James Lovelock Centenary: The Future of Global Systems Thinking

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Abstracts

GS1: Earth History

1. Typical Climate Perturbations Unlikely to Disrupt Gaia Hypothesis

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The Gaia hypothesis postulates that in certain situations life on a planet regulates its environment to be favorable for its own survival. Most planets experience numerous perturbations throughout their lifetimes such as asteroid impacts, volcanism, and the evolution of a star's luminosity. For the Gaia hypothesis to be viable, life must be able to keep the conditions of its host planet habitable, even with perturbations. Exogaia, a model created to investigate the Gaia hypothesis, has been used to test life's ability to regulate a host planet's climate with constant conditions, but not with changing conditions. In order to see how life responds to perturbations to its host planet, we created three perturbations in Exogaia: one rapid cooling of a planet and two heating events, one rapid and one gradual. For all perturbations, the planets on which life is able to survive without changes to its environment are also the planets on which life is most likely to survive the changes. Biospheres experiencing gradual changes to the environment are able to survive significantly stronger changes than those experiencing rapid perturbations, and the magnitude of change matters more than the sign. These findings arise from systems of hypothetical planets, but can be applied to perturbations throughout Earth's history such as the Chicxulub asteroid impact or the gradual increase in the Sun's luminosity. If the Gaia hypothesis is correct, then typical perturbations that a planet would experience may be unlikely to disrupt it.

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2. The relevance of biologically driven symbiotic novelty to the functioning of the Earth system

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Lovelock's Gaia hypothesis characterizes life as a planetary scale phenomenon, by means of which a self-perpetuating non-equilibrium biogeochemical state exhibits emergent homeostatic properties[1,2]. But what precisely is it about life that leads to any such homeostasis? I argue that life's unique influence on the Earth system is the generation of novelty, which I define as discontinuity in the distribution of cause-effect relationships within time: such that an instance of novelty is the objective earliest occurrence of a specific, subsequently repetitive, causal relationship connecting two changes[3]. Evolutionary innovation gives a direction to Earth history, whereby a previously unprecedented type of system comes into being from a definable timepoint onwards (e.g. through a transition in the level at which natural selection operates[4] or a qualitative change in biogeochemical cycling[5]). Symbiosis is a key part of such exploration of "feedback space" (and of course, the Gaia hypothesis[2]); and involves the coupling together of qualitatively different physiologies[6,7] into a single unit of selection at a fitness cost[8] . I suggest that (sometimes) symbiosis may couple together physiologies with opposite environmental impact, creating within the life-environment interface the kind of "integral rein control" system conducive to homeostasis[9,10]. The original Watson-Lovelock "Daisyworld" parable epitomizes such a system, and I argue that life's influence on the Earth-system is analogous to a tendency towards formation of adaptive symbioses between black (warming) and white (cooling) "daisies" [12]. More broadly, I suggest[3] that symbiosis exemplifies a general tendency towards novelty generation by interaction between systems that are functionally compatible but structurally distinct.

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3. Carbonate Weathering Resilience from the Eocene Arrival of Chalk

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Earth as a system has functionally self-regulated its carbon and climate systems through the long term feedback of silicate and carbonate weathering. However, the understanding and quantification of these processes in response to large Earth System perturbations is poorly constrained [1]. Large-scale carbonate weathering-induced resilience is scarce in its analysis, especially at highly weather-able pure calcite chalk cliffs. Modelled and proxy evidence demonstrates an increasing recovery efficiency from the Palaeocene-Eocene Thermal Maximum (PETM) relative to events predating it [2]. Although many conditions have been assessed for their resilience potential, the role of carbonate weathering has not received the same depth of analysis. Given uplift of Northern Hemisphere chalk massifs coincided with the recovery of the PETM, there is potential this exposure offered additional responsive resilience to the Carbon Cycle. Earth System model cGENIE will simulate the paleoenvironmental conditions for the PETM and the Pliocene warm period, to identify the resilience influence of the newly exposed chalk as a novel Earth System resilience investigation. Other factors such as the influence of Northern Hemisphere ice cover and sea level rise on carbonate weathering efficiency during Earth system recovery, will also be assessed. This analysis will be evaluated in the context of current Earth System model accuracy and ability to represent the Carbon Cycle. Ultimately, this research will contribute to the understanding of the Earths self-regulatory systems and effective resilience employed in response to carbon and climate perturbations.

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4. Clouds stabilize Earth's long term climate

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The Sun was dimmer earlier in Earth history, but glaciation was rare in the Precambrian: this is the “Faint Young Sun Problem”. Most solutions rely on changes to the chemical composition of the atmosphere to compensate via a stronger greenhouse effect, whilst physical feedbacks have received less attention. Here we show that a strong negative feedback from low clouds has had a major role in stabilizing climate through Earth's history. We perform Global Climate Model experiments in which a reduced solar constant is offset by higher CO_2, and find a substantial decrease in low clouds and hence planetary albedo, which contributes 40% of the required forcing to offset the faint Sun. Through time, the climatically important stratocumulus decks have grown in response to a brightening Sun and decreasing greenhouse effect, driven by stronger cloud-top radiative cooling (which drives low-cloud formation) a stronger inversion (which sustains clouds against dry air entrainment from above). This demonstrates the importance of physical feedbacks on long-term climate stabilization, and a reduced role for geochemical feedbacks.

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5. Daisyworld Misunderstood: Gaian Homeostasis is Inevitable

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The streamlined tuna is fit for purpose, needs a selective explanation. The boulder rolling to the bottom of a hill doesn't. Too many misunderstand Daisyworld-style explanations [1] of Gaian regulation as the former type. But Daisyworld is the latter: from some initial conditions a pattern of Daisyworld-homeostasis is inevitable, no selection needed.

Misunderstanding follows failure to distinguish between *Viability* and *Feasibility* [2]. Define *Viability*$_D$(T) as the steady-state quantity of D-daisies at T-temperature. In turn, daisies have *effect*(D) on T (e.g. black daisies are warmer). The D<->T interactions are parameterised by some perturbation L (e.g. solar Luminosity). Define *Feasibility-Range FR*(D,*effect*()) as the range of L-values supporting stable equilibrium with D>0: '*feasible* Luminosities supporting steady *Viability*>0'.

Using physically plausible equations [2] we prove *FR*(D,*effect*())⊇*FR*(D,*null-effect*). Any (+/-) effect that D has on T can only increase (never decrease) *Feasibility-Range*. This agrees with classical Daisyworld-homeostasis [1] (that used 'anecdotal' examples open to accusations of cherry-picking); but is now fully generalisable [2] (including to any number of D_i or of T_j without selection).

A change in *effect*() may increase *Feasibility-Range* whilst decreasing *Viability*. They are different, indeed orthogonal, though commonly confused: even Gaian advocates [3] misleadingly claim "Daisyworld is a special case in that traits selected at an individual scale also lead to global regulation". Actually interactions with Darwinian evolution are very different than this implies, and even random unselected trait-effects support such global regulation. Advances in Gaia theory are essential for understanding past, present and future homeostasis of this planet; but are hindered by such misunderstandings and misplaced appeals to selection.

