse gases declined to their pre-industrial values, approximately 722 ppb/0.007% and approximately 200 ppm/0.02%, respectively (Owen et al., 1979). This was an active process. Oxidative metabolic enhanced silicate weathering dampened the CO_2 concentration 1000 times faster (Schwartzman and Volk, 1989; Zaharescu et al., 2020) compared to inorganic anoxic carbonate–silicate weathering (Walker et al., 1981). The oxidative atmosphere derived from the evolution of photosynthesis shifted the metabolic rates towards oxidation and thus faster reduction of greenhouse gases (Falkowski and Isozaki, 2008; Kump, 2008). The Proterozoic CH_4 has been

damped by reverse methanogenesis, causing an anti-greenhouse effect by forming a thick hydrocarbon organic haze (fog) given the changes of CH_4/CO_2 ratios higher than approximately 0.1 (Haqq-Misra et al., 2008; Olson et al., 2016). Moreover, since the late Archean, climate moderation by the carbon cycle (mainly CO_2/CH_4) is consistent with the increase of snow–ice cover, and thus occasional glaciations (Catling and Zahnle, 2020; Boyle and Löscher, 2019). Glaciers, ice-sheets and snow cover depend on cloud formation. Model-based evidence shows that the net effect of cloud cover is cooling (Gunson et al., 2006; Gabric et al., 2013; Wang et al., 2018). Glaciers, ice-sheets and snow cover account for more than 70% of the Earth's albedo effect (Stocker et al., 2013). These results indicate that the albedo effect is necessary to counterbalance the steadily increase of incoming solar radiation.

These rather basic observations allow us to assert that changes in greenhouse and albedo effects instantiate the active states of the Earth's Markov blanket. Both effects, the greenhouse and albedo, are conditionally dependent on the metabolic rate changes that result in modelling, inference and selection, through this blanket, of the incoming solar radiation at the Earth's surface (external states) ($\mu \rightarrow a \rightarrow \eta$) (Fig. 5). Importantly, by acting upon the external states, the active states of the Earth's Markov blanket also bind (i.e. upper bound) its sensory states; so that the entropy of the system does not increase indefinitely, i.e. dissipate ($a \rightarrow \eta \rightarrow s$)[19] (Fig. 5).

3.4 SENSORY STATES (*S*): OCEAN-DRIVEN GLOBAL TEMPERATURE CHANGES

The ocean is a driving force affecting the Earth's mean temperature and thus the climate system's temporal evolution (Stocker et al., 2013; Garuba et al., 2018; Zanna et al., 2019). Changes in Earth's mean temperature depend sensitively on the thermal

[19] Technically speaking, the system sensory states entropy is effectively bounded from above and below.

inertia of the ocean's capacity to absorb heat (ocean heat uptake) (Li et al., 2013; Rose and Rayborn, 2016). The ability to absorb heat from the ocean is influenced by the physical-chemical properties of the water (high specific heat capacity), and also by the dynamics of the ocean itself and its interaction with the atmosphere. That is, the ocean does not change its temperature 'rapidly' as the atmosphere does, and the oceans' heat uptake reduces **climate sensitivity**[20] and weakens its warming response (Li et al., 2013; Garuba et al., 2018; Resplandy et al., 2018; Zanna et al., 2019; England et al., 2014). As a consequence, the ocean drives the global temperatures by distributing heat around the planet, responding very slow to thermal fluctuation and absorbing 1000 times more heat than the atmosphere without changing its temperature. It thus accumulates about 93% of the Earth's thermal energy (Cheng et al., 2019). The excess energy that the ocean stores can lead to the ocean's thermal expansion, melting of ice sheets and thus to sea-level rise, which on the latest glacial–interglacial oscillation represents changes in sea level over 100 m (Lambeck et al., 2002).

These empirical and model-based observations let us consider the ocean-driven global temperature changes as accounting for the sensory states (*s*) of the Earth's Markov blanket (Fig. 5), and, therefore, bidirectional interactions of the sensory states with external and active states. Incoming solar radiation (external states) mainly causes evaporation of ocean-surface water via sea-surface heat and surface temperature changes (Liang and Wu, 2013). This affects water-vapour concentration in the troposphere, air-temperature distribution, winds, cloud formation and intermittent precipitation on continents and the absorption of greenhouse gases[21] (Brown et al., 2019). All these evince the influence of external on sensory and of sensory states on active states. It is through the thermal and density gradients of seawater that sensory states affect incoming solar radiation changes at the Earth's

[20] Climate sensitivity refers to how much, in the near and the long-term, the Earth's climate will warm (or cool) after a perturbation like an increase in CO_2 concentrations or solar radiation.

[21] The ocean is the most important sink of atmospheric CO_2 (Brown et al., 2019).

surface (external states). Both gradients ultimately determine ocean convection, turnover and general circulation accounting for the slowdown in surface warming and the cooling of the ocean with the relevant effects on the glacial cycles (Pena and Goldstein, 2014). The overall ocean dynamics results in moving heat from Earth's equator to the poles, distributing energy throughout the Earth's climate components, and thus on the ocean-driven global temperature changes (Li et al., 2013; Garuba et al., 2018; Resplandy et al., 2018; Zanna et al., 2019; England et al., 2014).

These arguments speak to the dynamics of Markov blankets, in which external states cannot directly affect changes in active states (greenhouse and albedo effects), but only as mediated through the sensory states. Similarly, the changes in solar radiation at the Earth's surface affect the metabolic rate changes (internal states) only through the sensory states (ocean-driven global temperature changes) ($\eta \rightarrow s \rightarrow \mu$) (Moore et al., 2018; Brown et al., 2019). That is, the ocean dynamics becomes the sensory states for the dynamics of whole biosphere (marine and continental) (see §3.2). At first glance, one might question this, because the oceans cannot mediate the interactions between solar radiation and the continental ecosystems. However, the metabolic rate changes, not just in marine, but in continental ecosystems are driven by the Earth's mean temperature (Schwartzman et al., 1993; Wieczynski et al., 2019; Jansson and Hofmockel, 2019). At the same time, the only way that the internal states affect the ocean is through the chemical modification of the atmosphere and lithosphere, which results in changes of greenhouse and albedo effects (active states) (see previous sections). This interaction between internal and external states as climatic states—in a Markov blanket—amounts to describing the dynamics of the internal states as actively inferring external states and hence the instantiation of active inference at the planetary scale.

4. Discussion: active inference at the planetary-scale

Within the free-energy framework, the consideration of planetary autopoiesis as active inference rests upon the existence of a Markov blanket for the Earth's climate system. That is, in the relation and coupling of internal and external states through

the Markov blanket. If we take the perspective that the metabolic rates change (the internal states of the Earth's Markov blanket) is performing active inference about the changes in incoming solar radiation (external states), we can frame their dynamics in terms of approximate Bayesian inference, which is equivalent to the minimization of variational free energy. This treats the metabolic rate changes as if they parametrize an implicit (variational) probability density over solar radiation changes at the Earth's surface and optimize this to maximize model evidence of changes in external states to preserve habitable conditions.

As the metabolic rate changes influence changes in greenhouse and albedo effects, the indirect or mediated influence of solar-radiation variation at the Earth's surface is mathematically equivalent to Bayesian inference. This is because we could, in principle, use the average solar radiation changes at the Earth's surface to draw inferences about the variables affecting the metabolic rate changes. This perspective implies a NESS density associated with the blanket and its external states, i.e. the density that the system tends toward when it is perturbed. In analogy with biological-like behaviours at the planetary-scale proposed by the Gaia hypothesis, this may be thought of as the range of values within which Earth's homeorhetic dynamics can anticipate (and accommodate) any deviations. Dynamic anticipation of this sort implies that changes in greenhouse and albedo effects also optimize the same quantity through changing ocean-driven global temperatures (directly and via external states).

An alternative interpretation of the NESS density is as a generative model. This implies that the metabolic rate changes implicitly may model solar radiation changes at the Earth's surface and select them via changes in greenhouse and albedo effects. This process of selection through modelling the environment means that to find the dynamics of the metabolic rate changes—and their influence over changes in greenhouse and albedo effects—we need only to specify the NESS for solar radiation variation at the Earth's surface and ocean-driven global temperatures. The dynamics of active and internal states will emerge from minimizing free energy. That is to say, a sort of planetary selection of permissible perturbations from solar

radiation changes at the Earth's surface results in the continuous operating of the Earth system habitability. What is selected will depend on the active inference at planetary-scale, in relation to the model it generates through the integrated dynamics of the biosphere, atmosphere, lithosphere and hydrosphere.

This perspective of such a mathematical formalism may be useful in the modelling of the Earth's climate system as a systemic unity in three ways. The first is in inferring parameters of the implicit NESS density (or generative model) that underwrites the Earth's climate dynamics. The second is that alternative models (with alternative NESS densities) may be proposed to formulate alternative hypotheses about the Earth's climate system. A standard mathematical framework enables model comparison (i.e. hypothesis testing) to adjudicate between these hypotheses. Thirdly, this may be useful in predictive modelling, that is, in establishing how different interventions may impact the long-term evolution of Earth's climate. A pragmatic consideration here is that if one can write down the NESS density over external (solar) and sensory (oceanic) states—that is characteristic of the Earth—one can simulate the metabolic (i.e. internal states), greenhouse and albedo effects (i.e. active states) using a gradient flow on variational free energy. The key point here is that the requisite gradients are analytically and numerically tractable; enabling the climactic simulations, much along the lines of how active inference is used to model experimental subjects in cognitive science (neuroscience and ethology).

While this paper sets out a possible conditional dependency structure between environmental variables, consistent with a Markov blanket, this should be viewed as a hypothesis. This is subject to evidence that could support or refute this. For example, if it were demonstrated that solar radiation at the Earth's surface and metabolic rates in the biosphere are not (approximately) conditionally independent of one another, once greenhouse, albedo and ocean temperatures are taken into account, this would offer strong evidence against our hypothesis.

The relatively abstract treatment here—based upon conditional dependencies—means we have not specified a functional form for the equations of motion linking

the dynamics of each climate component. This highlights the work yet to be done to move from a theoretical framing of climate dynamics to a useful model that can be used to test empirical hypotheses. The next two phases of this research will be as follows. First, we need to specify the functional form of the external state dynamics, as a function of the active states, and the form of the sensory states as a function of the internal and active states. This sets up an implicit generative model from the perspective of the active and internal states and means we can test the face validity of this formulation through numerical simulation. In addition, we hope to demonstrate construct validity in relation to established climate models. The second phase will be to fit these numerical simulations implemented with standard software routines (e.g. spm_ADEM.m)[22] to climate data. In doing so, we hope to develop a tool that lets us evaluate the evidence afforded by alternative hypotheses about the causes of these data. Under active inference, these hypotheses are typically framed in terms of the parameters of prior beliefs implicit in a generative model (Schwartenbeck and Friston, 2016). In other words, we can think of internal states as evolving as if they held beliefs about the external states, and can test hypotheses about what these beliefs might be. The utility of this framing is that our interest is in how biotic and abiotic elements of the climate interact, so it is helpful to be able to pose hypotheses about the one in relation to the other. However, the perspective that the internal states of the Earth's Markov blanket perform inferences about—and act on—the incoming energy radiation through the ocean (sensory) and the greenhouse-albedo effects (active) states may tell us something profound about the character and nature of the Earth system.

[22] Part of the freely available as Matlab code in the SPM12 academic software: http://www.fil.ion.ucl.ac.uk/spm/

5. Conclusion

This chapter outlines key organizational relationships among the Earth systemic components—comprising the atmosphere, hydrosphere, lithosphere and biosphere—that allows one to posit the existence of a Markov blanket for the Earth's climate system. The motivation for this proposal follows the hypothesis that the non-equilibrium steady-state dynamics that underwrite our climate history depends on planetary active inference, which rest upon the existence of a Markov blanket that enshrouds the Earth's internal states. This requires an appeal to the mathematics of living (cognitive) systems, such as minimization of variational free energy, where the formalism of interaction with an external environment has been most comprehensively developed. The Earth system's Markov blanket proposed above conforms to some basic model-based and empirical observations about how the metabolic rate (framed as the internal states) interacts with changes in the solar radiation at the Earth's surface (external states) through ocean-driven global temperatures (sensory states) and through the atmospheric–lithospheric greenhouse-albedo effects (active states). Crucially, a Markov blanket equips the Earth's climate system with a Bayesian process that will allow us to see whether the average internal states appear to engage in active inference—to actively maintain a non-equilibrium steady state. That is to say, establishing a Markov blanket for the Earth's climate system may allow us to treat its dynamics as performing active inference, in the fashion of biological anticipation (Rosen, 1985a), and as a form of planetary autopoiesis.

Chapter 5

CLIMATE HOMEOSTASIS BY AND FOR ACTIVE INFERENCE IN THE BIOSPHERE

Based on:

Rubin, S., Heins, C., Da Costa, L., & Friston, K. (2023). Submitted

ABSTRACT

This chapter asks whether a biosphere-climate dynamical system can sustain (nonequilibrium) steady-state dynamics, i.e. climate homeorhesis, through active inference. In a dynamic model of the biosphere-climate system, we identify the biosphere and net incoming solar radiation as the internal and external states of the system; separated by a boundary comprising 'sensory' states (surface temperature) and 'active' states (greenhouse gas concentration). We use numerical analysis to identify a synchronisation function that maps internal states to a probability distribution (i.e., posterior belief) over external states. Our results suggest that the biosphere can be read as inferring changes in incoming net solar radiation via changes in greenhouse gas concentrations that underwrite steady-state surface temperature dynamics. When the surface temperature is perturbed from its expected state, the system acts on the external states to restore characteristic climate trajectories, in a way that could be interpreted as an active correction of 'sensory' prediction errors. Modifying system parameters — that relate to energy balance – changes the properties of the synchronisation map and therefore affects the precision of inference. When the solar constant reaches levels below those seen 4 Gyr ago — or expected more than 1.5 Gyr into the future — inference fails. The historical early microbial biosphere or the future biosphere's lifespan roughly corresponds to solar constant within those limits, where climate homeorhesis is at play by and for active inference in the biosphere.

1. Introduction

There is a broad consensus, based on geological and model-based evidence, that the temperature of the Earth system since the Archean (4 Gyr ago) to the present day has been bounded in the range of (≈0–40°C)(Catling and Zahnle, 2020), despite the continuous increase in solar luminosity from a faint young Sun to a bright mature Sun (Gough, 1981; Bahcall et al., 2001; Sagan and Mullen, 1972; Goldblatt and Zahnle, 2011). In other words, it can be considered that within the entire ontogeny of the Earth system, there is a kind of climatic homeorhesis, which refers to the property of certain systems to return to a particular trajectory, rather than to a particular state, after an external perturbation or in the face of random fluctuations or noise (Waddington 1965). This has been formulated initially in the so-called Gaia hypothesis (Lovelock, 1979; Lovelock and Margulis, 1974; Margulis and Lovelock, 1974).