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6. Climate feedbacks of the Mesozoic Earth System: the response of wildfire

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Large climatic swings are characteristic of the Early Jurassic and multiple shifts between cooler and warmer conditions have been recognized on timescales of 1 to 10 Myr. These changes in the climate are accompanied by other changes in the Earth System, as sea-level change and global and regional perturbations to biogeochemical cycles. The largest event is the Toarcian Ocean Anoxic Event (T-OAE), associated with extreme temperatures, weathering and erosion, nutrient cycling, global carbon burial. This lead to the deposition of black shales globally and coinciding with large igneous provinces. Complex dynamics of biogeochemical cycling and climate at this time reflect the integrated response to many drivers and feedback mechanisms. Multiple hypotheses have been proposed for how these drivers and feedbacks interacted, however, the driving/responsive role of fire is still debated. Moreover, the significance of the smaller warming and cooling events is unexplored during this time interval. Therefore, the Early Jurassic Earth System and Timescale (JET) project aims to reach a holistic understanding of these minor climatic oscillations during this time period with a multi-proxy approach.

This specific study, as part of the JET project, explores the Early Jurassic 'background' climate and the potential orbital cycles in a range of proxies: mineralogical, palynological and geochemical. But most important, examines the potential of climatic forcing on fire activity in the geological deep time. Next to this background study, I will look at the 'minor' events of the Pliensbachian: the Sinemurian-Pliensbachian 'warm event' and the Upper Pliensbachian 'cold event'.

7. Interplay between life and the solid Earth

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Major shifts in Earth's evolution led to progressive adaptations of the biosphere. Particularly the emergence of continents permitted efficient use of solar energy. However, the widespread evolution of the biosphere fed back to the Earth system, which has been argued as a cause for the great oxidation event or as an important component in stabilizing Earth's climate [1]. Furthermore, biologically enhanced weathering rates alter the flux of sediments in subduction zones, which establishes a potential link to the deep interior [2,3]. Dependent on the stability of water-carrying phases, subducted sediments can then induce partial melting and therefore the production of continental crust or even affect the mantle rheology. The mantle responds by enhancing its rates of convection, water outgassing, and subduction. Emerging feedback cycles ultimately determine the sensitivity of the coupled system to individual parameters, i.e. to the biologically enhanced weathering rate [4]. Modelling Earth's interior evolution with continental growth and a comparison with the geological record favour models with strong positive feedbacks, indicating a strong sensitivity of the system to initial conditions and perturbations [5]. This implies that life itself may play a crucial role in the evolution of the solid Earth. I will discuss the biosphere as a component in evolving Earth system feedback cycles and present concepts and models on how bioactivity may be accounted for in models of mantle convection and continental growth. How would the Earth have been evolved without life?

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[5] Höning D et al. (2019) Phys Earth Planet Inter 287:37-50

8. An analytical study of the robustness of planetary self-regulation.

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The Daisyworld model of Watson and Lovelock [1] demonstrates the potential for planetary self-regulation from life-environment interactions. In this model, atmospheric temperature on the hypothetical "Daisyworld" planet is determined by radiative balance, and thus depends on the planet's albedo and its sun's luminosity. The albedo is determined by the populations of two species of daisies, one black and one white. These populations are governed by two coupled differential equations, which model the daisies as having a constant death rate and temperature dependent growth rate. The model exhibits the curious property that the planetary temperature is maintained close to the optimal growth temperature despite significant changes in solar luminosity. Similar behaviour is also observed in models with greater numbers of species [2,3].

To celebrate the Lovelock centenary, we revisit the Daisyworld model, in similar analytical style to [4,5]. In contrast to these papers, we allow the death rates and the temperature dependency of the growth rates of the two species to differ. Similar to [4], we find that the planetary steady-state conditions are also determined by the roots of a single polynomial in this more general case. We also obtain explicit conditions for determining the stability of these steady-states that generalise the results of [5] without requiring the linear approximation of that paper. Furthermore, we prove that models with multiple daisy species will almost certainly be populated by at most two daisies at any one time. These analytical expressions allow an investigation of the robustness of the planetary regulation property.

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9. Does "ecological memory" provide a mechanism for ecosystem and Earth system resilience?

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Earth has remained consistently hospitable since life first emerged more than 3 billion years ago, but this continued habitability in the face of increasing solar luminosity, climate fluctuations, and occasional catastrophes is difficult to explain. Potential explanations range from active control of planetary conditions by life itself (the Gaia hypothesis) through to simple luck (the weak anthropic principle) [1,2]. However, the mechanisms by which life might stabilise the Earth system remain debated. One possible mechanism is that the potential capacity for ecosystems to "learn" – with ecosystems behaving like Hopfield neural networks of interacting species undergoing unsupervised Hebbian learning from a training pattern of environmental forcing, resulting in a distributed associative ecological memory of past conditions emerging [3,4] – might make ecosystems more resilient to perturbations, and that this could upscale to the planetary level. This phenomenon could potentially enhance biosphere and Earth system resilience, but has so far been hard to find evidence for in real-world ecosystems. Here, we outline a methodology for assessing the impact of ecological memory on ecosystem resilience. We posit that the stability of an ecosystem can be quantified using neural network approaches, by assuming that the community matrix is functionally equivalent to a neural network weight matrix and that its Hopfield network 'energy' is minimised at stable points. We present preliminary calculations and applications of this metric for case studies from palaeoecological data and ecosystem models, and consider next steps for assessing the impact of ecological memory on life/environment feedbacks from the local to global level.

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10. Multiple Steady-States in Earth's Long-Term Carbon Cycle

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Over the Phanerozoic Eon, global average surface temperatures and atmospheric pCO_2 levels appear to be bimodallly distributed [1], hinting at the existence of multiple steady-states in the long-term carbon cycle. Here we use a biogeochemical model to assess this potential. The model includes latitudinal variation of chemical weathering, temperature-dependent biotic weathering and oxidation of reduced organic carbon. Stable upper temperature steady-states (UTSS) can be found, which are driven by redistribution of biotic and abiotic carbon sinks to higher latitudes, consistent with the projected contemporary destruction of tropical rainforest with several degrees of global warming, and the loss of tropical forests in warmer periods of Earth history, such as the early Triassic [2]. Indeed, the early Triassic climate is a prime candidate for a UTSS, where a state change could be generated by the injection into the atmosphere of carbon dioxide from the eruption of the Siberian Traps at the P-T boundary [3]. Our results are consistent with the prospect that the anthropogenic perturbation to atmospheric carbon dioxide could potentially tip the climate into a modestly higher temperature steady-state, instead of relaxing back to pre-anthropogenic conditions.

References: [1] Mills BJW et al. (2019) Gondwana Research 67:172-186. [2] Sun Y et al. (2012) Science 338, 366.
[3] Kump LR (2018) Phil. Trans. R. Soc. A 376: 20170078.

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11. CAPITALISM IS NOT A THING: Limits of a Global Concept

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Arguments still rage about how exactly humans began irretrievable intervention in the planetary geosphere, atmosphere and biosphere. This paper assesses some of the most prominent literature from the past two decades that assign the historical causality to capitalism, especially those engaging with the concept of the 'Capitalocene'[1]. While firmly acknowledging their valuable insights, attempts to answer what exactly drives capitalism anywhere since the past 500 years inadvertently lead to common presuppositions of capitalism as not a *relation* but a *thing*.