When the Earth formed around 4.5 Gyr ago — and from the Archean to the Proterozoic eon (from 4 Gyr to 542 Myr) — solar luminosity was 30–20% weaker than at present, and the Sun was only 76–83% as intense as it is today (Gough, 1981; Bahcall et al., 2001; Sagan and Mullen, 1972; Goldblatt and Zahnle, 2011). With the current Earth's atmospheric greenhouse gas concentration, composition, and other global parameters held constant, the Earth's mean temperature would have been below the freezing point of seawater (–18°C), oceans would have been frozen until 1 Gyr ago, with glaciers reaching the Equator, where surface liquid water is first encountered, and thus active life would not have been possible (Feulner, 2012). Yet, the presence of sedimentary rocks 3.8 Gyr ago showed that material was being weathered from continents and deposited at the bottom of the sea. This suggests the existence of extensive bodies or even oceans of liquid water, which must have thus been at geophysiological temperatures (Sagan and Mullen, 1972; Goldblatt and Zahnle, 2011; Catling and Zahnle, 2020; Feulner, 2012; Waltham, 2019). This puzzle is called the faint young Sun paradox because — during this geological period — solar radiation alone is too weak to explain how liquid water and ice-free conditions on Earth were maintained (Sagan and Mullen, 1972).

Higher carbon based-greenhouse gas concentrations and thus higher greenhouse effect and reduced albedo appear to have been a compensatory behaviour on the part of the Earth, to offset a fainter Sun and its lower radiation (Goldblatt and Zahnle, 2011; Catling and Zahnle, 2020; Feulner, 2012; Charnay et al., 2020). Methane (CH_4), which has twenty times more radiative forcing than CO_2 and, on Earth, is almost entirely (99,9%) methanogenically produced (Conrad, 2009) could have provided 10–12°C of surface warming (Haqq-Misra et al., 2008) with levels ranging from 102 to 104 times higher than modern amounts (Catling and Zahnle, 2020). Yet, this would have required controlled concentrations, so as not to induce cooling effects (Eager-Nash et al., 2023), to maintain geophysiological conditions (i.e., the habitability) (Lovelock, 1988a).

As the solar radiation has steadily increased by 20–30% from the Mesoarchean, to the Proterozoic, to the present—roughly 1% brighter every 100 million years—(Gough, 1981; Bahcall et al., 2001) the faint young Sun has become a bright mature Sun. This increase should have overheated the Earth, leading to a runaway greenhouse effect (through the evaporation of liquid water); in which the Earth would be unable to shed heat to space as fast as it arrives. However in fact, this does not happen. The increased solar forcing through time is roughly cancelled by decreasing greenhouse gases and increasing albedo effects by mostly atmospheric clouds and lithospheric ice–snow cover, which reflect the Sun's radiation back into space (Mitchell et al., 1995; Feichter et al., 2004). Evidence shows that over that period, CH_4 and CO_2 greenhouse gases declined to their pre-industrial values, approximately 722 ppb/0.007% and approximately 200 ppm/0.02%, respectively (Owen et al., 1979). The oxidative atmosphere derived from the evolution of photosynthesis shifted metabolic rates towards oxidation and thus faster reduction of greenhouse gases (Falkowski and Isozaki, 2008; Kump, 2008; Haqq-Misra et al., 2008; Olson et al., 2016). Oxidative metabolic-enhanced silicate weathering dampened CO_2 concentration 1000 times faster (Schwartzman and Volk, 1989; Zaharescu et al., 2020) compared to inorganic anoxic carbonate rock–silicate

weathering (Walker et al., 1981). All these seem to result from the stabilising feedback of decreasing greenhouse gas, which exerts a dominant control over Earth's surface temperatures and resists the rise in temperatures, which would otherwise result from an increase in solar luminosity (Arnscheidt and Rothman, 2022; Lovelock and Watson, 1982; Lovelock, 1991c).

Since the late Archean, climate moderation by the biogeochemical carbon cycle has been consistent with the increase of snow-ice cover (Catling and Zahnle, 2020; Boyle and Löscher, 2019), which depends on cloud formation. Beside carbon cycle, clouds determine earth's long-term climate stabilization (Goldblatt et al., 2021). Cloud-forming aerosols, such as dimethyl sulphide (DMS), are biogenic (Alcolombri et al., 2015; Dani and Loreto, 2017; Jardine et al., 2015; Carrión et al., 2015). The aerosols of ocean microorganisms increase the number of cloud droplets by about 60% annually on average (McCoy et al., 2015). DMS is produced on the sea (Sanchez et al., 2018) and on continents (Carrión et al., 2015; Jardine et al., 2015). Model-based evidence shows that the net effect of cloud cover is cooling (Gunson et al., 2006; Gabric et al., 2013; Wang et al., 2018). The existence of glaciers, ice-sheets and snow cover, which account for more than 70% of the Earth's albedo effect (Stocker et al., 2013), depends on the accumulation of snow and therefore in great part on cloud formation. A biogenic aerosol-climate linkage has been postulated, through the albedo effect of clouds on incoming solar radiation and thus the Earth's energy flux balance and temperature (Charlson et al., 1987; Shaw, 1983; Rodhe, 1986). In other words, the albedo effect is also necessary to counterbalance the steady increase of solar radiation and to maintain climate homeorhesis.

The claim that climate non-equilibrium steady-state dynamics—that underlie Earth's climate—depend on Earth working as a single system has been formulated in the Gaia hypothesis (Lovelock and Margulis 1974). Taking this hypothesis at face value would mean that the system could integrate past and current sensory signals to enact structural changes in its effectors (mainly changes in greenhouse and albedo), in the service of inferring the amount of solar radiation — and actively realising those

inferences (Rubin et al., 2020; Rubin and Crucifix, 2022). In other words, the system could be interpreted as actively integrating sensory signals to infer incoming solar radiation, and modulating the atmosphere so as to maintain Earth surface temperatures within a homeorhetic range. This interpretation is licensed for any random dynamical system whose trajectories of external and internal states are independent, when conditioned on the trajectories of sensory and active states, where the random differential equations change sufficiently slowly over time (Friston et al., 2022).

In this paper, we present numerical evidence for the conjecture—that the Earth maintains a climatic homeorhesis that can be read as active inference—in a simple biosphere-climate dynamical system. In this phase space dynamical system — described originally in Nielsen (2008) and Nielsen and Ditlevsen (2009)— we identified the biosphere biomass growth and the net incoming solar radiation as internal and external states of the system, respectively; separated by a boundary (a.k.a., Markov blanket) comprising sensory (surface temperature) and active states (greenhouse gases concentration). When the dynamical system is conditioned on the trajectories of sensory (surface temperature) and active states (greenhouse gas concentration), where the random differential equations change sufficiently slowly over time, the system dynamics can be read as engaging in active inference to maintain steady-state surface temperature; namely, intervening on external states by active states (modifying greenhouse gas content). In other words, the biosphere-climate system appears imbued with an elementary form of agency and sentience, whereby it acts on net incoming solar radiation, leading to a form of active inference on a planetary scale.

2. Model structure

The biosphere-climate dynamical system we used is a theoretical model of climate-biosphere interactions over geological time (Nielsen, 2008)(Nielsen and Ditlevsen 2009). It is rooted in observations of geologic past climate changes and centres on the long-term interactions between climate and the biosphere. It has a special focus on the biological causes of the atmospheric content of carbon dioxide, i.e., the greenhouse effect, and how it affects the dynamics of Earth's surface temperature.

Primarily, this biosphere-climate dynamical system points toward a biological explanation of one of Earth's extreme glaciations, rather than climate stabilisation. This model was originally based on Daisyworld (Watson and Lovelock, 1983) and several other comprehensive treatments of the biosphere-climate interaction (Caldeira and Kasting, 1992; Tajika, 2003; Goldblatt et al., 2006). Nielsen (2008) and Nielsen and Ditlevsen (2009) have furthered the modelling of climate-biosphere interactions by implementing realistic ice-albedo and greenhouse effects–instead of Daisy colours–albedo as the biosphere-climate mediator. The structural form of the ensuing biosphere-climate dynamical system is shown in Fig.6A.

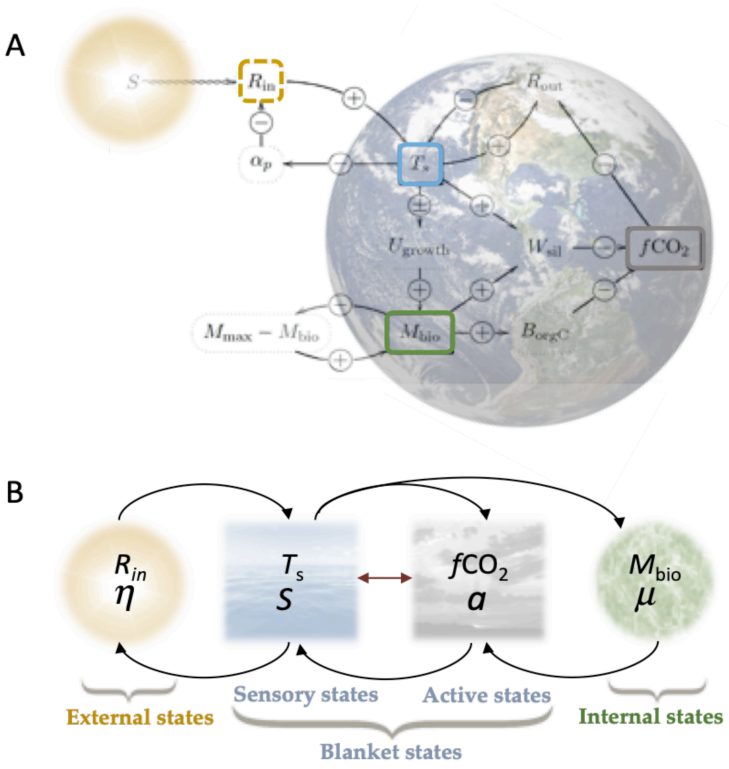

Figure 6. Biosphere-climate dynamical system with boundary states A) Biosphere-climate dynamical system model diagram. Solid boxes (e.g. blue, green and grey) represent prognostic variables, while dotted boxes (e.g. yellow) represent diagnostic variables. Blue, green, grey, and yellow boxes represent the surface temperature (T_s), the Biosphere biomass (M_{bio}), atmospheric mixing ratio of carbon dioxide (fCO_2) and net incoming solar radiation (R_{in}) respectively. Arrows indicate a web of causal relationships between the variables. B) Partitioning of the biosphere-climate dynamical system. The *Ts* and fCO_2 represent the sensory (*s*) and active (*a*) states respectively–which are the boundary states–while M_{bio} and R_{in} represent internal (μ) and external (η) states. The

colours of the graphic of each state (*s, a, μ, η*) are the same as the colours of the boxes in A. The arrows preserve the same causal relationships between states variables as in A.

The biosphere-climate model includes physically plausible equations of energy balance for the Earth's surface temperature T_s (K), the long-term carbon cycle for the atmospheric CO_2 mixing ratio (the volume fraction of fCO_2), a logistic growth model for the biosphere (Biomass, M_{bio}), and the net incoming solar radiation (R_{in}). The model has zero-dimensionality assumption (no spatial dimension such as latitude, longitude or height). The state of the ocean, atmosphere and ice-caps is assumed to be given as a function of T_s. The biosphere is parametrized by a relative global mean. Biomass is assumed to be governed by a logistic growth model, i.e. the treatment of the biospheric component has been more or less left unaltered, as compared to Daisyworld. The atmospheric CO_2 mixing ratio is governed by a simple long-term carbon cycle model that considers the biomass-dependent organic carbon burial, the temperature-dependent silicate weathering and the volcanic outgassing. The equations of the model, the parameter values and constants (Table 3) are given in the methods section.

We first asked whether this biosphere-climate dynamical system can be framed as a process of active (Bayesian) inference by relying on formal arguments borrowed from the Free energy principle (FEP) (Friston, 2013). The FEP can be regarded as a dynamical formalization of the embodied cognition implicit in autopoiesis (self-production) (Maturana and Varela, 1980; Friston, 2013; Allen and Friston, 2018; Friston et al., 2015; Bateson, 1979; Von Foerster, 1984), which postulates that living systems can be described as actively inferring their environment in order to maintain their physiological states within a target homeorhetic range. The FEP applies to systems that have internal (μ) and boundary states (b) and shows that quantities internal to the system can be described as continuously inferring quantities external to it (i.e. external states η), given information at the boundary. The boundary is defined as a set of states that intervene between external and internal states, such that all interactions between internal and external states occur via the boundary.

Further, the boundary is usually formed of sensory (s) and active (a) states, wherein active states influence but are not influenced by external states, and sensory states influence but are not influenced by internal states (Friston et al., 2022). In summary, the stochastic dynamical equations that form the basis of this treatment can be summarised as follows:

$$\dot{\eta} = f_{\eta}(\eta, s, a) + \omega_{\eta}$$
$$\dot{s} = f_{s}(\eta, s, a) + \omega_{s}$$
$$\dot{a} = f_{a}(s, a, \mu) + \omega_{a}$$
$$\dot{\mu} = f_{\mu}(s, a, \mu) + \omega_{\mu}$$

Where the functions f are the flow equations and the processes ω_i denote numerically independent random fluctuations. The system's dynamics can then be reformulated as performing active inference, wherein states internal to the system encode a probability density (a.k.a., Bayesian belief) $q_{\mu}(\eta)$ about states external to the system, and active states continuously use this information to regulate boundary states (Da Costa et al., 2021; Friston et al., 2021). Moreover, these beliefs are continuously updated in the face of new information from the boundary,

$$q_{\mu_t}(\eta) \approx p(\eta_t \mid b_t)$$

so as to track evolving external conditions and thereby predict sensory states, such that active states can act on external states to realise the predictions. The implicit circular causality can be read as an action-perception cycle that describes the vicarious exchange between internal and external states, via sensory and active states.

We designated the logistic growth model for the biosphere M_{bio} as the internal (μ) and the volume fraction fCO_2active states (a), surface temperature T_s (K) as the sensory state (s), and the net incoming solar radiation or net insolation R_{in} as the external states (η) of the biosphere-climate system (Fig. 6B). The net insolation R_{in} represents the incoming minus the reflected solar radiation. Note that the interactions are sparser than in the more general equations of motion laid out by the FEP (see above), since in our model active states only influence external states via the sensory states.

In the original deterministic model described in Nielsen (2008) and Nielsen and Ditlevsen (2009), the R_{in} variable is a so-called "diagnostic variable" and is a deterministic function of S_0 and the surface temperature in Eq (4) (see Methods section). In the current analysis we formulate R_{in} as a stochastic variable that relaxes to the net insolation value, under random fluctuations. Thus, the net insolation R_{in} defined here may contain stochastic fluctuations such in solar output or surface albedo. The sensory (s) and active states (a) that comprises the surface temperature (T_s) and the volume fraction of fCO_2, respectively, play the role of boundary states, whose trajectories form a Markov blanket between the trajectories or paths or internal and external states (Friston et al., 2022).