If the proponents of the capitalocene intended to replace the essentialist bifurcation between nature and culture with a discursive, historically situated relation of capitalism, one of its implications has been the essentialisation of capitalism instead. It takes the form of an innate human desire for accumulating profit and power. Is this essentialism the general price to pay for attributing causality in histories on a global spatiotemporal scale? What sort of politics does this global centring of capitalism produce? Might getting outside the frame of the capitalocene, an offspring of world-systems theory[2], allow for a more substantial and inclusive kind of politics? The paper concludes with some recommendations on how to navigate the crooked line between essentialism and incoherence, explanation and meaninglessness while narrating environmental histories with capitalism as the dominant form of relation producing our global present.

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12. Biospheric evolution is coarsely deterministic

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The general pattern of the tightly coupled evolution of biota and climate on Earth has been the very probable outcome from a relatively small number of possible histories at the macroscale, given the same initial conditions [1]. Thus, the evolution of the biosphere self-selects a pattern of biotic evolution that is coarsely deterministic, with critical constraints likely including surface temperature as well as oxygen and carbon dioxide levels in the atmosphere. Major events in biotic evolution were likely driven by environmental physics and chemistry, including photosynthesis, and oxygenic photosynthesis, the emergence of eucaryotes from the merging of complementary metabolisms and finally multicellularity and even encephalization [2,3]. The following is a test of the difficulty for steps in major evolutionary emergences: if a potential constraint is released at the time of emergence then it was virtually inevitable ('easy"). The upper temperature limits of growth (T_u) of the main groups of living organisms corresponds to the climatic temperature at the times of their first emergence [2,4], assuming a very warm Archean climate [4,5,6]. The T_u is a very likely primitive character determined by intrinsic biochemistry/biophysics, e.g., there are no hyperthermophilic phototrophs, even though they had three billion years to adapt to a T_u above 80°C.

The pattern of biospheric evolution argued here raises the potential of similar coevolutionary relationships of life and its environment on Earth-like planets around Sun-like stars. If biospheres emerge in a strongly habitable context, their survival is likely enhanced by strong coevolutionary mechanisms [7,8].

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13. The History of Atmospheric Oxygen: Regulation by Fire

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The concentration of oxygen in our atmosphere is a critical variable for life on Earth; it allows us to breathe today and likely played a significant role in the evolution of animals [1]. Atmospheric oxygen has risen from trace to present-day levels in multiple steps over the past few billion years. However, over the past 400 million years, despite oxygen in the atmosphere being replaced 100 times, concentrations have remained at levels similar to those found today [2,3]. Such stability suggests mechanisms have been in place to keep oxygen at relatively constant levels throughout this period. However, such mechanisms and what their respective forcings are remains heavily debated and this has led to disagreements on the variations in atmospheric oxygen during the Phanerozoic.

In his early books, James Lovelock proposed that fire may play a vital role in the regulation of oxygen [4]. More recently, research suggests that continuous records of charcoal over the 400 million years indicates the presence of fire, and that small changes in atmospheric oxygen concentration have large effects on the probability of ignition [5,3]. The research presented here uses the Lund-Potsdam-Jena managed Land (LPJmL) Dynamic Global Vegetation Model to gain a deeper understanding of the relationships between fire, vegetation and oxygen. By running oxygen experiments we evaluate the strength of fire-oxygen feedbacks and apply this to the history of oxygen. This should better our insight into the regulation of atmospheric oxygen and further our understanding of the Earth system as a whole.

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14. Generalized Langevin Equations and the Climate Response Problem

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There can be few greater scientific challenges than predicting the response of the global system to anthropogenic disruption, even with the array of sensing tools available in the "digital Anthropocene". Rather than depend on one approach, climate science thus employs a hierarchy of models, trading off the tractability of Energy Balance Models (EBMs) [1] against the detail of Global Circulation Models. Since the 70s Hasselmann-type stochastic EBMs have allowed treatment of climate fluctuations and noise. They remain topical, e.g. their use by Cox et al to propose an emergent constraint on climate sensitivity [2]. Insight comes from exploiting a mapping between Hasselmann's EBM and the original stochastic model in physics, the Langevin equation of 1908.

However, it has recently been claimed that the wide range of time scales in the global system may require a heavy-tailed response [3,4] to perturbation, instead of the familiar exponential. Evidence for this includes long range memory (LRM) in GMT, and the success of a fractional Gaussian model in predicting GMT [5].

Our line of enquiry is complementary to [3-5] and proposes mapping a model well known in statistical mechanics, the Green-Kubo "Generalised Langevin Equation" (GLE) to generalise the Hasselmann EBM [6]. If present LRM then simplifies the GLE to a fractional Langevin equation (FLE). As well as a noise term the FLM has a dissipation term not present in [3,4], generalising Hasselmann's damping constant. We describe the corresponding EBM [7] that maps to the FLE, discuss its solutions, and relate it to existing models.

References: [1] Ghil M (2019) Earth and Space Sciences, in press. [2] Cox P et al. (2018) Nature 553: 319-322 [3] Rypdal K. (2012) JGR 117: D06115 [4] Rypdal M and Rypdal K (2014) J Climate 27: 5240-5258. [5] Lovejoy et al (2015) ESDD 6:1–22 [6] Watkins N W (2013) GRL 40:1-9 [7] Watkins et al, to be submitted to J Stat Phys.

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15. Earth self-organisation in five stages

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Earth evolution is a process of self-organisation against the backdrop of chaos. Throughout, planetary self-organization is driven by selecting the most effective mode of planetary entropy export. We distinguish between five successive stages, each exhibiting a different mode of 'ratcheting' differentiation: (1) formation of the earth as part of the solar system; (2) differentiation between the core, the mantle, the crust, the ocean and the atmosphere as major constituent parts; (3) regular convection without life; (4) emergence and evolution of life (the Gaia stage); and (5) 'civilization,' characterized by the combined forces of tool use, thinking and communication (the civilome stage). Each stage provides the constitutive configuration for further development. This approach of Strong Earth System Science eliminates the biocentric and anthropocentric delusions which used to obscure the debates on Gaia and the Anthropocene. Primarily, it is the earth that does the evolving and the civilizing. In particular, Strong ESS provides the key for a new, sublime worldview, the successor of the Enlightenment: 'our identity is earth.' Armed with this worldview we can address the conundrum of global change.

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16. Questions on escape from self-regulation

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1. James Lovelock has said "The self-regulation of the Earth demands both positive and negative feedback" [1]. But when there is repeated positive feedback in a system, a small change can trigger more and more disturbance. Why does self-regulation require positive feedback?
2. People have found ways of creating mechanisms governed by positive feedback. Is there a tipping point at which self-regulating by negative feedback systems tips control over to positive feedback systems?
3. We humans are units of ever larger and more complex emergent phenomena and increasingly hierarchical societies. In our large, complex societies what is the best interaction of bottom-up and top-down? How in hierarchical human societies do emergent phenomena arise?
4. Where small changes lead to disproportionately large effects or tipping points, we refer to "complexity" or "chaos", in which relationships are neither linear nor based on circular feedback loops. Where are the high-risk areas in our ignorance of complexity?

Ernst Mayr argued that the adaptive value of higher intelligence is very low [2]. This leads to the final three questions.

5. Besides logical, deductive reasoning, what mental functions do we need in order to comprehend an increasingly complex world?
6. Which is the greater risk – artificial intelligence systems, we humans or the interface?
7. The continued positive feedback of unrelenting global capital growth on a finite planet now ties cultures into one complex and fragile system. Almost all the eggs of Homo sapiens are in one basket. Where will this lead to?

References: [1] Lovelock J (2014) A Rough Ride to the Future. UK, Penguin. 64 [2] Mayr E (1995) Can SETI Succeed? Not Likely, *Bioastronomy News* 7: 3

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17. Fire in the Earth System

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Fire is an important part of our Earth system, influencing vegetation dynamics, atmospheric chemistry, the hydrological cycle and carbon cycle, and land surface albedo. It is both a natural process, concomitant with the origin of the first plant forms [1], and anthropogenically influenced as part of the development of early human society as far back at 1,000,000 years ago [2]. Fire has been suggested as the main determining factor in alternative stable states of forest and savannah [3], and with increasing temperatures, drought and land-use change in some areas, there are concerns that fire may contribute to tipping large carbon stores such as the Amazon forest into sources of carbon [4,5]. Here we show that fire is an important process in the present day simulation of vegetation in the land surface model JULES, and that in years of extreme drought such as El Niño, this can lead to large decreases in terrestrial carbon uptake. Using Representative Concentration Scenarios with HadGEM2-ES to drive JULES, burned area is projected to increase in many areas in the future under high emissions scenarios of climate change [6].

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18. Analytical tools for studying Earth system resilience in the Anthropocene: from frameworks to simulation models

Donges, J.F.[1,2], Lucht, W.1, Heitzig, J. [1], Barfuss, W. [1], Cornell, S. [2], Lade, S. [2,3], Otto, I. [1], Schlüter, M. [2], and Wiedermann, M. [1]

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In the Anthropocene, societal processes have become critical to understanding planetary-scale Earth system dynamics. The conceptual foundations of Earth system modelling have externalised social processes in ways that now hinder progress in understanding Earth resilience and informing governance of global environmental change. New approaches to global modelling are needed to address these challenges, but the current modelling landscape is highly diverse and heterogeneous, ranging from purely biophysical Earth System Models, to hybrid macro-economic Integrated Assessments Models, to a plethora of models of socio-cultural dynamics. World-Earth models, currently not yet available, will need to integrate all these elements, so future World-Earth modellers require a structured approach to identify, classify, select, and combine model components [1]. Here, we develop a framework for ordering the multitude of societal and biophysical subsystems and their interactions [2]. We suggest three taxa for modelled subsystems: (i) biophysical, where dynamics is usually represented by ``natural laws" of physics, chemistry or ecology (i.e., the usual components of Earth system models), (ii) socio-cultural, dominated by processes of human behaviour, decision making and collective social dynamics (e.g., politics, institutions, social networks), and (iii) socio-metabolic, dealing with the material interactions of social and biophysical subsystems (e.g., human bodies, natural resource and agriculture). We present the copan:CORE framework as a flexible tool to construct World-Earth system simulation models [3]. As an example, we study a stylised model of socially transmitted discount rates in a greenhouse gas emissions game to illustrate the effects of social-ecological feedback loops that are usually not considered in current modelling efforts.

References: [1] Donges JF et al. (2017) Anthropocene Review 4: 151-157 [2] Donges et al. (2018) Earth System Dynamics Disc., doi:10.5194/esd-2018-27 [3] Donges and Heitzig et al. (2018) Earth System Dynamics Disc., doi:10.5194/esd-2017-126

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19. Applying the DAISYWORLD model to study planetary boundaries of biosphere-atmosphere interactions

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Biosphere and atmosphere interact through greenhouse gas dynamics. The biosphere can act as a carbon sink (at least during its lifetime) reducing atmospheric greenhouse gas concentration and affecting temperature. Eventually, carbon captured by the biosphere will be released to the atmosphere by decomposition. Since the beginning of its measurement in the 1950s, CO_2 concentration on the Earth has kept raising and it is now over the safe boundary established to avoid sudden cascade reactions and feedbacks that can result in dangerous outcomes for our society [1]. To investigate this dynamic, the DAISYWORLD model [2] seems to be an appropriate tool to test hypotheses and apply model experiments. The objective of the here presented study is to use a modified DAISYWORLD model [3] to test the impact of different climatic conditions as well as possible stability ranges. We tried five different emission scenarios, and in none of them the two population reached a stable state, although the white daisies took an advantage over the black ones. The results indicated that the biosphere was not able to compensate impacts of the atmospheric CO_2 concentration. This set up is used in two ways. First, we tried to adapt the parameters, to detect conditions to stabilize the system, second, to apply mitigation options to stabilize the system. Despite the simplicity of the system, we plan to transfer the results to the real world and go then back to the model to implement more environmental variables.

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20. Effects of the food system on biodiversity, feedbacks on ecosystem services, and consequences for human well-being

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Land cover and land use change are expected to be the main drivers of biodiversity loss in the 21st century. With the loss of biodiversity, the provision of ecosystem services could be compromised with severe consequences for human well-being, including the loss of stability and productivity of food systems. The ‘Sustainable and Healthy Food Systems’ project (SHEFS) aims at providing policy makers with novel, interdisciplinary evidence to define future food systems policies that deliver nutritious and healthy foods in an environmentally sustainable and socially equitable manner.

Our group explores how the rapid expansion and intensification of industrial agricultural land and the projected pattern of urbanization in southern Africa will affect biodiversity in the future, and how changes in biodiversity will feedback on ecosystem services related to food systems and human health. Forcing a coupled Species Distribution - Demographic model with different climate change and land use change scenarios, we aim at providing insights in possible future species distribution and abundance, estimate the consequences for ecosystem service provision, and support food and environmental policy decision making.

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21. Model Hierarchies for Understanding Atmospheric Circulation

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Model hierarchies are fundamental to our understanding of the large-scale circulation of Earth's atmosphere. They have played a critical role in forming and testing our ability to simulate and predict the natural variability of the atmosphere, such as the variations of the extratropical jet streams, and for exploring how the climate will respond to external forcing, such as increased carbon dioxide.

During the poster presentation I will discuss simple models that have formed the basis of our understanding of the atmosphere and how they connect to the comprehensive models used for climate prediction through the model hierarchies. I will describe three principles that help organize the model hierarchies and discuss benchmark models that have been influential in understanding the large-scale circulation in the midlatitudes, middle atmosphere, and tropics.
This abstract is based on the plain language summary of my recent review paper in Reviews of Geophysics of the same name. The paper is available here: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2018RG000607

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22. Cloud computing and community management: Understanding changing resilience in the Kenyan rangelands

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When combined with new cloud computing facilities, the ever-increasing amount of remote sensed satellite data provides a basis to gain a greater understanding of the changing Earth and the state of ecosystems. In this study, the resilience of an ecosystem is defined as the ability of a system to maintain its internal structure while subject to external perturbations and the return rate of the system to its initial state following a significant perturbation [1,2].
This project uses Google Earth Engine (GEE), a cloud computing geographical information system (GIS) platform [3], in order to undertake spatial and temporal ecosystem resilience analysis in semi-arid regions. The first study area in this project will be community conservancies under the umbrella of the Northern Rangelands Trust (NRT) in Kenya. NRT consists of over 30 community managed conservancies which cooperate to increase both social and ecological resilience in a region afflicted with drought [4]. This initiative offers a solution to the 'tragedy of the commons' resource problem associated with semi-arid rangelands by supporting communities to develop sustainable land management approaches. Analysis from this study will support this work.
This study highlights the utility of big data analysis for sensing the planet and aims to quantify the impact of community conservation on vegetation resilience in the Kenyan rangelands. This is done using vegetation indices and drought metrics from remotely sensed data such as Landsat and MODIS.