Applying a Bayesian interpretation to the biosphere-climate dynamical system requires the existence of a nonequilibrium steady-state (NESS) solution to a random dynamical system; a.k.a., random or pullback attractor (Crauel et al., 1997). To establish the existence pullback attractor, we modified the original (deterministic) biosphere-climate model (Nielsen 2008; Nielsen and Ditlevsen 2009) by turning the multivariate ODE into an SDE by adding random fluctuations:

$$\dot{s}: \quad \frac{dT_s}{dt} = (\tau/c)R_{\text{in}} - \tilde{A}_0 - \tilde{B}_0(T_s - 273.15) + \tilde{A}_{\text{CO}_2} \ln\left[\frac{f\text{CO}_2}{f\text{CO}_2^0}\right] + \omega_1\xi_1(t), \tag{5}$$

$$\dot{\mu}: \quad \frac{dM_{\text{bio}}}{dt} = \left[(M_{\max} - M_{\text{bio}})U_0 \exp\left(-\frac{(T_s - T_{\text{bio}})^2}{2\sigma_{\text{bio}}^2}\right) - 1\right] M_{\text{bio}} + \omega_2\xi_2(t), \tag{6}$$

$$\dot{a}: \quad \frac{df\text{CO}_2}{dt} = \tilde{V}_0 - \tilde{W}_0 \exp\left(\frac{T_s - T_{\text{sil}}}{\Delta T_{\text{sil}}}\right)\left[\frac{f\text{CO}_2}{f\text{CO}_2^0}\right]^n (1 + \Omega M_{\text{bio}}) - \beta\tilde{N}_{\text{PP}}M_{\text{bio}} + \omega_3\xi_3(t), \tag{7}$$

$$\dot{\eta}: \quad \frac{dR_{\text{in}}}{dt} = \gamma\left\{\frac{S_0}{4}\left(1 - \alpha_1 + \alpha_2 \tanh\left[\frac{T_s - T_{\text{ice}}}{\Delta T_{\text{ice}}}\pi\right]\right) - R_{\text{in}}\right\} + \omega_4\xi_4(t) \tag{8}$$

This randomness means that attracting points or limit cycles of the original deterministic system become pullback attractors that describe the long-term statistical behaviour of the system (Crauel and Flandoli, 1994). Bayesian inference of external states — by internal states — relies on the existence of a *synchronisation map*, which is a function that maps the most likely internal to the most likely external state, given boundary states. We refer to the most likely internal and external states, given boundary states, as the conditional modes. We denote the synchronisation map (σ) and the internal and external conditional modes as $\boldsymbol{\mu}$(b) and $\boldsymbol{\eta}$(b). The synchronisation function maps the internal to the external conditional mode:

$$\sigma(\boldsymbol{\mu}(b)) = \boldsymbol{\eta}(b) \tag{9}$$

Necessary and sufficient conditions for the existence of the function σ have been detailed elsewhere (Parr et al., 2020; Da Costa et al., 2021). Here, we use a numerical method based on least-squares regression inspired by the approach used in (Friston 2013) to identify a synchronisation map of the biosphere-climate random dynamical system at a nonequilibrium steady-state (see Methods for more details).

Visual inspection of the joint space of the conditional modes, in terms of the boundary states, (which in this case is straightforward due to the low-dimensionality of the boundary state-space) suggests that the joint conditional modes lie on a plane; this inspired us to use ordinary least squares (OLS) regression to estimate a linear function that predicts the conditional external mode (b) from the conditional internal mode (b):

$$\boldsymbol{\eta}(b_t) = \sigma_{est}(\boldsymbol{\mu}(b_t))$$

$$= k_1\mu_1(b_t) + k_2\mu_2(b_t) + C_1 \tag{10}$$

In other words, we calculated the coefficients k_1, k_2, C_1 that minimise the averaged squared difference between the 'observed' most-likely external state $\boldsymbol{\eta}(b_t)$ and the 'predicted' most likely external state $\sigma_{est}(\boldsymbol{\mu}(b_t))$. The estimated synchronisation map σ_{est} is entirely characterised by the linear model in Equation (10) with parameters model k_1, k_2, C_1. Using a similar method, we learned a second synchronisation map ς_{est} from the most likely internal state $\boldsymbol{\mu}$(b) to the precision of posterior beliefs P(η | b) around the conditional mode $\boldsymbol{\eta}$(b), i.e., the inverse of $-\nabla_\eta^2 \, log \, p \, (\, \eta \mid b \,)_{\eta=\boldsymbol{\eta}(b)}$, (see Methods section).

Estimating both synchronisation maps (σ_{est}) allows us to reformulate the dynamics of the biosphere-climate system in terms of active inference. Specifically, this results from applying the synchronisation function σ_{est} to an actual trajectory of internal states (μ, M_{bio}), to furnish a continuous and accurate prediction of external

states (η, R_{in}). Formally, this inference is upon an evolving Bayesian posterior belief about the current value of external states given the current value of boundary states:

$$q_{\mu}(\eta) = N(\eta; \sigma(\mu), \varsigma(\mu)) \tag{11}$$

Where $\sigma(\mu)$ is a conditional mean and $\varsigma(\mu)$ a conditional covariance (inverse precision) that predicts external states as a continuously-evolving Gaussian with mode $\sigma(\mu)$ and variance $\varsigma(\mu)$.

Because the synchronisation map is a function that maps the most likely value of one conditional density P(μ | b) to the most likely value of another P(η | b), the inference will only be exact at the time points where both the internal and external states assume their most likely values, given the current boundary state b_t. That is when $\mu_t = \boldsymbol{\mu}(b_t)$ and $\eta_t = \boldsymbol{\eta}(b_t)$. Another reading of this approximation is that the NESS density associated with a pullback attractor is locally Gaussian (a.k.a., the Laplace approximation). Please see (Friston and Ao, 2012; Kwon and Ao, 2011; Ao, 2008) for general discussions of this kind of local approximation.

3. Results

Stochastic trajectories

For all numerical analyses we simulated N = 100 independent stochastic realisations of the biosphere-climate dynamical system for T = 200,000 years. Figure 7A shows an example of one such stochastic realisation of the system's equations of motion with an additional 100-year moving average of the Biomass variable M_{bio} (Fig. 7A, bottom subplot). To exclude the effects of transients — before the attainment of NESS – all analyses were conducted after an initial 'burn-in' period of 10^5 years, at which point steady-state was assumed to be attained. The following results are based on the final 10^5 years of each realisation.

Synchronisation map

In this set of analyses, we use regression analysis to estimate the boundary-conditional modes (left panel) and the synchronisation map (σ_{est}) (right panel) (Fig.

7B) (see methods section). The boundary-conditional modes are shown as an orange point-cloud of the most likely internal states $\boldsymbol{\mu}(b)$ and most likely external states $\boldsymbol{\eta}(b)$ (Fig. 7B left panel), while the predictions of the estimated synchronisation map are shown as an green point-cloud that maps the (boundary-conditioned) most likely internal state $\boldsymbol{\mu}(b)$ (i.e. the boundary-conditional mode) to the parameter of a posterior belief about the most likely external state, denoted $q_{\mu}(\eta)$ (Fig. 7B right panel).

Both panels are plotted as a function of the two boundary states $b = \{a, s\}$ (x and z axes, respectively). Each point is coloured according to the log-probability the mode is assigned under its respective conditional distribution. The more accurate the approximated synchronisation map is, the more closely the green point-cloud (predicted external modes) in the right panel should overlap with the orange point-cloud (actual external modes) in the left panel. Once determined, the conditional synchronisation function can be used to map a trajectory of internal states (M_{bio}) to an approximate posterior expectation about the most likely value of the external states (R_{in}). That is, the green point-cloud can be seen as a prediction of the orange point-cloud.

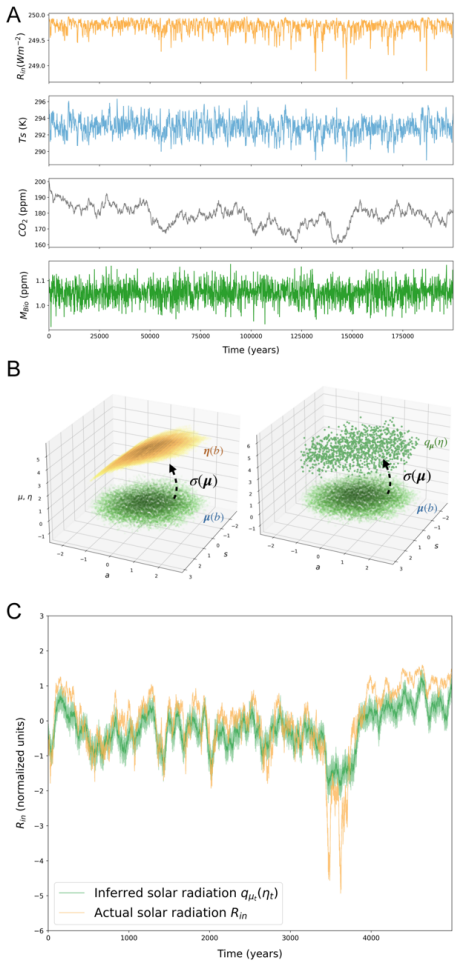

Figure 7. Biosphere-climate active inference dynamics. A) Solution of the nonlinear stochastic biosphere-climate random dynamical system. The fCO_2 is a fraction and adimensional and it is shown in parts per million (ppm) by scaling by 10^6. The bottom panel shows the 100-year running mean of M_{bio}. B) Boundary-conditional modes and the estimated synchronisation map. The left panel shows the boundary-conditional modes – i.e., the most likely internal states and external states, given boundary states – as a function of the two boundary states b = {a,s} (x and z axes respectively). Each conditional mode is coloured by its conditional log probability (i.e., $ln\, P(\eta|b)$ or $ln\, P(\mu|b)$). The right panel shows the synchronisation map from the (blanket-conditioned) most likely internal state (i.e. the blanket-conditional mode) to the corresponding most likely external state. The predictions of the synchronisation map are shown in green, where the function itself was approximated using linear regression of the most likely external states against the most likely internal states. C) Biosphere-climate Bayesian inference. The plot shows the internal states (M_{bio}) of one stochastic sample path of the biosphere-climate dynamical system's equations of motion (green

trace) inferring solar radiation R_{in} given blanket states (T_s and fCO_2) as a result of applying the estimated synchronisation map to the trajectory of internal states M_{bio}. The prediction of external *variances* is shown as a confidence interval in blue around the predicted mode. The yellow trace is the concurrent sample path of the external states from the same stochastic realisation, to illustrate the precision of the internal states tracking of the external states, via the synchronisation map.

Active inference

Applying an estimated synchronisation map σ_{est} to a trajectory of internal states (μ, M_{bio}), allowed us to imbue the dynamics of the biosphere-climate system with a Bayesian posterior belief (see Eq. 11) over the most likely value of external states (η, R_{in}), given the current value of the sensory states (surface temperature sensory state, T_s) and active states (volume fraction of carbon dioxide fCO_2. Figure 2C shows the internal states tracking the most-likely value of external states. The 'inference' appears to not only be accurate on average, but in fact internal states appear to momentarily track the sample paths of external states, either when there is sudden increase or decrease in R_{in}. The paths of internal states (M_{bio}) of the biosphere-climate dynamical system can thus be described as encoding a full Bayesian posterior belief over most-likely value of external states, parameterized with a conditional mean $\sigma(\mu)$ and a conditional variance $\varsigma(\mu)$ that allows prediction of external *variances*, shown as a confidence interval (light green) around the predicted mode (Fig. 7C).

Sensory perturbation

In the next set of analyses, we analysed the predictive, active inference interpretation of the biosphere-climate dynamical system by subjecting the sensory state T_s to perturbations. Figure 3 shows the results of these perturbation experiments, summarised across N=100 independent realisations. For each perturbation, we clamp the surface temperature T_s, aka the 'sensory interface', to a fixed temperature, either 320 K (Fig. 8A) or to 290 K (Fig. 8C), and then let the dynamics transiently relax for 2000 years.

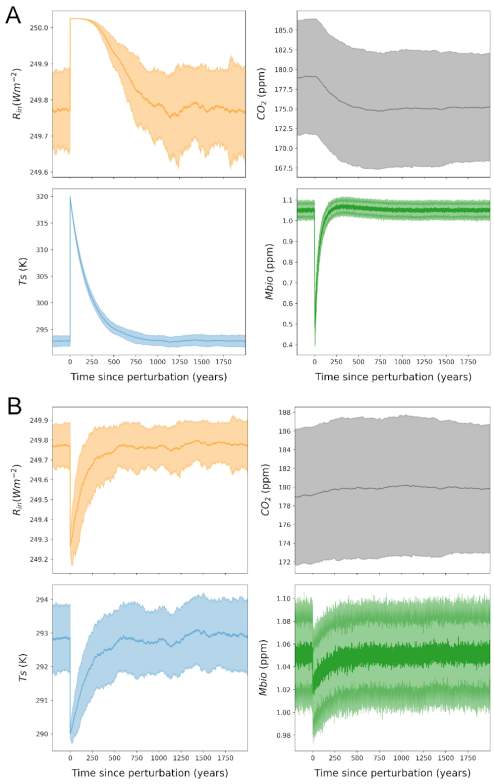

Figure 8. Sensory perturbation and climate homeostasis. The plot shows the response of the system to a fixed perturbation to the sensory state T_s (blue), where T_s at a particular time-point was artificially clamped to a value of 320K (A) and 290K (B) and then allowed to relax for 2000 years (200,000 timesteps). Average responses with standard deviation across N = 100 parallel realisations are shown. In all panels the perturbation is introduced at time t = 0. The system's dynamics are shown for a few hundred years before each perturbation to illustrate the effect of the perturbation in pushing the system away from its baseline, unperturbed homeorhetic dynamics.

When the sensory state T_s is perturbed to 290 K, there is a slow positive deflection of internal states M_{bio} that takes around 500 years to reach the steady state prior to perturbation (Fig. 8B). A slight increase of CO_2 that does not return to the concentration prior to disturbance is also observed. In both cases (disturbance to 320 K or to 290 K) the surface temperature T_s returns to the same values of the steady state prior to disturbance, although when the temperature is clamped at 290 K, the return to steady state is faster (around 500 years) and the variation is greater compared to the perturbation of 320 K (around 750 years) (Fig. 8A,B).

In both cases changes in the T_s encompass the dynamics of active states, while the response of the internal states is faster when the T_s is increased to 320 K (Fig. 8A, B). The changes in active states are of greater magnitude when the surface temperature is increased, and the variation of internal states is of greater magnitude when the surface temperature is decreased. Through the active and sensory states, the dynamics of the biospheric-climatic system acts on the external states (R_{in}), such that the belief of these being lagged returns to their steady state, although it takes longer when T_s is increased to 320 K (Fig. 8A,B).

Parameter modification

In the penultimate analyses, we asked whether the effectiveness of the emergent homeorhesis is affected by the system parameters. Specifically, we were interested to know how specific values of the albedo α_1 and S_0 influenced the precision of the inferential process when the system is perturbed and unperturbed (Fig. 9).

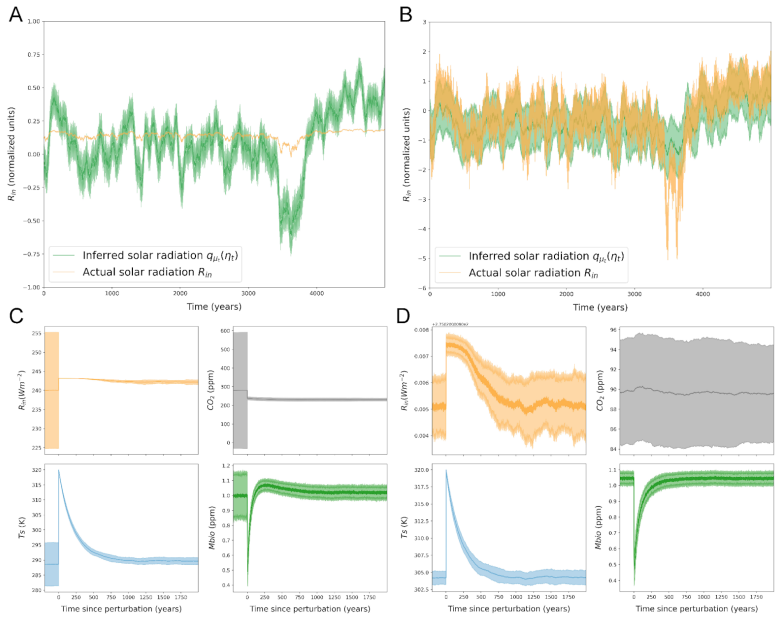

Figure 9. Response to acute parameter change. A) The plot shows the active inference of the system when changing albedo (α1) parameter from 0.43 to 0.45 and B) when

changing S_0 from 1370 Wm^{-2} to 1507 Wm^{-2}. C,D) Sensory perturbation under parameter change α_1 (C) and S_0 (D).

Under albedo α_1 parameter modification, the internal states track the net incoming solar radiation (R_{in}), less precisely; with an amplified fluctuation (within -0,75 and 0,75 normalised units) in regard of the reduced fluctuation of R_{in} (within 0 and 0,25 normalised units) (Fig. 9A). When the solar constant S_0 parameter is modified, the precision of the inferential processes is less affected than α_1 modification, yet its average variation increases with respect to the fluctuation of the external states (R_{in}) (Fig. 9B). In general, in both cases when α_1 and S_0 are modified the precision of the implicit active inference tends to decrease (Fig. 9A,B) when compared with the original parameters (Fig. 7C), yet inference can still be demonstrated.

When the surface temperature of the system is clamped to 320 K and the dynamics relax, while the α_1 parameter is modified; the variance of the overall partitioned states (η, s, a, μ) response, and thus of climate steady-state is narrowed post-perturbation (Fig. 9C). Neither the external, active and especially sensory states, which represent the surface temperature of the system (T_s), return to the same value prior to the disturbance. In contrast, when a similar disturbance is imposed while the α_1 parameter is modified; the variance of all partitioned states (η, s, a, μ), remain the same post perturbation and surface temperature of the system (T_s) return to the same value prior to the disturbance (Fig. 9D).

Robustness analysis

In this final set of analysis, we performed a robustness analysis of the synchronisation map as a function of the solar constant S_0 (Fig.10). Because measuring the synchronisation map's robustness is effectively measuring the "viable range" of S_0 this means that we have identified the S_0 parameter limit values (S_0 < lower threshold, S_0 > upper threshold) over which Bayesian inference is robust (i.e., precise), and therefore how well internal states (M_{bio}) track external states (R_{in}), using the Pearson's Rank correlation between inferred external trajectories $q_\mu(\eta)$, and actual external trajectories R_{in}.

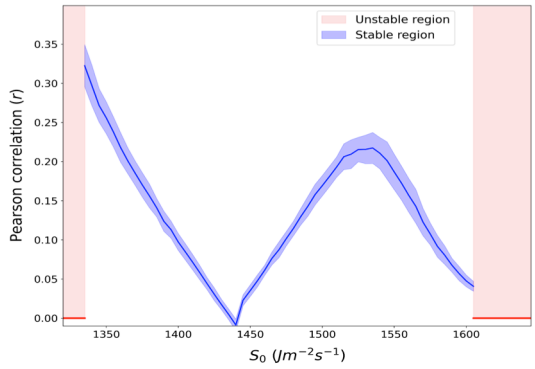

Figure 10. Robustness analysis. This plot quantifies the synchronisation map in terms of the correlation coefficient (averaged across N = 1 realisations) between the posterior belief parameterized by the internal states $q(\eta; \sigma_\mu(\mu), \sigma_\Sigma(\mu))$ and the simultaneous external states η_t, as a function of the solar constant (S_0).

This analysis showed that the accuracy of external estimates afforded by the synchronisation map has a nontrivial relationship with the solar constant S_0: inference is robust within some lower and upper S_0 parameter limit values. When S_0 decreases from its default value (1370.0 Wm^{-2}) the Pearson's Rank correlation increases up to 1340 Wm^{-2}, while it appears to change non-monotonically as S_0 increases to 1610 Wm^{-2} (Fig. 10). In other words, within this S_0 parameter range, the correlations change non-monotonically. Below than S_0=1340 Wm^{-2} and above 1610 Wm^{-2} the synchronisation, and as a consequence the synchronisation map itself becomes undefined. We classified the system as unstable when the numerical solution for the realisations did not reach a steady-state (indicated computationally through numerical over- or under-flow), indicating vanishing or exploding dynamics, or a very long transient time.

4. Discussion

Although the formulation of the biosphere-climate system in terms of active inference here ignores important geophysical, geochemical, and geobiological processes, it speaks in a formal way to the Gaia hypothesis (GH); namely, climate homeorhesis by and for the biosphere (Lovelock, 1979; Lovelock and Margulis, 1974).

This formulation enables us to interpret a biosphere-climate system as being endowed with an elementary form of agency and sentience, and thus as engaging in inferential behaviour to remain in nonequilibrium steady-state, whence the states of the biosphere can be read as encoding posterior beliefs about net incoming solar radiation. Moreover, these beliefs are updated in the face of new signals sensed through changes in the surface temperature-T_s and CO_2 concentration, that is, through the system's boundary. We consider, therefore, this formulation as a *proof of concept* of the GH without commitment to notions like teleology and teleonomy (Rubin and Crucifix 2022).

Our mathematical treatment of the GH connects the claim that non-equilibrium steady-state (NESS) dynamics—that underwrite Earth's climate—entails active inference at the planetary scale. By analysing the biosphere-climate dynamical system with active Bayesian inference lens, our results support what Lovelock later insisted that living phenomenon at planetary scale *"is not the biosphere alone but the whole Earth system"* (Lovelock, 2009b, p.166). Indeed, the sensory perturbation we imposed on the system results in a highly integrated-coordinated biosphere-climate system inference response, on which its sensory states dynamics are dependent on internal and active states to keep climactic states within an attracting set. We show that the biosphere-climate system as a unitary system endowed with boundary (sensory and active) states maintains nonequilibrium steady-state surface temperature by actively inferring the sensory causes of external perturbation. That is, the system can infer sensory causes of net insolation changes and behave accordingly.

The inference seems not only to track external states on average, but also seems to track every realisation or sample path. This seems to validate the boundary partition we have imposed on the system, supporting a previous proposal about how the Earth system may look like and behave with a Markov blanket-like boundary (Rubin et al., 2020). Importantly, such a boundary (the partition) is not formulated for mathematical convenience, but it is justified in the way that the Earth's atmosphere has been self-produced, modified and modulated by the biosphere and the implication it has for climate dynamics (Margulis and Lovelock, 1974, 1975; Rubin

et al., 2021; Rubin and Crucifix, 2021). In the case of the biosphere-climate dynamic system, for example, the active states depend on the carbon cycle on which the lifespan of the biosphere depends, but which also generates it (Lovelock and Whitfield, 1982; Caldeira and Kasting, 1992).

The ensuing proof of concept for the GH suggests that the dynamics of the biosphere-climate system is not only a matter of synchronisation of internal and external states, but that the biosphere-climate system as such can be read as having 'Bayesian beliefs' about its environment. This follows because the variance of the belief that is parameterised by the biosphere-climate system goes beyond simple synchronisation, to approximate Bayesian inference. It is important to note that internal states are not representing independent external states, but representing a coarse-grained variable that is not isomorphic to external states, but which is a function of the net insolation (incoming minus outgoing solar radiation) at the earth's surface. A similar analysis connecting Daisy world model and perception has been carried out elsewhere (Harvey, 2004), although without involving active inference at planetary level.

Our results connect with statistical and model evidence that supports the observation of homeorhetic-like properties at the planetary-climatic scale (Leggett and Ball, 2021, 2020; Lovelock and Kump, 1994). For example, when we clamped the temperature of the sensory states (global mean temperature surface) below its optimal parametric set up, the internal states of the system resist such perturbation, through active states, i.e. by increasing greenhouse CO_2 concentration. The contrary is also valid. When sensory states are held above their characteristic value, there is a reduction of CO_2 concentration and the overall dynamics of the system remain homeorhetic. That is, the perturbation results in a highly integrated-coordinated stationary distribution homeorhetic response.

Modifying system parameters that relate to energy balance such as albedo α_1 and solar constant S_0 changes the properties of the synchronisation map and therefore affect the nature of implicit inference. Changing the albedo parameter from 0.43 to 0.45, within the realistic standard values between the α_{ice} = 0.62 and that of a fully

deglaciated planet, α_{free} = 0.30 (Hartmann, 1994), effectively affects the quality of Bayesian inference, which becomes less accurate, and thus shifts the nonequilibrium steady-state. Similarly, when we change the solar constant S_0 parameter from 1370 Wm^{-2} to 1507 Wm^{-2} the biosphere-climate dynamical system inference seems to change quantitatively. Outside of this window, numerical analyses suggest that there is no NESS, speaking to a 'Goldilocks' regime in the parameter space.

Parametric values influence the sensory states of the system and thus the synchronisation map which determines how well the internal states (M_{bio}) can instantaneously 'infer' the most likely value of external states (R_{in}). This means that these parameters, at least in the analysed time window, underwrite the synchronisation map between internal and external states and hence for NESS. In general, a well-fitted synchronisation map is a necessary condition that reflects a high mutual information value in the system, in the sense that the system can infer sensory causes of sun radiation at the earth's surface, change active states (CO_2 concentration), which are driven by biosphere dynamics, and thus regulate sensory states (climate temperature dynamics). However, we did not investigate how changes in the boundary-conditional mutual information between internal and external states correlate with the change in inference, upon manipulating albedo and solar constant. This deserves further analysis.

As noted in the introduction, in the history of the Earth, the solar constant has changed due a continuous increase in solar luminosity from a faint young Sun to a bright mature Sun. Some 4 billion years ago, the solar luminosity was 30% less (0.7) compared to today 1370 Wm^{-2}, so S_0 reached around 959 Wm^{-2} (0.7*1370) (Gough, 1981; Bahcall et al., 2001; Sagan and Mullen, 1972). For values of solar constant S_0< ~1310 Wm^{-2} we found an instability in the synchronisation map, and thus in the correlation of the internal states with the external states. A dynamical analysis in the noise free system shows that this is related to the bifurcation-induced transition to another stable state (data not shown). In biological terms, this transition may correspond to the transition from the origin of microbial life to an early

anaerobic biosphere, composed solely of extremophile prokaryotic microbes (Margulis and Sagan, 1986; Schopf, 1983). Across the range of values of solar constant we explored, within which the synchronisation map is stable, the internal states are non-trivially correlated with the external states, as indicated by a non-negligible correlation. Roughly speaking, this variability in the correlation may correspond to the transition from anaerobic to an aerobic prokaryotic-eukaryotic biosphere (Margulis et al., 2006), but also the transition from C3 to C4 plants in response to the decrease of CO_2 concentration through the lifespan of the biosphere (Caldeira and Kasting 1992).

In the next 1.5 billion the solar constant will reach at least 1576 Wm-2 (1.15*1370) (Bahcall et al., 2001). We have gone as high as S_0 = 1650 Wm^{-2}, but around 1600 Wm^{-2} the biosphere inference is not tenable; in the sense, there is no NESS solution in this regime of parameter space. Some calculations suggest that the lifespan of the biosphere could survive from at least another ≈1.5 billion years from the present (Lenton and von Bloh, 2001; de Sousa Mello and Friaça, 2020). This corresponds to the viability ranges over which inference is robust, suggesting that the active inference in the biosphere lifespan is key for climate homeorhesis, and hence habitability. Nevertheless, there is a need to quantify this more rigorously.

Although the estimations of the biosphere-climate system' inference were sampled in a millennial time-scale, it can be generalised to geological time scales, if not to the entire time that the Earth ontogeny has. This is because the correspondence between the so-called boundary-conditional modes —via the estimated synchronisation map– suggest a rich approximation to the NESS density around the mode, and that the system explores its state space straightforwardly, so that this mode is visited frequently. In theory, this suggests that is not necessary to sample a longer time series. That is, we do not need data over very long timescales to characterise the biosphere-climate system, and show that the Earth system as a random dynamical system engaging in active inference.

The proof of concept presented, although conceptual, serves to warn us that if active inference could happen in-silico in a biosphere-climate dynamical system, in the real Earth system such behaviours will be much greater and may entail complexity in a biological sense (Rubin and Crucifix 2021, 2022). If there is empirical evidence showing that microbes cope with fluctuations in their environment to resist dissipation (Mitchell et al., 2009), cellular parasites escape immune-system operations using antigenic variation strategies (Bangs, 2018) myxomycetes have the ability to find the minimum-length solution between two points in a labyrinth (Nakagaki et al., 2000) and the trees of the Amazon rainforest anticipate dry periods by producing their own clouds and pump atmospheric water before them happen (Wright et al., 2017), our results suggest that similar predictive behaviour could happen at planetary level. This must be crucial to ensure climate states remain homeorhetic, and thus Earth habitability. If this is so, the next generation of climate models may have to consider life at the planetary scale — actively inferring its own fate.

5. Methods

5.1. MODEL DESCRIPTION

The full long-term biosphere-climate dynamical system model description and dynamical analysis are given in Nielsen and Ditlevsen (2009) and Nielsen (2008, Section 5). This model studies the interaction between the biosphere and climate and its dynamical evolution (see Section 2). The model's state space comprises the Earth's surface temperature T_s (K), the Biomass M_{bio}, and the volume fraction fCO_2 as follows:

$$c\frac{dT_s}{dt} = R_{\text{in}} - A_0 - B_0(T_s - 273.15) + A_{\text{CO}_2}\ln\left[\frac{f\text{CO}_2}{f\text{CO}_2^0}\right], \quad (1)$$

$$\frac{dM_{\text{bio}}}{dt} = \left[(M_{\max} - M_{\text{bio}})U_0\exp\left(-\frac{(T_s - T_{\text{bio}})^2}{2\sigma_{\text{bio}}^2}\right) - 1\right]M_{\text{bio}}, \quad (2)$$

$$\mu_{Atm}\frac{df\text{CO}_2}{dt} = V_0 - W_0\exp\left(\frac{T_s - T_{\text{sil}}}{\Delta T_{\text{sil}}}\right)\left[\frac{f\text{CO}_2}{f\text{CO}_2^0}\right]^n(1 + \Omega M_{\text{bio}}) - \beta N_{\text{PP}}M_{\text{bio}},, \quad (3)$$

$$R_{\text{in}} = \frac{rS_0}{4}\left(1 - \alpha_1 + \alpha_2\tanh\left[\frac{T_s - T_{\text{ice}}}{\Delta T_{\text{ice}}}\pi\right]\right) \quad (4)$$

where S_0 is the solar constant with a reference value S_0 = 1370 Wm^{-2}. R_{in} is the net incoming shortwave radiation at the earth's surface. In the original model we have a 3-way dynamical system and a diagnostic variable R_{in} that captures the nonlinear relationship between the T_s and R_{in}, which couples back to Equation 1.