References: [1] Holling, C.S. (1973). *Annual review of ecology and systematics* 4(1), pp.1–23. [2] Pimm S. (1984). Nature, 307.
[3] Gorelick, N et al. (2017). *Remote Sensing of Environment* 202, 18–27 [4] Northern Rangelands Trust (NRT) (2019) https://www.nrt-kenya.org/

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23. Biologizing the Gaia Theory: Is the planet Earth an anticipatory system that minimizes free energy?

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In previous work [1], we showed that metabolic molecular self-production by closure to efficient causation is feasible and offers a rigorous claim that the living condition of the Earth is given by the structural realization of the (Metabolism, Repair)-Autopoietic organization at the planetary domain. Here, we examine whether, anticipation and autonomy (active inference by minimization of free energy), the central tenets of the (M,R)-Autopoiesis, are coextensive to the Gaia phenomenon. That is, whether the Gaian behaviours are autonomous [2] and best modelled as a function of future states, $[x(t)=f(x(t-\psi), x(t), x(t+\omega))]$, rather than merely as a function of past $x(t-\psi)$ and present states $x(t)$ of feedback reactive systems [3]. The motivation for this has hitherto used the following argument: biological systems that do not use anticipative models of themselves and their ambiance to preserve their physiological bounds cannot exist, because the entropy would increase indefinitely. Therefore, biological systems actively must minimize free energy [4]. Although, at the planetary scale, this is an open question, the (M,R) mathematical formulation of the Earth system process of self-production entails anticipation as the constitutive autonomy of the Gaia phenomenon. This contrasts with the regulator thesis and the weak and strong interpretation of the Gaia hypothesis, on which Gaia is a reactive, error-counteracting system. Furthermore, in biologizing Gaia theory, its conjectures and refutations [5] become parsimonious because they represent only local and temporal simulable approximations of anticipative autonomous behaviours, which are causal, yet are not mechanisms.

References: [1] Rubin SdC and Crucifix M (2019) *submitted* Journal of Theoretical Biology [2] Varela F (1979) Principles of Biological Autonomy. Nord Holland. New York [3] Rosen R (1985) Anticipatory Systems. Springer, New York [4] Friston K (2013) Journal of the Royal Society Interface 10(86): 20130475 [5] Kirchner JW (2003) Climatic Change 58(1-2): 21-45

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24. Variations in Earth's Rotation Rate and Atmospheric Angular Momentum

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Conservation of angular momentum of the entire Earth – Atmosphere system implies that variations in atmospheric angular momentum must be reflected in Earth's angular momentum. This gives the well-established result that variations in atmospheric winds lead to variations in the length of day. Here we show that fluctuations in the length of day measured by very long baseline interferometry of radio-telescope observations are predictable out to years ahead. This predictability decays non-monotonically with lead time, peaks in winter and is mainly triggered by the El Nino Southern Oscillation. These signals represent a test of our climate models and provide a source of ultra-long range predictability from within the atmosphere, where they migrate polewards with time and eventually affect the mid latitude flow.

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25. Can Global Atmospheric Chemistry Models Simulate Surface Ozone in China?

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Surface level ozone has detrimental effects on ecosystem health, crop growth and climate change. For example, surface ozone concentrations of 45 ppbv have been estimated to cause a 13% reduction in crop yields, which has serious implications for food security under global change and concomitant increases in global population and food demand. The accurate simulation of surface ozone concentrations in China is crucial to enable the informed development of effective mitigation strategies that protect ecosystem and crop health.

Here, we evaluate surface ozone simulations in 8 state-of-the-science global atmospheric chemistry models against ozone measurements from the Ministry of Environmental Protection of China. The models include 6 models from the Coupled-Chemistry Model including the HadGEM3-ES model from the Met Office Hadley Centre, and results from the GEOS-Chem model at 2 different horizontal spatial resolutions.

Analyses of correlation (R^2), point-for-point accuracy (normalised mean bias), and spatial variability were carried out for monthly averages between 2013-2017 at up to 1497 urban sites across China. All models simulate urban surface ozone concentrations in the summer, autumn, and winter seasons with reasonable accuracy, but were consistently unable to predict surface ozone concentrations in spring. Generally, the models overpredict surface ozone concentration. HadGEM3-ES over-predicts in summer and under-predicts in winter.

Furthermore, the spatial accuracy of the models was tested by analysing four highly polluted urban regions in China. This analysis, focussing on the GEOS-Chem and HadGEM3-ES models, demonstrated the limitations in model ability to capture spatial variability.

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26. Reducing our carbon footprint and resource use on the Exeter Kidney Unit

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Introduction

Chronic kidney disease affects 10% of the worldwide population and over 2 million people are dependent on dialysis or a kidney transplant to stay alive [1]. Greater than 80% patients who receive treatment for kidney failure live in affluent countries with universal access to healthcare [1]. In the UK renal medicine was amongst the first medical specialties to measure its environmental impact. The Climate Change Act calls for an 80% reduction in carbon emissions by 2050 [2-4]. The NHS will only reach its targets by considering all aspects of practice, to reduce carbon emissions. The Exeter Kidney Unit serves a population of one million with five satellite dialysis units. We undertook a multi-disciplinary team project to make changes towards greater environmental sustainability in our unit.

Method

We identified the following areas for change:

- Reducing duplication in disinfection cycles across 24 haemodialysis machines by one quarter.
- Replace 12 existing haemodialysis machines with new machines that can be switched to a 'standby' mode following priming to save water.
- Patients were asked to bring their own blanket to dialysis saving on emissions and resource use incurred by hospital laundry.
- Expanding home haemodialysis numbers results in a reduction in water usage and domestic recycling of packaging. Thirty staff pledged to 'Meat Free Monday'.

Results

The potential carbon footprint reduction was 7161.63 KgCO2e, potential water savings were 258,336 litres and financial savings were calculated as £8000.0.

Conclusion

As NHS staff we are responsible for improving the quality of our services including introducing changes to be more environmentally sustainable to protect the health of current and future generations.

References: https://kidney.org.uk/
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/371103/Health_Effects_of_Climate_Change_in_the_UK_2012_V13_with_cover_accessible.pdf
https://digital.nhs.uk/data-and-information/national-indicator-library/carbon-dioxide-equivalent-emissions-for-nhs-trusts
https://sustainablehealthcare.org.uk/who-we-are

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27. No health without planetary health

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The World Health Organisation constitution, adopted in New York in 1946, defines health as "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity"[1]. Although not without its critics, it was considered groundbreaking in its time for including mental and social domains, along with the physical, and overcoming a negative definition of health as merely absence of disease. It has never been adapted in over

70 years. Planetary health, by contrast, refers to “the health of human civilization and the state of the natural systems on which it depends”[2]. Can the two be reconciled?

The Anthropocene marks an era when the activities of a single species (of human) have become, either temporally or permanently, the major determinant for the future direction of the biosphere and the myriad of species it contains. By contrast, the richness and diversity of nature supplies most of what it means to live full and enriched lives from aesthetics and beauty to life saving drugs[3]. The transformative solution required is recognition of the physical and natural environment as the source of all life when nurtured in harmony, not exploited to extinction in polluting ways. Human and all other living health is a PART of planetary health. A special transformative approach from health and care is that most solutions for long term climate health ALSO offer immediate well known, understood, practical health and well-being benefits (e.g. meaningful jobs, sustainable food, insulated houses, renewable energy, planned and welcome migration).