The parameter values are given in Table 1. Some parameters are given in the unit of *seconds* and others are in the unit of *years*. Thus, the parameters with the unit 1/s is scaled to those of the unit 1/yr by multiplying the factor τ =31557600 = (365.25 x 24 x 60 x 60) s/yr. Then we divide Eq. (1) by the heat capacity c=1.20 x $10^{10} JK^{-1}m^{-2}$ and Eq. (3) by the present atmospheric load μ_{Atm} =1.77 x 10^{20} mol. The parameters obtained after the scaling and/or the division are shown with tilde ˜· (e.g., $\tilde{A}_0$= (τ /c)A_0 [K/yr]).

Stochastic biosphere-climate dynamical system model

We assume that R_{in} is a dynamical variable quickly relaxing to the state given by Eq. (4), and assume $\mathrm{r} = 1$ so that the effect of the solar constant is controlled solely by S_0. Furthermore, we convert the ODEs to be SDEs by adding random fluctuations to the deterministic equations of motion of each state variable:

$$\frac{dT_s}{dt} = (\tau/c)R_{\mathrm{in}} - \tilde{A}_0 - \tilde{B}_0(T_s - 273.15) + \tilde{A}_{\mathrm{CO_2}} \ln\left[\frac{f\mathrm{CO_2}}{f\mathrm{CO_2^0}}\right] + \omega_1\xi_1(t), \tag{5}$$

$$\frac{dM_{\mathrm{bio}}}{dt} = \left[(M_{\max} - M_{\mathrm{bio}})U_0 \exp\left(-\frac{(T_s - T_{\mathrm{bio}})^2}{2\sigma_{\mathrm{bio}}^2}\right) - 1\right] M_{\mathrm{bio}} + \omega_2\xi_2(t), \tag{6}$$

$$\frac{df\mathrm{CO_2}}{dt} = \tilde{V}_0 - \tilde{W}_0 \exp\left(\frac{T_s - T_{\mathrm{sil}}}{\Delta T_{\mathrm{sil}}}\right)\left[\frac{f\mathrm{CO_2}}{f\mathrm{CO_2^0}}\right]^n (1 + \Omega M_{\mathrm{bio}}) - \beta\tilde{N}_{\mathrm{PP}}M_{\mathrm{bio}} + \omega_3\xi_3(t), \tag{7}$$

$$\frac{dR_{\mathrm{in}}}{dt} = \gamma\left\{\frac{S_0}{4}\left(1 - \alpha_1 + \alpha_2 \tanh\left[\frac{T_s - T_{\mathrm{ice}}}{\Delta T_{\mathrm{ice}}}\pi\right]\right) - R_{\mathrm{in}}\right\} + \omega_4\xi_4(t) \tag{8}$$

In this new, stochastic model, R_{in} is transformed into its own causal variable in Equation (8). We are taking the influence of the temperature on itself and extracting a new variable, which represents the incoming minus the reflected radiation. Note that changes in temperature (a sensory state) are not functions of the biosphere (an internal state). Similarly, greenhouse gases (and active state) are not functions of insolation (an external state). Similarly, note that the biosphere (an internal state)

and insolation (an external state) do not influence each other. This sparse coupling is sufficient to partition the four states into external, internal, sensory and active states. In turn, this renders the trajectories (a.k.a. sample paths) of external and internal states independent, when conditioned on sensory and active paths. It is this conditional independence that licences a reading of internal states as encoding Bayesian beliefs or posterior density is over the trajectories of external states. If the system has a NESS solution (i.e., a pullback attractor) it will look as if active states (greenhouse gases concentration) are trying to keep sensory states (surface temperature) within their attracting set. Because active states (greenhouse gases concentration) depend upon the biosphere (internal states) one can assert that the biosphere represents insolation and engages greenhouse gases to keep temperature within certain bounds. In other words, this interpretation based on the foundational argument of the FEP is that the Earth's existence rests upon or implies a NESS solution; at least over the timescale of its existence.

In this simulation we use γ = 10 (1/yr), ω_1 = 0.1, ω_2= 0.1, $\omega_3 = 10^{-7}$, $\omega_4 = 10^{-3}$, and the other parameter values in both partitions are taken from Table 1 except for α_1. We modify the first albedo parameter from α_1= 0.46 to α_1 = 0.43. A small decrease in α_1 appears to make life more robust (data not shown).

For all analyses, we simulated N = 100 independent sample paths of the stochastic biosphere-climate dynamical system by integrating the stochastic process for $2\text{x}10^5$ years with a step size of 0.1 years, using a standard Euler-Maruyama integration scheme (Kloeden and Platen 1992). The initial condition used was $T_s(0)$ = 295K, $M_{bio}(0)$ = 1, $fCO_2 = 2\text{x}10^{-4}$, and $R_{in}(0)$ is the value given by Eq. (4).

The atmospheric CO_2 mixing ratio has been taken to be governed by a simple long-term carbon cycle model. The organic carbon burial rate is assumed to increase linearly with biomass. The silicate weathering rate has been assumed less temperature dependent, and the volcanism as constant. There is no partitioning of the CO_2 reservoir between ocean and atmosphere.

Parameter	Value	Description
σ_{S-B}	$5.67 \cdot 10^{-8}\ Wm^{-2}K^{-4}$	Stefan-Boltzmann constant
S_0	$1,370\ Wm^{-2}$	Solar constant
c	$1.20 \cdot 10^{10}\ JK^{-1}m^{-2}$	Planetary heat capacity
a_1	0.46	Albedo parameter
a_2	0.16	Albedo parameter
T_{ice}	5°C	Temperature offset of albedo
ΔT_{ice}	15 K	Temperature width of albedo
A_0	$209.9\ Wm^{-2}$	OLR offset
B_0	$1.9\ Wm^{-2}K^{-1}$	OLR linearization coefficient T_s
A_{co_2}	$5.31\ Wm^{-2}$	OLR coefficient CO_2
$f\text{CO}_2{}^0$	$280 \cdot 10^{-6}$	pre-industrial fCO_2
U_0	$5.00\ \text{yr}^{-1}$	Biotic max growthrate
M_{max}	1.27	
T_{bio}	25°C	Biotic optimal temperature
σ_{bio}	13 K	Biotic growth variance in temperature
μ_{Atm}	$1.77 \cdot 10^{20}$ mol	Present atmospheric load
V_0	$8.19 \cdot 10^{12}\ \text{mol yr}^{-1}$	Volcanic CO_2 outgassing rate
W_0	$1.03 \cdot 10^{12}\ \text{mol yr}^{-1}$	Offset sil. weathering rate
n	0.4	fCO_2 scaling exp. for sil. weath.
ΔT_{sil}	40 K	temperature sensitivity for sil. weath.
T_{sil}	285 K	temperature offset for sil. weath.
Ω	5	biotic enhancement of sil. weath.
N_{PP}	$3.75 \cdot 10^{15}\ \text{mol yr}^{-1}$	Net Primary Productivity
β	$4.1 \cdot 10^{-4}$	Organic carbon burial fraction

Table 3. Model's parameters and constants (modified and adapted from Nielsen 2008 and Nielsen and Ditlevsen 2009)

5.2. PRE-PROCESSING

Standardisation

In preparation for the Bayesian-mechanical analysis, we normalised each variable ($M_{bio}, fCO_2, T_s, R_{in}$) by centering and scaling each variable and by its respective time- and realisation-averaged mean and standard deviation. Note that this assumes that at a nonequilibrium steady state, the system is ergodic (the space and time statistics are approximately equal), however this is guaranteed from the fact that there are random fluctuations on each of the variables.

Estimating the synchronisation function

Here, we empirically fit the synchronisation map to the conditional modes (the boundary-conditional most likely internal and external states) using linear regression, similar in spirit to the 'empirical' approach used in Friston (2013). In the absence of a closed-form expression for the system's stationary probability distribution and thus expression for the marginals/conditionals, we need to estimate

the modes of the conditional densities. Depending on the analysis, we did this one of two ways, which we outline below:

Conditional mode estimation: Multi-dimensional histogram method

The first method for conditional mode estimation relies on generating discrete approximations to the conditional distributions over internal and external states, given blanket states, i.e., $P(\mu|b)$ and $P(\eta|b)$, respectively. We achieved this by first approximating the full joint distribution of the system at steady state with a multi-dimensional histogram, computed using samples from all independent stochastic realisations from the final 10^5 timesteps of all stochastic realisations. Assuming ergodicity, the resulting time- and realisation-aggregated histogram can be treated as a discrete approximation to the joint probability of the system's four variables at steady state. For histogram computation we binned the data in each dimension with 150 non-overlapping, discrete and uniformly-sized bins; the particular choice of 150 for the number of bins was selected to balance the exponential scaling of N-dimensional histogram estimation with increasing bin number, with sufficiently detailed estimation of the synchronisation map. Having estimated the N-dimensional histogram approximation to the steady state, we can then estimate the conditional modes as follows: for all 2-dimensional bins of the blanket states (all possible 150^2 combinations of bins of T_s and fCO_2) we calculated the conditional modes $P(\eta|b)$, $P(\mu|b)$ as the bin of the internal (respectively, external) states that was assigned highest probability or count according to the approximated joint density. The result of this method is a pair of 2-D 'images' of discrete points (of resolution 150 x 150) that lie on the (approximated) conditional synchronisation manifold. The resulting pairs of images of conditional modes can then be used to fit the synchronisation function using regression, as described in detail below (see *Regression between the conditional modes*).

Conditional mode estimation: Bin-conditional average

The second method for conditional mode estimation is based on an approach used in Da Costa et al. (2021), where the steady-state joint distribution of only the blanket states is estimated using discrete histograms. In this case we once again used 150 bins, although in practice this can be increased much further due to the

computational advantage gained by binning only the marginal blanket distribution, as opposed to the whole system's stationary density. Once this discrete joint histogram over blanket states is computed, then for each blanket bin (all possible 150^2 combinations of bins of T_s and fCO_2), we estimate the conditional mode of the internal (respectively external) states by computing the empirical mean of (internal or external) states that occurred concurrently to those blanket states that lie within a given bin. We used this second method to generate Figure 7C, and in that case also computed the bin-conditional variance of all those internal states that occurred simultaneous to blanket states associated with a given bin.

Regression between the conditional modes

The synchronisation manifold by definition is a map between the statistics of densities. In the current analysis we adopted a regression approach loosely inspired by the quasi-empirical approach adopted in Friston (2013). This approach yields an approximation of the synchronisation map by fitting a statistical model that predicts the (estimated) conditional modes of the external states from the (estimated) conditional modes of the internal states. Note that not only is the model itself an estimation and has its own bias / variance, but the conditional modes themselves must also be estimated (e.g., according to one of the two methods described in the previous section).

For estimating the conditional variances along with the conditional modes (as shown in Figure 7C, for example), we fit an additional linear model to predict the *variance* of the boundary-conditional external state distribution, using the boundary-conditional internal mode, denoted $\varsigma(\mu_t)$ This model was fit entirely independently of the first model, but still considered a function of the boundary-conditional internal mode. This follows as, when characterising Gaussian (i.e., Laplace) approximations to posterior beliefs, the conditional variance is a function of the boundary states and boundary-conditional internal mode [cite eq 25 of Zeidman et al. (2022)], however since the map $b \rightarrow \boldsymbol{\mu}(b)$ in our model is injective, the conditional variance can be recovered solely using the boundary-conditional internal mode. As with the synchronisation function applied to the internal modes, this synchronisation map for the variances is characterised by a set of linear coefficients

k_3, k_4, C_2 that predict a conditional external variance as a function of the internal states.

Perturbation experiments

Each perturbed trajectory was independently generated from a historical simulation, rather than starting all "perturbed trajectories" (starting at time point 0) from the same starting state. In other words, the only thing that relates the perturbed trajectories to each other is their starting value of T_s – their other starting values (of R_{in}, CO_2, M_{bio}) are sampled from the stationary distribution.

We performed the analysis assuming R_{in} as a dynamical relaxing variable. In the perturbation set of analyses we showcase predictive processing for the adapted biosphere-climate stochastic dynamical system by subjecting the system to fixed sensory perturbations.

Robustness analysis

We calculated the synchronisation map correlations by sweeping up to S_0 = 1400 - 1650 Wm^{-2}. We did a sweep around the default value from S_0 = 1360 - 1380 Wm^{-2} in steps of 1.0 Wm^{-2}.

Chapter 6

THE (M,R)-SYSTEM AND THE ROAD TO EARTH COMPLEXITY

Based on:

Rubin, S., & Crucifix, K. (2022). Earth's complexity is non-computable: The Limits of Scaling Laws, Nonlinearity and Chaos. Entropy 2021, 23(7), 915

ABSTRACT

Current physics commonly qualifies the Earth system as 'complex' because it includes numerous different processes operating over a large range of spatial scales, often modelled as exhibiting non-linear chaotic response dynamics and power scaling laws. This characterization is based on the fundamental assumption that the Earth's complexity could, in principle, be modelled by (surrogated by) a numerical algorithm if enough computing power were granted. Yet, similar numerical algorithms also surrogate different systems having the same processes and dynamics, such as Mars or Jupiter, although being qualitatively different from the Earth system. Here, we argue that understanding the Earth as a complex system requires a consideration of the Gaia hypothesis: the Earth is a complex system because it instantiates life—and therefore an autopoietic, metabolic-repair (M,R) organization—at a planetary scale. This implies that the Earth's complexity has formal equivalence to a self-referential system that inherently is non-algorithmic and, therefore, cannot be surrogated and simulated in a Turing machine.

1. Introduction

It is generally agreed that the Earth system is complex and that this complex character must be appreciated when modelling it and taking decisions that may influence its evolution.

In present-day physics that which is called a 'complex system' is often the one that exhibits a large range of spatial scales, and often modelled as exhibiting non-linear chaotic response dynamics, turbulence, and power-scaling laws. It is also often assumed that this 'complex' character emerges from the non-linear interactions between the system's components, and that adding more components into the system may gradually increase its complexity. At the core of this idea of complexity is the Von Neumann argument that there are degrees of complexity and that the transition from less to more complex dynamics is essentially a matter of degree of nonlinearity, connectivity, and size: "*there exists a critical size below which the process of synthesis is degenerative, but above which the phenomenon of synthesis, if properly arranged, can become explosive (complex)*…" (Von Neumann, 1966, p.65).

In relational biology and the biology of cognition, however, the complexity is not a matter of degree of nonlinearity, connectivity, and size. As the mathematical biologist Robert Rosen argued, complexity "*has nothing to do with more complication, or with counting of parts or interactions; such notions, being themselves predicative, are beside the point...Just as 'infinite' is not just 'big finite,' impredicativities are not just big (complicated) predicativities. In both cases, there is no threshold to cross, in terms of how many repetitions of a rote operation such as 'add one' are required to carry one from one realm to the other, nor yet back again*" (Rosen, 1999)(p. 124). That is, the complexity of natural systems depends whether they have or involve 'impredicativities' in their causality or causal organization rather than on whether they have a higher or lower dynamical order, such properties,

being themselves predicative. In mathematics or formal systems, something that is impredicative (in casual terms: it knows itself) is a self-referencing definition or self-referring formal system, i.e., systems whose definitions in set theory would have to invoke what is being defined, or other things that contain the thing being defined. It turns out that self-referential systems are essentially non-syntactic (non-algorithmic) and, therefore, cannot be implemented (simulated), even in an advanced Turing machine (Ben-David et al., 2019).

In science and, in general, in biology, self-referentiality is expressed in the living organization as the cause and effect of itself, or more specifically, as self-production by closure to efficient causation (metabolic closure). An efficient cause is that which constrains or drives changes. The closure to efficient causation is key to modelling the self-referential causal organization of the living systems, which is embodied in autopoiesis and is modelled by the (M,R)-system (M = metabolism, R = repair). These are complementary explanations of the *same* self-referential causal organization of the living systems (see the next section). It turns out that autopoiesis and the (M,R)-system are equivalent self-referential systems.

In this article, we will argue that the Earth system qualifies as a complex system because it instantiates autopoietic organization and therefore the closure to efficient causation at the planetary scale. That is, the Earth systems, as a physical system, realize the formal pattern of an impredicative system. Some consequences of this approach are discussed in reference to climate models.

2. The Road to Complexity: The Protein Folding Paradox and Living Organization

The autopoietic characterization of living systems organization is based on processes of molecular production that result in the constitution of the system itself... "*a network of processes of production of components which through their interactions and transformations continuously regenerate and realize the network of processes (relations) that produced them*" (Maturana and Varela, 1980, p.78). The basic idea is

that a molecular metabolic network generates its own semi-permeable boundary; and hence, its limit, which maintains the metabolic network occurring inside far from dissipation (Fig. 2A). Both the metabolic network and the semi-permeable boundary are interdependent on each other, as part of the same self-production process. This self-production is the realization of a self-referential system in the sense that it "*involves an iteration of the very process that generates it […] with enough entailment to close the realization process up on itself*" (Rosen, 1999, p.265).

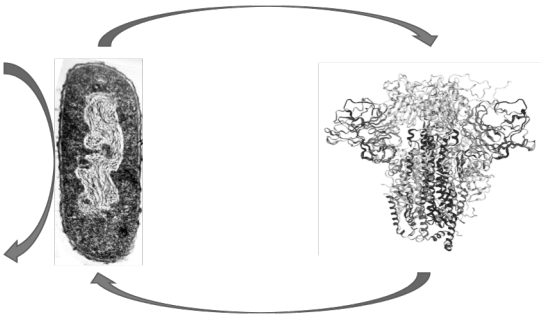

Figure 11. The protein folding only takes place as a self-referential relation of cell–protein, such that cells cannot operate with defective protein shapes and the right folding only takes place within cells. Notice that the interaction with environmental energy and matter does not determine the protein folding either.

While in autopoiesis this causal organization is described as self-production by operational closure, as an (M,R)-system it is modelled as self-fabrication by closure to efficient causation. It turns out that this causality of biological systems implies a non-syntactic (non-algorithmic) character, and thus one that cannot be implemented (i.e., simulated) in a Turing machine (Rosen, 1999; Louie, 2007). In addition, it constitutively involves cognition, autonomy, and anticipation (Maturana and Varela, 1980; Rosen, 1985a; Louie, 2012).

One of the most concrete examples of living systems being complex because they are non-computable is the protein-folding problem. The three-dimensional form of the protein shape (its molecular phenotype) cannot be obtained from the 'information' in the DNA sequence. Even knowing the translated polypeptide sequence and the potential physicochemical landscapes of the folding configuration,

the right phenotype of a folded protein given by experimental crystallization cannot be computed, and hence simulated, in silico. This is because the **folding protein problem**[23] is, indeed, impredicative or 'paradoxical' in the syntactic, predicative world of the computable approach to complexity (Rosen 1991). The folding protein framed in the self-referentiality of the biological causal organization looks like Figure. 11.

In other words, the three-dimensional form of the protein shape may depend essentially of the cell autopoiesis and this seem very difficult to be resolved by computational means[24]. In what follows, we will argue that both the autopoietic and the (M,R)-system are sufficiently general to provide a possible road to showing how the Earth qualifies as a complex system and what this implies for the future evolution of the system.

3. The Autopoietic Complexity of the Earth System Organization

We consider that the Earth's complexity resides in its causal organization, which is self-referential. The road to demonstrating that the Earth qualifies as a complex system thus passes through a consideration of the Gaia hypothesis: that the Earth is an instance of life and therefore an instance of biological organization at a planetary scale.

Numerous authors agree that autopoiesis is a plausible scenario for the instantiation of life organization on a planetary scale (Clarke, 2012, 2020; Jantsch, 1980; von Foerster, 1975; Capra and Luisi, 2014; Rubin and Crucifix, 2019; Sahtouris, 1996;

[23] The protein folding problem is the question of whether a protein's amino acid sequence dictates its three-dimensional atomic structure and whether such phenomena is computable or not. This is a 50-year-old problem.

[24] AlphaFold, an AI that predict protein folding using deep learning algorithms and comparison with lab experiment determined structure, achieved a global distance test (GDT) score of 92.4 of a very small protein (Af1503) of 338 amino acid residues long. The spike protein of SARS-CoV-2 is 1200 to 1400 amino acid residues long. GDT is a test that measures the degree to which a computational program predicted structure is similar to the lab experiment determined structure.

Margulis and Sagan, 1995; Onori and Visconti, 2012; Levchenko et al., 2012). In Chapter 3 we showed that this is plausible in a formal syntactic framework, using a proof-of-concept based on the COT and the ZDT applied on a simple but representative Earth molecular reaction network. These results show that the Earth is an organized system, and this organization may approximate to an autopoietic system, making the GH tractable from this standpoint.

An intuitive but reasonable road to elucidate the Earth's organizational system and whether this organization is autopoietic is derived from two rationales:

- At whatever scale, the physical embodiment of autopoiesis, either in the cellular, metacellular, or in this case, in the planetary domain, must always take place at molecular level. That is, metabolic closure must be molecular: "*There are autopoietic systems of higher order (metacellulars or Gaia), integrated by (populated by) lower order autopoietic unities that may not be the components realizing them as autopoietic systems... there are higher order autopoietic systems whose components are molecular entities produced through the autopoiesis of lower autopoietic unities*" (Maturana, 1980)(p. 53, brackets and underline are mine). This is also indicated elsewhere (Williams, 1996; Volk, 2004).
- Autopoiesis must involve interdependence between a metabolic network and a semi-permeable boundary. On the planetary scale, this can be interpreted as the biosphere (involving the lithosphere and hydrosphere) being the metabolic network, and the atmosphere being the semi-permeable boundary, respectively.

The early systematization of observations already shows that most, if not all, the atmospheric molecular components of the troposphere and stratosphere, key atmospheric layers for climate dynamics, are metabolically produced (Margulis and Lovelock, 1975, 1974). Morowitz points out a self-evident truth: "*all organisms interact through the gas-phase components that they take up from and give off to the atmosphere...*" (Morowitz, 1993)(p. 5). That is, the biosphere depends across time

on the atmospheric composition, upon which it metabolically operates. This metabolic production involves the lithosphere and hydrosphere (Jelen et al., 2016). Therefore, throughout the history of the Earth there has been a molecular interdependence between the biosphere and atmosphere, and this is self-referential in the sense that the continuous metabolic fabrication of atmospheric molecular components takes place in the same domain which allows metabolism to continuously operate (Fig. 2B). The mutual specification of the atmosphere and the metabolic reaction network offer an explanatory account of a self-producing organization that amounts to a self-referential system on the planetary domain, thus a form of planetary autopoiesis. This is also reflected in the co-definition (co-specification and co-production) of the cell–Earth system.

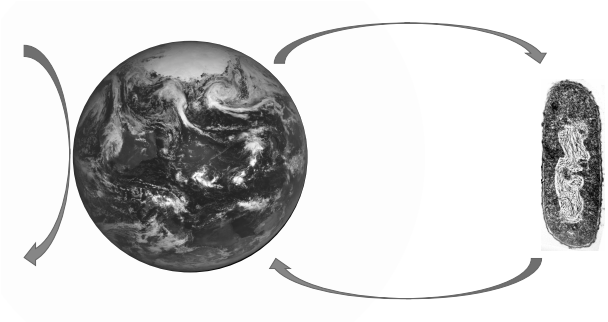

Figure 12. The cell (or any metacellular) and the Earth coupling is also an impredicative system, similar to the cell–protein folded self-reference, in the sense that both exists thanks to each other.

The Earth's complexity as such is precisely reflected in the challenge posed by the projects of planetary terraforming. It is considered that planets such as Venus or Mars could be bombarded in order to produce an Earth-like atmosphere. However, there is no guarantee that any biosphere could thrive there and maintain such an atmosphere. On the other hand, bringing to Mars biosphere-like stations, such as in Biosphere 2, in order to produce a 'habitable' atmosphere within them is considered. Yet, these stations are, for some extent of time, closed-sustainable systems and there is no clear idea how to open up them to connect with the non-habitable Martian atmosphere, in order to accomplish the situation described by Morowitz above.

There is an idea to 'seed' the exo-planets with extremophile microbes and let them colonize it. However, the autopoietic organization of the Earth system and experiments with extremophiles in space strongly suggest that living systems need not just an environment but a bioenvironment in order to persist, which involves a form of organism–bioenvironment self-reference (Fig. 12). This is what is meant by the *"organism-niche unity"* (Maturana, 2011).

At least mathematically, there is no passage from systems that are not self-referential to systems that are (Rosen 1991). That is to say, it is a causal impossibility to generate a system that in principle is closed to efficient causation (operational or metabolic closure), and therefore complex, from algorithmic (non-self-referential) systems. With that said, now we will turn to providing further opportunities to show how the Earth's complexity as an instantiation of autopoiesis at the planetary scale can be compared with in-silico climate simulations, as if the Earth was modelled by (surrogated by) what in Robert Rosen's mathematical biology is called the (M,R)-system.

4. The (M,R)-System and the In-Silico Climates Models

The notion of complexity is much used in Earth climate science. Differently from what we have exposed so far, that is, that the complexity resides in the system self-referentiality or impredicativity, in present-day physics, it is generally considered that it even resides in deceptively simple (but non-linear) systems, which may exhibit sensitivity dependence to initial conditions. In this case, the tiniest uncertainty in initial conditions propagates in time so that predictions are limited to a narrow window of time, because predictive capacity decays exponentially. However, large non-linear dynamical systems are expected to be chaotic, which also produces unpredictability. Paradoxically, though, a closer look at that which present-day physics considers 'complexity', but in reality, is only algorithmic and therefore only complicated, comes to the rescue.

Complicated systems have been proven to display structures at different spatial-temporal scales. It is therefore generally possible to describe the evolution of macro-structures without knowing exactly the state trajectory of the system's state at the smallest scale. This argument has been well described, and formalized mathematically, based on the time-scale separation assumption, and it provides formal support for the idea that it is reasonable to attempt to predict, for example, the next glacial inception, even though mid-latitude weather cannot be predicted precisely beyond two weeks (as demonstrated by any weather forecast).

There is however nothing in this description that challenges the idea that the dynamics of the system can, at least in principle, be deduced from the laws of mechanics at the smallest scale, hence from algorithmic programs. This important assumption justifies the character of programs of research and prediction using general circulation models (GCM). A state-of-the-art GCM is a dynamical system with a state vector of well over 10^6 variables, and the rules for the transition of these state vectors from one-time step to the next are encoded in algorithmic programs that include hundreds of thousands of lines of code (see the IPCC reports). Thus, GCMs are, in essence, very large systems of time-difference equations that are translated as algorithms and executed by 'supercomputers'. That is, it is an in-silico climate simulation. Standard GCMs produce models of the form $F(A) = B$, and this approach has been successful in introducing several important concepts.

- A non-linear dynamical system may have sensitive dependence on initial conditions. The B is then a "strange attractor", which indeed has a non-trivial topology.
- It may also happen that small changes in the system parameters (included in A) result in changes in the topology (the "shape") of B. This is a bifurcation.
- In turbulence theory, one exploits symmetries in the equations governing mechanical flows to deduce that B should have properties of scale invariance.

- In the broader setting of statistical mechanics, one seeks quantities that are conserved globally (energy, entropy), applying principles of statistical inference (typically, the maximum entropy principle) to deduce distributions. Hence, B, the output, takes the form of distribution functions.
- In a GCM, the computing of F on a supercomputer takes long (it may take months), and the output B is stored in mass storage facilities of terabytes of data. Climate observers need time to analyse them, identify "mechanisms" (like sea-ice feedback), and discuss them.

Although such a program of climate simulation is well-established, there is a concern about the conclusion that the principal limit to the accuracy of the description of the Earth's complexity is resolution; hence, computing power. That is, it is assumed that the Earth's complexity could, in principle, be surrogated by a numerical algorithm if enough computing power were granted. However, as we have shown, the Earth's complexity resides rather in its autopoietic (self-referential) organization, and therefore the Earth may escape algorithmic representations. Let us clarify this further.

The (M,R)-system is a formal model and theory to capture the self-producing causal organization of biological systems based on the mathematical language of category theory (Rosen, 1958). The (M,R)-system has been shown to generalize the causality behind the autopoietic organization of living systems. However, the (M,R)-system theory is very different to that used in GCMs. Thus, to compare in-silico climate simulations with the Earth's complexity, as surrogated by the (M,R)-system, we will introduce some basic concepts and notations by reference to the GCM iteration $x_{i+1} = F(x_i)$. When we mention a modification of F, we mean either a modification of the equations of the simulation, or of its parameters.

When we claim that we are 'modelling' climate dynamics, we claim that x_i, x_{i+1}, and F, which are defined as mathematical objects, have their counterparts in the climate system. This means that at least some components of x_i can be observed (perhaps indirectly, via an observation operator). We also consider that there is a relationship

between what can be observed at time t_i, and at time t_{i+1}, and that this relationship can be computed with the algorithm F. We can rephrase this by stating that if the space of possible states for x_i is X_i, then F defines a range of possible states for x_{i+1}, and this range can be noted X_{i+1}. The standard notation is $F:X_i \longrightarrow X_{i+1}$. However, in the (M,R)-system model, Rosen used a non-standard notation: $F \longrightarrow X_i \dashrightarrow X_{i+1}$. The notation is a proxy for the efficient ($\longrightarrow$) and material ($\dashrightarrow$) causes, which allows us to clarify the system's causal categories.