References: [1] World Health Organization. Constitution of the World Health Organization as adopted by the International Health Conference, New York, 19–22 June 1946; signed on 22nd July 1946 by the representatives of 61 States (Official Records of the World Health Organization, no.2, p.100) and entered into force on 7th April 1948. [2] "Safeguarding human health in the Anthropocene epoch: report of The Rockefeller Foundation–Lancet Commission on planetary health" (2015) The Lancet 386:1973-2028 14th November 2015. [3] Chivian E. Why doctors and their organisations must help tackle climate change: an essay by Eric Chivian (2014) BMJ 348:g2407.

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28. Golding and Lovelock: An encounter between literature and science

Bradley Osborne[1]

The subject of my poster is the friendship between James Lovelock and the author William Golding (1911-1993). My wider research examines the development of Golding’s conception and representation of nature across his work. The poster will provide outlines of Lovelock’s friendship with Golding, the mutual influence they had on each other’s work, and the broader implications for Golding scholarship and for the study of literature and the environment.

The name for Lovelock’s hypothesis, ‘Gaia’, after the Greek goddess of the Earth, was originally suggested by Golding when they met in Bowerchalke in the mid-1960s. [1] My research looks at the impact that Lovelock’s hypothesis had on Golding’s ideas about the natural world in his later writings. I make extensive use of the unpublished drafts and notebooks held at Special Collections in Exeter, which reveal a greater degree of influence than has been previously acknowledged by critics. I also plan to visit the Lovelock archive at the Science Museum to determine the extent to which Golding influenced Lovelock; so far, archival evidence suggests that Golding read and commented on Lovelock’s fiction. [2]

In their article on Gaia 2.0, Timothy Lenton and Bruno Latour call on humans to add self-awareness to the Earth’s processes of self-regulation. [3] Literature is one of the primary modes through which we develop awareness of our world. We must therefore ask what role literary criticism should play in this; my research into Golding’s engagements with environmental science is well-placed to contribute answers to this question.

References: [1] Lovelock acknowledges his debt to Golding in *The Ages of Gaia* (Oxford: OUP, 2000), 3.
[2] EUL MS 429/2/9. [3] Lenton T and Latour B (2018) *Science* 361: 1066-1068.

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29. The Other World that is Still Possible

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In our recently published book [1] we argue that there are two critical material requirements for still having a remaining chance, if rapidly diminishing, of keep global warming below the IPCC goal of 1.5 °C, namely, global solarization of energy supplies coupled with rapid phase out of fossil fuels and the transformation of agriculture to agroecologies. We critique "A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies" [2] because it would not provide the energy capacity for climate mitigation and adaptation, as well as falling short of creating equity between the global South and North, in particular by keeping most of humanity in the state of energy poverty. Even with the implementation of projected state-of-the-science energy efficiencies in all sectors, the likely necessary level of primary energy consumption by 2050 will be greater than the present level of 18 TW, closer to 25-30 TW.

The only feasible way to avoid climate catastrophe are radical changes in both the physical and political economies, notably the degrowth/dissolution of the Military Industrial Complex (MIC) and implementation of a Global Green New Deal as a pathway for global ecosocialist transition. As the global solar power infrastructure grows and replaces fossil fuels then the capacity to recycle without the negative impacts of the latter will grow with a goal of phasing out mining and actually increasing the material throughput (via industrial ecologies), especially as the huge material infrastructure of the MIC is recycled.

References: [1] Schwartzman P and Schwartzman D (2019) The Earth is Not for Sale: A Path Out of Fossil Capitalism to the Other World That is Still Possible. Singapore: World Scientific. [2] Grubler et al. (2018) Nature Energy 3: 515-527

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30. Spaceship Earth – from attractive metaphor to architectural analogue

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"Spaceship Earth" is an attractive and compelling metaphor for our planetary system. Ecologists now have a good understanding of the whole-earth system-of-systems and the many coupled systems that in combination generate its dynamic behaviour – notably the dynamic interactions that maintain an environment hospitable to life. Systems Engineering has emerged as a general technique for realising, managing and retiring "engineered" systems of all sorts. Notably, the Systems Engineering community now has well established architectural patterns and implementation approaches for making successful spacecraft capable of supporting human life during extended self-contained missions.

Ecologists and systems engineers will need to work together to understand the problems facing us in the Anthropocene, and to conceive and implement – indeed, to "engineer", in its widest sense of "to cunningly contrive" - viable governance systems and intervention strategies for the Anthropocene. The spaceship earth metaphor and the spaceship engineering architectural pattern provide a nearly-shared fuzzy mental model between the communities. Very few members of the public, or engineers, have a good mental model of how Gaia works. Many of both have usable mental models of spacecraft, based on professional experience and/or popular fiction.

The "Spaceship Earth Challenge" seeks to turn a fuzzy metaphor into a formal analogue. It invites participants to develop a formal reference architecture drawing explicit parallels between earth systems and spaceship systems, to allow ecologists and engineers to share mental and formal models, with each other and with the general public. The poster presents current status of our thinking and invites constructive debate.

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31. Free online courses from the Global Systems Institute

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Free online courses offer the ability to engage a global, online audience and inspire the theme of climate action. Since 2018, the Global Systems Institute has produced a series of these courses to 26,000 learners from over 150 countries. Through the use of videos, articles, discussions and quizzes, learners are able to better understand the science of the climate system and explore the potential solutions at a variety of scales, from local to global. We also study the way that we value nature and potential irreversible changes in climate and social systems. Our global courses also offer the unique opportunity to share stories of the different ways that climate change is impacting their lives. Learners from the United Kingdom could talk directly to learners from Fiji or the Mauritius who are already putting in place adaptation measures to combat sea-level rise. In this poster, we will introduce you to our courses, share our highlights from the past 18 months, and unveil our newest course – Invisible Worlds.

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32. Lovelock as a Map Thinker