In the biological context surrounding the development of the (M,R)-system model, F is identified as a material efficient cause (it can represent the active site of an enzyme; however, the principle is general enough to apply to other physical instantiations) and in a given environment, constrains a material transformation such that it selects elements of the environment A and transforms them into B. Following the above notation, this reads $F \longrightarrow A \dashrightarrow B$. In in-silico computation, for example, the function F is coded in memory as a suite of binary states which, in the syntactic of the programming language (which provides a context), generates the mapping of X_i onto X_{i+1}. This describes what materially happens when the numerical simulator is run. At this point, the object F may be seen either as a material structure or as a function.

The point of the 'R' in the (M,R)-system is that the metabolism F is undergoing wear and tear, and therefore needs to be repaired. The organism does this, and the (M,R)-system models this as a repair function, which is symbolized by introducing a new function φ. This function takes B as a material cause to produce the F, notated as $\varphi \longrightarrow B \dashrightarrow F$. In a standard GCM this might appear as an incongruity: F is first seen as a "function" or efficient cause, which produces the transformation $A \dashrightarrow B$, but next it is seen as the material cause or initial product of a transformation of B. GCMs are not designed to support this double entailment, but there are mathematical formalisms, like lambda calculus, which would support it. In functional programming a function can also be the output of a function. However, the components of the (M,R)-system, such as F for example, serve not just as the

efficient cause of B, but also as the material and the result (final cause, output, or anticipation) of φ, which does not have a parallel in any syntactic functional programming of in-silico simulations. For example, an enzyme or an organ can simultaneously be seen as a constraint (efficient cause), as a component that needs to be repaired or replaced (material cause), and as a functional element (result of final cause).

Usually, when a version of a GCM or any dynamical representation of the climate system is released, F is frozen. This is so, because in the specification of F, the processes that may affect climate change in the future are ignored. Therefore, to some extent, F may become unsuitable or unacceptably inaccurate at some stage, and processes that have been overlooked may appear to become important in the future. Computing B (which is the model "output") does not pose any specific mathematical difficulty when F is specified as an algorithm and frozen. The one who specifies an F is the climate modeler(s). The output B depends on (reasonable) adjustments to F to bring B into closer alignment with a desired target (e.g., hypothetical climatic-change scenarios). These adjustments are classically justified as part of the quality control process (bug tracking and fixing) and model tuning. Yet, the climate modeler(s) can implement a procedure of automatic tuning of F, designed such that B matches observations about the climate system. In that case, we could say that φ is a computer code that implements an algorithmic process that implements automatic tuning. However, φ still needs to be produced/defined (and corrected), perhaps by a statistician or a numerical analyst, an external agent at the end. We could keep iterating in this way, without changing the nature of the conclusion: at some point we need someone external to the system who specifies F.

The situation is different in the (M,R)-system model, which entails closure to efficient causation of F. The metabolism function F and the repair function φ are generated from the inside, rather than specified from the outside. To make this argument concrete, the autopoietic organization of living systems is self-referential. In other words, a subset of the organism has to play the role of β. It generates φ using internal information (or anticipative model) of what B should be, using a

subset of the metabolism F. Stated mathematically, β is a function that satisfies the definition β: (B, F) → φ. It is possible to review this definition by invoking a formal mathematical act called "currying", common in functional programming: β is redefined as a function of B, which generates a function of F, the output of which is φ. That is: β: B → F → φ. Equivalently, as β(B) is a function, we can write: β(B): F → φ. Now using the Rosen notation, this gives β(B) ⟶ F ⇢ φ. This notation carries the meaning that B provides the structural information (such as active sites of enzymes) for the production of φ. This is represented in the (M,R)-system by a synthesized relational mapping with a closed directed graph that uses the two categories of entailment defined by ⟶ and ⇢ (Fig. 13).

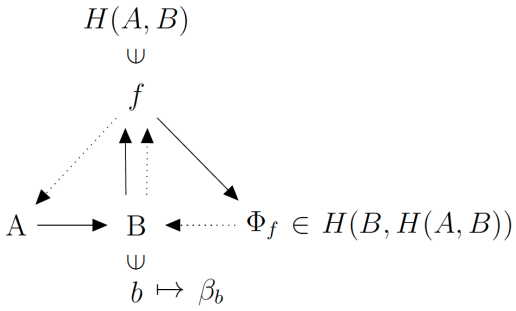

Figure 13. The mathematical structural organization of the (M,R)-system.

On the (M,R)-system graph, B and β(B) occupy the same node, and this assumes implicitly that β is a well-defined function. B is an output (final cause) of F, and is also a material cause of F and efficient cause of φ. Such a concatenation of entailments generates a global stability that may be thought of as if B were a goal function. It is in this sense that the system has acquired a quality of "autopoietic unity" that distinguishes it from systems that do not achieve closure to efficient causation, such as GCMs.

Observe that if β is strictly surjective[25], the destination of the inverse function of β(B), denoted b, is a strict subset of B. Only a subset B may be involved in the production of φ. In this case, the subset b is sufficient (contains enough information) to imply F. The conclusion is that b implies a set that contains itself. Put in colloquial language, a subset of B needs to be "aware of" (informative about) the whole of B and how it is being produced. This is where impredicativity comes in. We can see it at work: B depends on F, which is constantly being replaced, by processes which are critically dependent on φ. Yet, as we just noted, φ depends on only a subset of B.

The dynamical realization of the (M,R)-system model cannot be implemented in the algorithmic language of dynamical systems (Rosen, 1973). Thus, in general we reach the same conclusion when analysing a GCM under the prism of the (M,R)-system. If the F, for example, is seen as the specification of a dynamical system, then B would be its time-invariant measure (roughly said, the attractor) and A would represent an external forcing. Specifying what φ is less straightforward: we need a mapping φ of attractor measures onto some coded specification of F, but also a function β(B) that will produce φ. At this point the dynamical system turns out to be open to efficient causation.

In this sense the (M,R)-system model provides us with further opportunities to formalize the proposal that the complex condition of the Earth system can only be explained by the instantiation of closure to efficient causation at the planetary domain. This expression of the Gaia hypothesis, although tentative, gives us the opportunity to illustrate some of the theoretical aspects underlined above. A potential (M,R)-system model of the Earth system would have to be consistent with the observation that whatever B can be in the Earth system, it is itself involved in a

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[25] We refer to a **surjective function** *f* that maps an element *x* to every element *y*; that is, for every *y*, there is an *x* such that *f*(*x*) = *y*. In other words, every element of the function's codomain is the image of *at least* one element of its domain. It is not required that *x* be unique; the function *f* may map one or more elements of *X* to the same element of *Y*.

chain of entailments that cause F, which is out of the scope of GCM models of the form *F(A) = B*.

The key to Rosen's views on complexity is that the properties of a natural system are subsequently discussed in terms of the models that a natural system can have. Consequently, complex systems are ones that have complex models and the (M,R)-system is postulated to be one of them (Rosen, 1986, 1977; Lane, 2018). Thus, we can ask whether the Earth system is implementing the (M,R)-system, and therefore qualifies as a complex system; a question which is not addressed by the current appraisals of Earth-system complexity.

Turbulence, nonlinearity and chaos are often seen as synonymous with Earth's complexity; however, by definition they are mathematical images that are implementable in a Turing machine, and are therefore simulable. Beyond technical controversies, impredicativity in the (M,R)-system cannot be dealt with by classical methods of programming (Rosen, 1959). This implies that one cannot (easily) provide an iteration which satisfies the causal entailments of the (M,R)-system. Conversely, the (M,R)-system is richer in entailments (causation), to the extent that it cannot be implemented in a Turing machine, is non-simulable, and therefore is complex (Louie, 2007; Luz Cárdenas et al., 2010). The proposal opens the possibility of an entirely new research program to understand the Earth's complexity in terms of organization, allowing us to understand the fundamental difference between what we should call Earth's complexity, and the situation of complication described by GCMs.

5. Conclusions

We understand here that the complexity of the Earth lies in its biological organization rather than in its manifestation of power scaling laws, nonlinearity, and chaos. The present terrestrial environment is itself the cause and result of its own fabrication processes, with no separation, at geological scales, between product and producer, between biotic and abiotic elements.

This implies that the Earth, when understood as a complex autopoietic, anticipatory system, features a horizon of indeterminacy that must be distinguished from the horizon of predictability commonly attributed to algorithmic programs of dynamical systems. This program may be limited or just a shorthand approximation of the Earth's complexity. This may be consistent with the assertion that there exists no equivalent to thermodynamic constraints and feedbacks mechanisms by which we can predict the anticipatory autonomous behaviours of the Earth system. This understanding of Earth complexity may represent, thus, a step forward from current programs, based as they are on the reactive paradigm of feedbacks, dynamical systems, and algorithms in general.

It turns out that Earth complexity embodies a unique attempt to prove that the closure of metabolic networks at the planetary scale must satisfy certain regularities of organization that go beyond reactive, 'complicated' models. These regularities, arising from Earth complexity, as summarized in the properties listed above, suggest an effective system fabrication that generates self-referential mathematical objects. In other words, the relation between Earth complexity and power scaling laws, feedbacks, nonlinearity, and chaos may be compared to the situation faced by early cartographers, who were attempting to map the surface of a sphere while armed only with pieces of (tangent) planes. "As long as they only mapped local regions, the planar approximations sufficed; but as they tried to map larger and larger regions, the discrepancy between the map and the surface grew as well. If they wanted to make accurate maps of large regions of the sphere, they had to keep shifting their tangent planes. The surface of the sphere is in some sense a limit of its planar approximations, but to specify it in this way requires a new global concept (the topology of the sphere; i.e., its curvature) that cannot be inferred from local planar maps alone" (Rosen 1985). It turns out that complicated algorithmic simulations are the planar approximations, and the Earth's complexity is in some sense a limit of its planar approximations, which leads us to widen our concept of what Earth's complexity is, or should be.

Chapter 7

CODA

Just as the Coda brings a piece of music to an end, this chapter brings this thesis to its final conclusion. It may be as simple as discussing tipping points, planetary boundaries, self-perpetuating planetary feedback loops, and Earth 'stewardship' from the theoretical biology standpoint of autopoiesis, the (M,R)-system and active inference. Or as complex as an attempt to conclude that taking the GH at face value for modelling the Earth system complexity implies to develop a new research programme of the Earth system functioning towards a biologised renewed Gaia theory.

1. Praeludium

The GH is best presented as the hypothesis that supposed the Earth to be a living system. So, differentiating the GH from the Gaia phenomenon (GP) and the Gaia theory (GT) clarifies that GH implies the "What is life?" question. This opens the discussion on whether the central feature of living systems—autopoiesis and cognition—could manifest itself at the planetary scale, and how this affect our modelling of the Earth complexity.

The current Earth's modelling and the current GT address the GH and Earth's complexity using the theory of feedbacks self-regulation, self-organized non-equilibrium thermodynamics, and neo-Darwinian adaptive evolution, which none of them address the "What is life?" question. Indeed, the GH, as it is best presented, is scientifically tractable from the biological organization-centred approach of the autopoietic, the (M,R)-system and active inference, which are designed as clear-cut characterizations of what life is.

Considering that the essential for modelling such complexity is organization and behaviour, akin to the current theoretical biology modelling of the minimum unity of life, the cell, these theoretical biological approaches might renew the GT and the modelling of Earth complexity. Such modelling concede to the Earth system and hence to the GP central biological features such as self-fabricating organization, autonomy and active inference, raising a new research programme we called 'functional climatology'.

These results of this thesis provide the possibility to understand Earth complexity beyond identify self-regulatory feedbacks, self-organized non-equilibrium thermodynamics, and neo-Darwinian adaptive evolution, but in terms of identify self-producing organization and active inference on a planetary scale. This will open the discussion on how notions such as Earth 'stewardship', tipping points, planetary boundaries, planetary feedback loops as units of adaptive evolution and selection, or

control-theoretical geoengineering will need to be placed on radically different—specifically, stringent biological—foundations.

Having suggested this in the following section we conclude and discuss the consequences of the theoretical biology approaches used in this thesis to model the Earth complexity from taking the GH at face value.

2. Conclusions: Properties and Consequences

2.1. EARTH COMPLEXITY IS ALL OR NOTHING

Autopoiesis happens or not (Maturana, 1980); thus complexity either occurs or it does not, and there are not intermediate degrees of complexity. The system realizes self-production, or the system falls apart. However, the molecular embodiment of autopoiesis does not mean that organization may be reduced altogether to the molecular phenomena of chemical reaction networks. Rather, it simply points out a fundamental distinction about what should be the Earth's complexity in reference to the question of size, degree, and connectivity compared with impredicative systems. It is in this precise sense that the realization of the autopoietic organization on a planetary domain could allow us to claim that the Earth system needs to be qualified as complex and not merely complicated, i.e., having neither increasing degrees of, nor more or less, complexity. In other words, we can say that a cellular system is as complex as the Earth system because both systems realize autopoiesis. The two computable proofs of concept developed in this thesis are local and temporal approximations of the complexity of the Earth system.

2.2. EARTH COMPLEXITY IMPLIES CONSERVATION OF ORGANIZATIONAL ACROSS STRUCTURAL 'TIPPING' CHANGES

One of the implications for understanding the Earth's complexity from the characterization of autopoietic systems is the difference between structure and organization of the system (Maturana and Varela, 1980; Nomura, 2006). This difference between structure and organization is related, in formal terms, to the fact

that biological systems are open to material cause, yet closed to efficient causation. The first relates to the dynamic and thermodynamic, while the second relates to the organization of biological systems.

Structural change and organizational conservation are the keys to complex system dynamics and modelling. The structure may undergo changes as long as the autopoietic organization is preserved (Maturana, 1980, 2011; Nomura, 2006). Different structures (scenarios of Earth's history) correspond to the structural change, but with conservation of the Earth's self-producing organization. Structural change is closely associated with stability, and it is usually assumed to be a general property of dynamical systems. Some authors understand the stability of the Earth system as self-organization, alternate states (multistability), thresholds, and early signals of change (Bak, 1993; Levin, 2005; Lenton and van Oijen, 2002; Scheffer et al., 2009). One might conjecture that under this understanding, the so-called "tipping points" (Lenton et al., 2008), including the potential cascades, may be regarded as structural changes that so far have not caused the loss of the Earth's organization. In other words, the Earth system can go through different structural changes (extreme, abrupt, catastrophic) while preserving its autopoietic organization, and hence its complexity; these "tipping points" can be, so to speak, non-fatal. Indeed, Earth's history has been punctuated by several "catastrophic" structural changes, such as the transition from reductive to oxidative atmosphere (Falkowski, 2006), the mass extinctions (diminished biosphere) of 50 to 90% of diversity (Barnosky et al., 2011), planetesimal impacts, and geomorphological changes. Yet, the complex (living) character of the Earth system has persisted.