Rasmus Grønfeldt Winther

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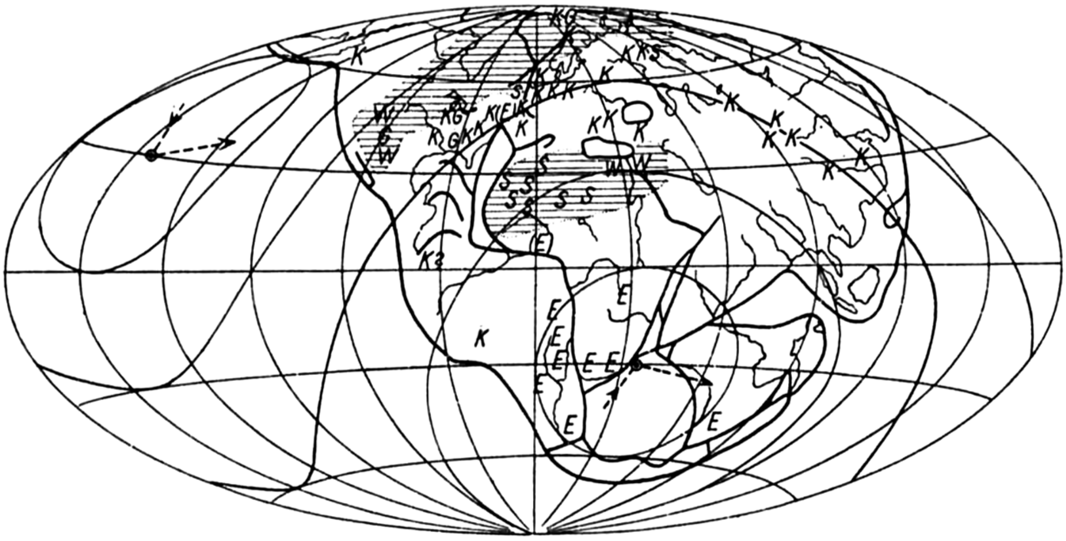
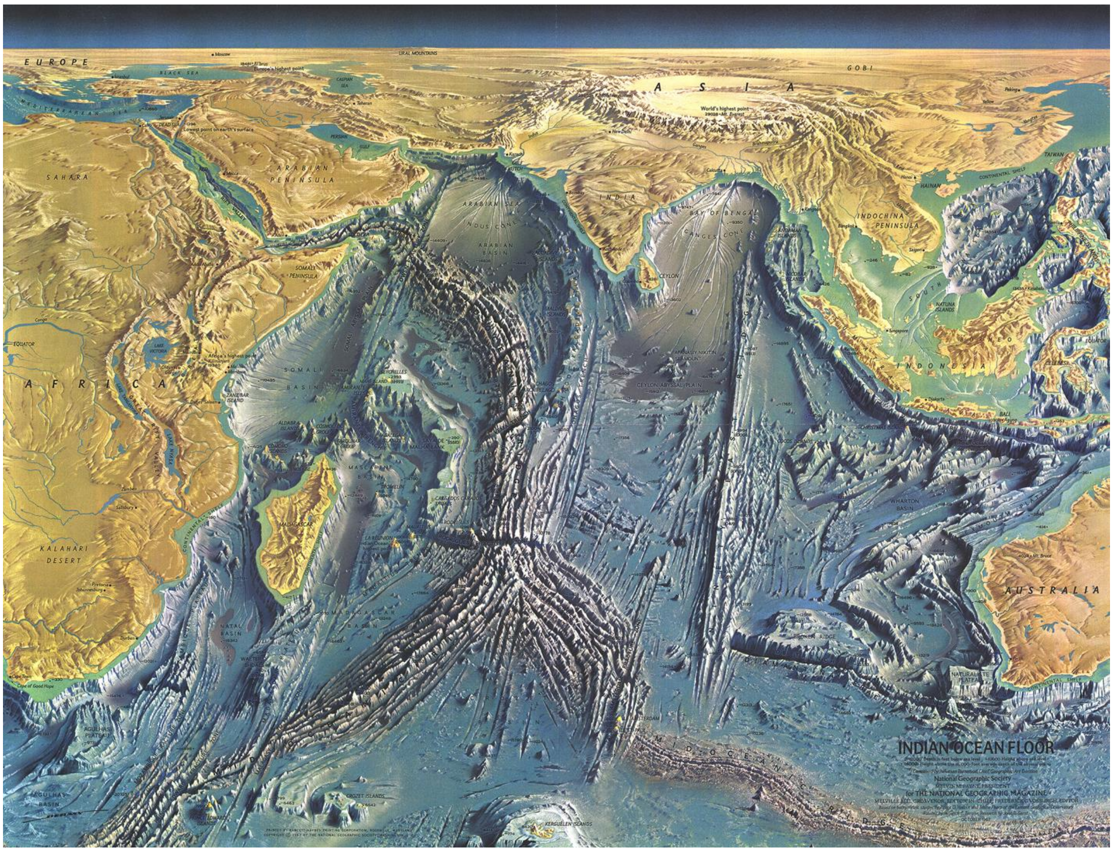
Maps and *map thinking* are ubiquitous. Many kinds of scientific representation are premised on organizing different kinds of spaces, from geographic maps to the state space maps of mathematical modeling to analogical maps and metaphors. One way to understand James Lovelock's rethinking of Earth as a system or organism is as providing a new way to map-think our Globe. His cybernetic or organismic (or both) perspective provides a different *set of maps* replacing—or perhaps complementing—more standard geochemical and geological maps (e.g., Alfred Wegener, Marie Tharp). Building on my forthcoming book [1] as well as on a recent anthology chapter [2], I aim to provide a deeper understanding of the plurality of representations in the Earth Sciences by interpreting Lovelock as a revolutionary map thinker.

References: [1] Winther, RG. 2020. *When Maps Become the World*. Chicago, IL: University of Chicago Press. https://www.press.uchicago.edu/ucp/books/book/chicago/W/bo45713064.html [2] "Mapping the Deep Blue Oceans" 2019. *The Philosophy of GIS,* edited by Timothy Tambassi, Springer, 99-123. https://www.academia.edu/37794550/Mapping_the_Deep_Blue_Oceans



A geological, literal map superimposing the current-day position of the continents onto their position during the Carboniferous period, ca. 300 to 360 mya. In the earlier era, much land was concentrated near the South Pole, while the North Pole was out to sea. The Carboniferous period poles are the physical rotational poles of Earth, not the magnetic poles. *E* = ice traces (*Eisspuren*); *K* = coal (*Kohlen*); *S* = salt; *G* = gypsum; *W* = desert sandstone (*Wüstensandstein*); hatch marks = arid zones (Alfred Wegener [1929] 1966, 137).



The *Indian Ocean Floor* panorama by Heinrich Berann, Marie Tharp, and Bruce Heezan was a foldout map in the October 1967 issue of *National Geographic*. Subscriptions to that magazine numbered six million in the US alone. This panorama shows both the lowest and highest points on Earth's land surface. (Heinrich Berann / *National Geographic* Creative / *National Geographic* Image Collection.)

Lovelock's Maps

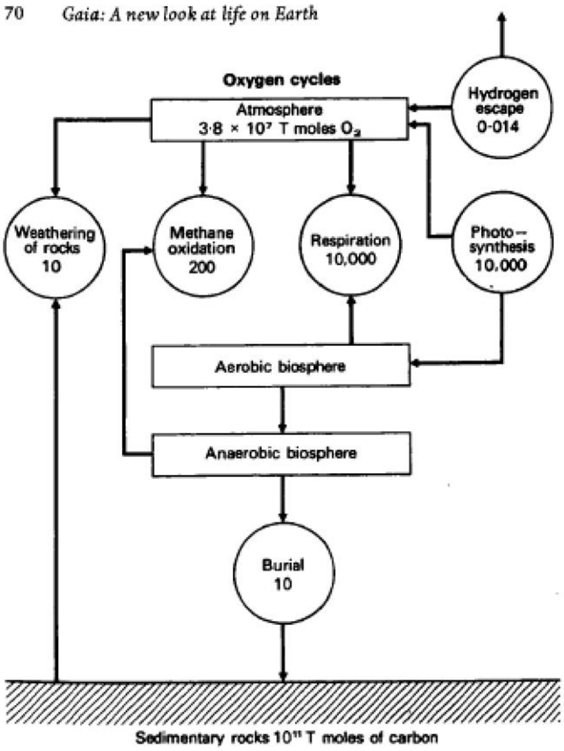


Fig. 6. The fluxes of oxygen and carbon between the major reservoirs of the Earth's atmosphere, surface, and oceans. Quantities are shown in units of terramoles. A terramole of carbon is 12 megatons and of oxygen 32 megatons. Figures inside the circles are annual fluxes. Figures in the two reservoirs, the atmosphere and the sedimentary rocks, indicate their size. Note how the carbon, en route for burial in the sedimentary layers beneath the sea and the marshes and wet lands, is for the most part vented back to the atmosphere as 'marsh gas', methane.