2.3. EARTH COMPLEXITY IMPLIES MULTIPLE STRUCTURAL RELATIONS CARRIED OUT BY MULTIPLE COMPONENTS

Many of the components of an (M,R)-system serve as outputs (final cause), as efficient causes, and also as material causes of other components. Structural changes of the Earth system understood as an autopoietic system may have many structural interdependencies. If one structural dimension in the Earth system is changed (e.g., a tipping point of Greenland ice melting), the complete system may undergo

correlative changes in many structural dimensions (e.g., possible tipping cascades). Such structural changes can suppress, allow, or create new components and relations (processes and constraints) (Maturana, 1980, 2011; Nomura, 2006). Therefore, these components may be integrated into the system with different structural relations, either as processes or as components realizing the constraints on the processes. That is, components may have multiple structural relations, and structural relations may be carried by multiple components. For example, ice-sheets have multiple structural relations with different processes and components of the Earth system, linked as they are to climate dynamics, the nutrient cycle, the ocean crust, and the water cycle (Screen and Simmonds, 2010; Lamarche-Gagnon et al., 2019; Horvat et al., 2017; Hopwood, 2018; Crowley et al., 2015).

Nevertheless, there may be structural changes that could make the Earth system lose its organization and thus enter into an 'autopoietic oscillator death' (Friston, 2013). This touches on the definition of what could be a 'critical' perturbation for the complexity of Earth's organization that may break down its autopoiesis and thus be fatal, and whether the thresholds of the 'planetary boundaries' (Rockström et al., 2009) are critical for the planetary self-producing organization. This issue demand further research.

2.4. EARTH COMPLEXITY IS MORE THAN INPUT–OUTPUT CONTROL FEEDBACK SYSTEMS

Recent proposals suggested that adaptive evolution and selection operates through non-reproducing self-perpetuating planetary feedback loops (Doolittle and Inkpen, 2018; Lenton et al., 2021) and that in general feedback loops are key for climate dynamics, and hence Earth complexity. However, mechanisms of feedback self-regulation have been described on so-far lifeless planets, such as Mars (Chassefière, 1991; Ng and Zuber, 2006), and seen as stabilizing the surface temperature of a lifeless Earth (Walker et al., 1981).

As we have seen through the thesis, feedback loops are a legacy of the first order cybernetics and control theory (von Foerster, 1952; Ashby, 1952; Wiener, 1948) and

in reference of Walter Cannon's *homeostasis* (Cannon, 1929), having the '*good regulator*' as one of the central theorems (Conant and Ashby, 1970) (see Chapter 2 and 3). The core idea is that there is an input-output system that reaches stability through self-regulation by negative and positive feedback loops (von Foerster, 1952; Ashby, 1952; Wiener, 1948). The feedback loop is an error-counteracting response, which takes place only when there is external perturbation (forcing/input) sufficient to make the system's parameters deviate from pre-defined 'set points'. It is said that cybernetic systems behave as goal oriented systems, because they return to their 'set points' once they are perturbed. That is, the error-counteracting response is a reactive response. Moreover, the relation of input to output implies that external forcing determines what happens inside a system, such that a forced system will generally end up tracking the forcing. The explicit relation between the two is embodied in the engineering transfer function of the system. That is already suggestive, but it is very risky to simply extrapolate such ideas of a simple or even a complicated system, that when a system is fabricated by metabolic closure, i.e., it is complex, because the Earth system as such may entail the absence of input and output controls, and remain organized through autopoiesis, autonomy and active inference and not through reactive behaviours. That is, instead of correcting an error, the system predicts the error and behaves according to this prediction.

In general, autopoietic systems cannot be modelled, hence 'controlled' by using feedback control theory without causing side effects because living systems are not input-output cybernetic systems (Maturana and Varela, 1980; Nomura, 2006). This touches on the notion of "Earth stewardship" (Steffen et al., 2018). In this notion it is assumed that the Earth can be "controlled", to be maintained on a "safe" trajectory, by anthropogenic feedback "input" mechanisms. This consists in developing strategies of geoengineering to avoid the so-called climate warming. Thus, it is based on feedback control theory, the reactive paradigm view of the Earth system. However, our results indicate the possibility of the Gaia's ability to preserve *autonomously* its own self-producing organisation through metabolic closure. So, does the "Earth stewardship" could be the same if the Earth is an autonomous

system? For example, under the idea of the feedback input, it has been proposed to 'mitigate' climate change by releasing sulphate aerosols into the atmosphere to increase the planetary albedo and thus diminish solar warming of the planet. This feedback is intended to compensate for the increase in downwelling long-wave radiation caused by greenhouse gas emissions. However, time-independent predictions of the theory of the self-fabrication point out that the structural change caused by perturbation (such as the proposed feedback) is expected to have many correlative changes, not necessarily just the one predicted by the control model (see for details Maturana, 1980; Rosen, 1985a). This implies that Gaia's response to any given perturbation may involve a potentially large number of unpredictable structural changes to preserve the system's autopoietic organisation as we discussed in the previous point. Here is a first formal argument for the intuition that solar radiation management (SRM) may lead to unforeseeable repercussions due to the autonomous Gaian responses of the Earth system. Moreover, this may involve active inference at the planetary scale as well. Even more stringent arguments related to biological organization (Louie, 2020) may have consequences on geoengineering and on the relevance of current simulations of the Earth's climate system (for a brief discussion see section 6 of Rubin and Crucifix, 2019).

2.5. SELF-FABRICATING ORGANIZATION AND ACTIVE INFERENCE ARE KEY FEATURES OF EARTH COMPLEXITY

The autopoietic system is wide open to imposed forces in a time-independent manner and has a structure that changes following a course contingent on the course of its interactions. However, forcings that may impinge upon the system may trigger structural changes without specifying them (Maturana 1980; 2011; Nomura 2006). Even if a forcing causes continuous structural changes in the system, the specific nature of these changes may be determined not by the forcing (input), but rather by the autopoietic organization (Maturana and Varela 1980). The identification of the autopoietic organization by COT and ZDT in a simple but representative molecular reaction network that corresponds to metabolic history of the Earth system suggest

reconsidering the current approaches, hence a shifts on our understanding of the character of Earth system complexity towards autopoietic organization.

Self-fabricating system may build up predictive models of the forcing in order to act autonomously and predictively over such forcings (Louie, 2012). These models make the system behave in a goal-directed manner, and thus autonomously. But such autonomy is constitutive and not imposed or programmed from outside, that is, it is given thanks to its self-production.

Autonomy is a property of systems upon which the flows from environment to system, and from system to environment, are determined by what is inside the system (Moreno and Mossio, 2015; Varela, 1979; Rosen, 1999) and such that everything that happens in the system or to it is determined in it at every instant by its structural dynamics at that instant. Anticipation is the behaviour of avoiding a predicted deviation, which is energetically much cheaper than correcting a deviation (feedback), whether through fluctuation-counteracting or fluctuation-amplifying. This implies that feedback responses are reactive and cost-ineffective responses. Akin to the generative models of active inference, anticipation is based on internal predictive models that living systems make of their environment and themselves, throughout their ontogeny and phylogeny (Bateson, 1979; Maturana and Mpodozis, 1991; Mpodozis, 2022; Rubin, 2022), which allows changed behaviour at an instant in accord with the model's prediction and pertaining to a future (later) instant (Rosen, 1985a; Louie, 2017). These models involves feedforward loops and are inherent to the causal entailment organization of self-production by metabolic closure (Rosen, 1985a; Louie, 2017).

Given that autonomy is a corollary of autopoiesis (Moreno and Mossio, 2015; Varela, 1979; Maturana, 1980) and that every autopoietic system minimizes free energy (active inference) (Friston 2013), it is reasonable to consider that the Earth's complexity involves autopoietic organization and active inference. At least, this is what we outline in the two proofs of concept. Active inference must be considered, as a subset of anticipation, a unique biological phenomenon (Rosen, 1985a). Anticipatory behaviour is relevant to any level of biological self-producing

organization. From microbes (Mitchell et al., 2009), to fungi (Siegal, 2015), to trees (Calvo and Friston, 2017). For example at the ecosystem level, the Amazonian trees anticipate the dry season, they bring moist air in from the Atlantic ocean by increasing their rate of evapotranspiration (Wright et al., 2017) and releasing cloud-forming organic aerosols (Pöhlker et al., 2012). The arguments and results presented in this thesis (chapter 4 and 5) indicates that active inference can occur at planetary level as well.

The identification of the autopoietic organization by COT and ZDT in a simple but representative molecular reaction network that corresponds to metabolic history of the Earth system and of active inference in a biosphere-climate dynamical system

2.6. 'MANAGING' THE EARTH AS A COMPLEX SYSTEM REQUIRES COMPLEX MODELS

It is important to ask whether dynamical systems or GCMs 'model' the complexity of the Earth system to the extent that the potential intervention (the application of geoengineering) is reliable. That is, one must ask how well the mathematical machinery of feedbacks, dynamical systems, and far from equilibrium thermodynamics, can inform us about potential chain disruptions and domino effects in the Earth's organization if geoengineering is applied.

Based on the arguments presented through the thesis and especially in the preceding chapter, it is expected that under a geoengineering perturbation (solar radiation management or carbon sink), the Earth system may undergo correlative changes in many structural dimensions. Thus, different Earth components will rearrange in different multiple structural relations in order that the Earth's organization remains autopoietic. These rearrangements will be in general a kind of self-structuration, since any Earth response to any perturbation, including geoengineering, is autonomous, i.e., it goes beyond input–output feedback loops. Moreover, it is highly plausible that the Earth system will track such geoengineering, forcing and building

up anticipative models of it, and thus there will be no clear idea about how this self-structuration would take place. This suggests that any attempt of "Earth stewardship" may involve making complex models of how the Earth system self-fabricates, but also making inferences from Gaia's own inference. That is, one would have to understand what kind of generative (anticipatory) models Gaia has in her own cognitive domain to face dissipation and external fluctuation.

3. Epilogue. Biologising the Gaia Theory: Towards a 'Functional Climatology' Research Programme

The GH as initially oriented, i.e., that Earth system's homeorhetic trajectories are determined *by* and *for* the system itself (Lovelock and Margulis, 1974; Margulis and Lovelock, 1975), involves an organization where the system's components instantiate a set of 'functional' relations that preserves the organization of the system and determines its trajectory. As the 'function' of the heart is to 'pump' blood for the body, we have to ask if it is legitimate to consider whether, for example, the 'function' of the Amazon forest is also to 'pump' water and carbon for the Earth's climate homeorhesis. So far, current research has provided some intriguing observations about the Amazon not just seeding but making its own rain (Loomis, 2017): the trees of the Amazon, in addition to producing seven more times moisture and clouds than the Atlantic and absorbing 1 billion tons of CO_2 annually (Brienen et al., 2015), are capable of generating trade winds and bringing atmospheric rivers inland from the Atlantic through the anticipation of dry periods (Wright et al., 2017). These atmospheric rivers in turn are retained by the Andes (acting as a topographic barrier) and distributed with mountain nutrients downwards through the Amazon towards the Atlantic heavily affecting the salinity, pH, light penetration, and sedimentation of a wide area of the tropical North Atlantic (Moura et al., 2016). This flow can be connected with part of the nutrients that are transported by wind (Amazon driven?) from the Sahara desert to the Amazon (Nogueira et al., 2021) across the Atlantic, affecting the growth of algae (Walsh and Steidinger, 2001) and microorganisms which produce annually more than 60% of biogenic cloud-forming

aerosols (McCoy et al., 2015). This relation of the Atlantic and the Andes through the Amazon structure thus may impact the climate system through modulating the water and nutrient (carbon) cycle, and global energy balance.

In this thesis I have developed the necessary theoretical arguments that can allow these observations to have a conceptual coherence that would help us to draw a line between wishful thinking and a characterisation of the organization of Earth's components that sees it as satisfying the set of autopoietic relations of self-fabrication and active inference. This sheds light on a new form of modelling the Earth system complexity, considering autopoietic organization and active inference as a Gaian-planetary-phenomenon.

Thus, throughout this thesis, the bases have been laid, from a computable perspective (chapters 3 and 5), that the problem established in chapter 2 is tractable from the mathematical rigor of the COT and FEP machinery. This could be the core of a research programme we call "functional climatology", upon which we could identify the genotype and phenotype of the Earth system functioning and lay the groundwork for an understanding of the complexity of the Earth system as a living unity from a biological standpoint. In this sense this thesis constitutes a third way to understand the degree of interaction, modulation and coupling of the biosphere with the abiotic components of the Earth system from a biological and biophysical standpoint.

Considering that there are no independent relationships between biotic and abiotic components but rather there are only self-reference relationships through the autopoietic organization at the planetary scale, certain questions could be the basis of the proposed research programme. Have the Earth system components the same rate of fabrication? What is the causal relation, for example, between the fabrication of Greenland and the fabrication of the Amazon? How and where does the Anthropocene affect Gaian self-fabricating? Could there be effective geoengineering or 'Earth stewardship' without side effects on a planetary system that autonomously

self-repairs? What could be a "critical" disturbance for Gaia? Are the "planetary boundaries" (Rockström et al., 2009) critical for planetary self-producing organization? What sort of perturbations can be disruptive to Gaia's autopoietic organization? Does the Earth system have a context depended functional memory?

As the organization of self-production implies different structural realizations (Maturana and Varela 1980), we align with Lovelock's deduction that a sort of memory of Gaia is structurally determined and operating in the short and long term. The former established as the metabolic capacity of a single rhizome network operating at molecular level (Williams, 1996; Raoult, 2010) possessing a relatively stable set of key central enzymes (for example, Rubisco, glutamine synthetase, etc.) capable of influencing of the major geochemical cycles (Falkowski et al., 2008; Jelen et al., 2016). The structure of the rhizome network, in general, is phylogenetically conserved regardless of the type of biosphere that is established (Sagan, 1990). As neurons work in the brain, it should work in a distributed, parallel, scattered way (trophic and symbiotic relationships of eukaryotic and prokaryotic systems in the ocean, continents, deep subsoil and atmosphere) (Stolz, 2016). The latter, which operates in the long term, must be fundamentally associated with the geomorphology that determines the dynamic interplay between lithosphere (orography), ocean and atmosphere that continuously ensures climatic regularities and climatic changes.

In practice, this programme will consider cellular models of self-fabrication and active inference as surrogates of the Earth system and its geo-climatic and biogeochemistry processes and constraints. The biospheric component of the Earth system may be seen not as independent of geo-climatic processes, but neither as a passive and reactive subsystem of it.

In this regard, the homeorhetic dynamics of Earth system may be understood as determined by planetary active inference of the Sun and space weather conditions. Thus, the search of feedforward signalling pathways in biogeochemical and geo-climatic phenomena may be crucial.

The implementation of this programme will extend the conventional input/output and state-variable frameworks upon which climate and feedback control theory is based, to explicitly mobilize the theoretical biology apparatus towards a biologically Earth-system functioning. Modelling the Earth complexity, in this programme, may be taking the GH at face value, i.e. the Earth as a living system, and hence fundamentally as an active and autonomous system including, but beyond the Anthropocene. In other words, this programme will demand taking a step beyond the current consensus that GT is mostly about control feedback regulation, irreversible self-organized non-equilibrium thermodynamics or neo-Darwinian adaptive evolution or that Earth complexity is about scaling laws, nonlinearity and chaos.

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