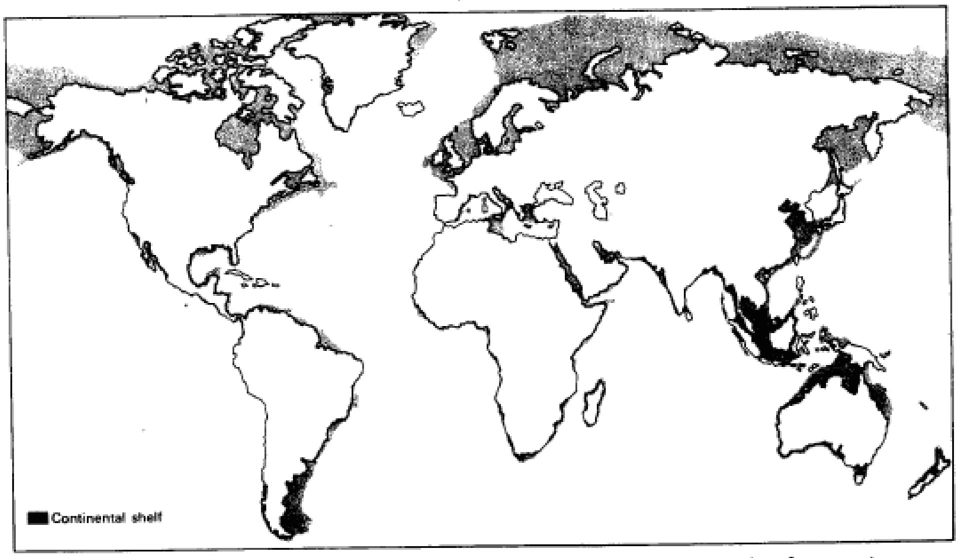


Fig. 8. The continental shelves of the oceans. These regions, which occupy an area as large as the African continent, may be crucial in the homoeostasis of our planet. Here carbon is buried which sustains oxygen in the air, and here is the source of many other gaseous and volatile compounds essential for life.

33. Empowering and supporting scientists to connect with policy

Inika Taylor[1*] and Cathy Cole[1]

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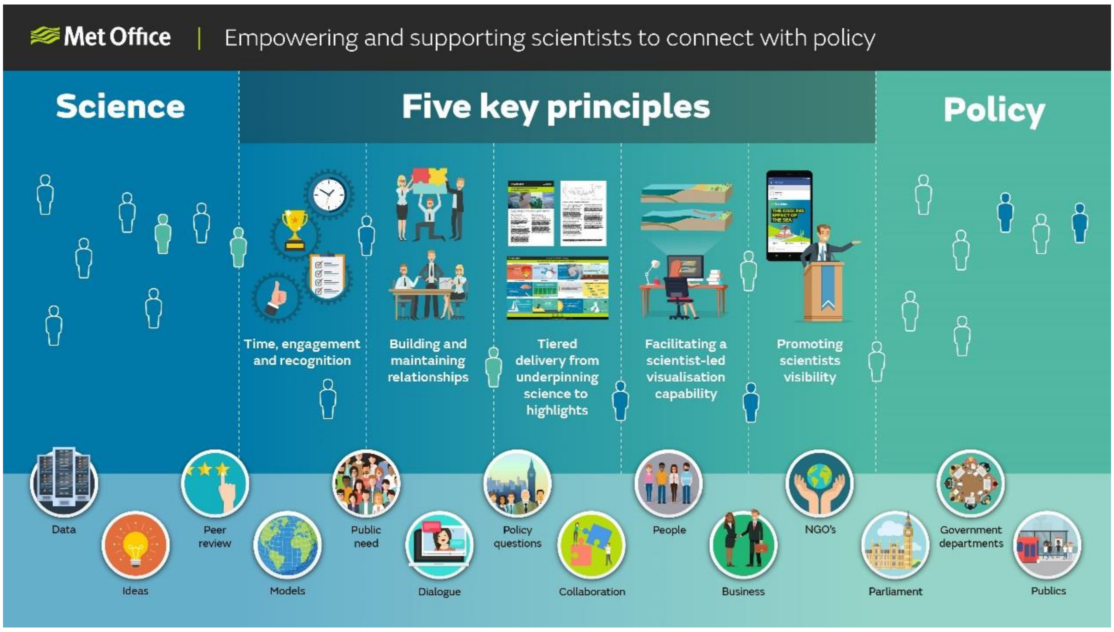
Scientists have both an opportunity, and a responsibility, to actively communicate and translate their science to ensure that the best and most appropriate available evidence is accessible to policy-makers. We propose an approach for empowering and supporting scientists to bring their science to the attention of policy-makers. We present findings from a survey of scientists working within the Met Office Hadley Centre Climate Program; from consultations with organisations involved in the process of translating science into policy, both nationally and internationally; and from a review of the science communication literature. We identify the main challenges in communicating science for policy and explore opportunities to overcome them.

Based on this collection of evidence, we present recommendations for connecting scientists with policy based on five key principles: 1) Time, engagement and recognition; 2) Building and maintaining relationships; 3) a Tiered delivery approach, from underpinning science to highlights; 4) Facilitating a scientist-led visualisation capability; and 5) Promoting scientists visibility. Scientists benefit from support by an experienced scientific communications team to translate and deliver their science and co-develop policy relevant science questions with policy-makers.



34. Communicating Climate Science Through Poems, Songs, Theatre & Visual Art – The Story of "Climate Stories"

Bernd Eggen [1]; Natalie Garrett [1]; Jane Strachan [1]; Peter Stott [1,2]; Pierrette Thomet; Tom Powell [2], Freya Garry [1,2]. and many others

1 - Met Office Hadley Centre
2 - University of Exeter

Poems, songs, theatre & prints are powerful communication media to engage the wider public on important scientific issues such as climate change. We present a kaleidoscope of creations from the collaborative project "Climate Stories".
In May 2018, climate scientists from UK Met Office and the University of Exeter spent an inspirational three days under the lead of artists from the disciplines of creative writing, theatre making, print making and song writing. Through hands-on workshops the scientists were introduced to the narrative possibilities of each art discipline, both for their own creative development and with a view to using them in their outreach work as climate scientist. Participants then chose their favourite arts discipline(s) to take forward into a series of collaborative workshops with community groups in and around Exeter, which produced a stunning variety of responses to the challenges of climate change, through a process of non-hierarchical co-creation. The results have been published in a book, a dedicated web site and YouTube clips. Climate Stories enabled the public, artists and scientists to co-develop new creative approaches to explaining and dealing with environmental change, and the project has wider relevance both geographically and in subject matter, as a blueprint for the development of more effective public engagement skills in the wider science community.
Hear musical outputs from Climate Stories during conference registration and at the 'Earth' themed open-mic night on Monday. Join us and share your stories about climate change, and tweet your drawings, creative writing, or voice recordings to @StoriesClimate.