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CAUSALITY AND COMPLEX SYSTEMS IN THE GEOSCIENCES

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Key messages:

- Geoscientists often conceptualize parts of the world as complex open systems in which nonlinear feedback mechanisms lead to patterns and of which the historic development needs to be reconstructed.
- While geoscientists share the object of their investigations – the Earth, many different approaches and methods coexist to study causes and mechanisms of patterns in time and space.
- Two case studies illustrate how the variety of approaches and methods can lead to confusions and disagreements amongst geoscientists of different disciplines.
- The variety of implicit conceptualizations of causation is one of the factors underlying confusions and disagreements. It is unclear how geoscientists integrate mechanistic and probabilistic ways of causation, and whether this affects how they decompose complex open systems.

Key readings:

- Baartman, J.E.M., Melsen, L.A., Moore, D. and van der Ploeg, M.J. (2020). On the complexity of model complexity: viewpoints across the geosciences. Catena 186, 104261, https://doi.org/10.1016/j.catena.2019.104261.
- Kleinhans, M.G., McMahon, W.J. and Davies, N.S. (2023). What even is a meandering river? A philosophy-enhanced synthesis of multi-level causes and systemic interactions contributing to river meandering. Geological Society, London, Special Publications 540, https://doi.org/10.1144/SP540-2022-138
- Ladyman, J., Lambert, J. and Wiesner, K. (2013). What is a complex system? European Journal for Philosophy of Science 3, 33-67. https://doi.org/10.1007/s13194-012-0056-8
- Wimsatt, W.C. (1994). The ontology of complex systems: levels of organization, perspectives, and causal thickets. Canadian Journal of Philosophy, supp. 20, ed. M. Matthen and R. Ware, University of Calgary Press, 207-274. https://doi.org/10.1080/00455091.1994.10717400

DOI: 10.4324/9781003528937-72

48.1 Introduction

Geoscientists study cause-effect relations for patterns and behavior of phenomena with spatiotemporal scales that range from molecular dynamics to planetary evolution over billions of years. These phenomena involve interactions between physical, chemical and biological phenomena as well as humans and societies. Recognizing and studying 'systems', such as a river system, an ecosystem, the climate system, System Earth and the solar system, is a central practice in geoscience. Indeed, the literature, the conferences and the curricula are rife, if not rampant, with references to systems and complexity. For example, several of the open access Copernicus journals of the European Geosciences Union and the journals of the American Geophysical Union, both of which have a large minority of international members from all continents, mention 'systems' and associated terms such as holism, resilience, tipping points and regime shifts in the description and in their names, for example, the journal Hydrology and Earth System Science (HESS) and the Journal of Advances in Modeling Earth Systems (JAMES). Clearly, geoscientists aim at descriptions and explanations of, and predictions for, the patterns and dynamics of the world or parts of the world that they conceptualize as complex systems. This includes the world or part of it in the past. The planet was so different in many aspects at many points in its five billion year history that it could well be seen as a family of other planets, at some past times with similarities to Venus or Mars. While Earth system science aims to provide unifying models and geoscientists often joke that they study a sample of n=1, the explanations of particular situations in the past remain disunified and historical, with the causes of inherited patterns and dynamics on a certain spatiotemporal scale no longer acting. Prediction is also an aim: recent decades have seen significant changes in how geoscientists study and conceive Earth systems and view the role of humans in them. The coining of the 'Anthropocene' acknowledges this, as does recent research in methods and applications of geo-engineering, such as releasing aerosols in the atmosphere to reduce solar radiation. Geoscience has in this sense three aims: to identify the causes of the planet's dynamics, to uncover the historical development of the planet and to predict its future development (Kleinhans et al. 2005).

Geoscientists could benefit from the methods of history and philosophy of science (HPS), but these are rarely applied because of unfamiliarity with HPS literature (Kleinhans 2021). For example, recognition and critical examination of assumptions underlying knowledge claims and methods of mechanistic and probabilistic causation would benefit from HPS. How much the pluralistic practices of the geosciences are at odds with the beliefs voiced by geoscientists also is quite a relevant question for the education of new generations of geoscientists. Vice versa, geoscience needs historical and philosophical attention, but so far received very little attention compared to, e.g., physics and biology (Kleinhans et al. 2005, Suárez – this volume). Geoscientific examples can be found for all monistic accounts of causality, suggesting that addressing epistemological and methodological questions on geosciences in practice will involve constructing a causal mosaic *sensu* Illari and Russo (2014). The practice of the geosciences is rich in different methods and interdisciplinarity, which raises the question whether the geosciences are implicitly being pluralist about research methods and to what degree they realize this (Maziarz – this volume). Geosciences may therefore be inspirational for research in HPS. As Hasok Chang states in '*Inventing temperature*' (2004, p. 236), 'history and philosophy of science can seek to generate scientific knowledge in places where science itself fails to do so; I will call this the complementary function of history and philosophy of science, as opposed to its descriptive and prescriptive functions'. For example, what geoscientists mean by 'system', 'model', 'cause', 'complexity' and so on, has developed and diversified over time, but geoscientists themselves are not always very clear about their terminology and methods, and I frequently witnessed confusion in conferences and between authors and reviewers, especially from different disciplines, which will be illustrated with examples later.

To paraphrase Chang, this complementary function of HPS is particularly useful where geoscientists do not deal with questions on context-dependence of their findings from probabilistic or mechanistic causation, or with the steer by the historic development of central concepts such as ‘complex open system’ and the role of humans therein, although these issues are relevant to the practice of geoscience. Here I first provide two example cases that illustrate the diversity of methods and the interdisciplinarity in the practice of the geosciences. Then I expand on a central complication in seeking causes and effects: the temporality and historicity of causes and underlying patterns and behavior of geoscientific phenomena at certain scales. Finally, I sketch the variety in ways in which geoscientists conceptualize mechanisms and complex systems, which raises confusion amongst geoscientists and raises philosophical questions about research context-dependence of identified causes and of the implicit conceptualization of causality.

48.2 Two geoscientific examples of research into causes and effects

Meandering rivers have a sinuous, predominantly single-thread channel that is deeper at outer-bend banks. The channel has shallow bars at the inner-bend banks that are likely to become emergent in low-flow conditions, meaning that they primarily develop during floods. The entire channel position shifts over time but generally maintains a constant width and a constant meander wavelength (periodicity) with limited variation. The quasi-regularity of the pattern warrants the search for a single mechanism that causes meandering. This has been investigated with a great variety of methods. Data from many rivers show statistically significant correlations between average channel width, and meander wavelength to some average flood flux and to the properties of the floodplains flanking the channels, such as its cover by vegetation and mud. That vegetation and mud have an effect has been demonstrated by simulations and scale experiments. Perturbation theory based on the physics of flow and sediment transport predict bends and bars to form at wavelengths similar to those observed, depending on flow discharge, bed sediment properties, and channel dimensions, which ignores the floodplains. This illustrates that patterns and dynamics are usually described in causal terms, because the chosen properties are relevant to the phenomenon.

What geoscientists consider a ‘cause’ depends on their methodology, suggesting the existence of a variety of conceptualizations of causality. Kleinhans et al. (2023) expand this for the example of river meandering. Seen through a philosophical lens, it could seem that meander researchers use statistics to gain confidence that the mechanisms indeed make a difference to the pattern and are not merely an effect of the pattern, or have a cause in common with the pattern. This is how the combination of multiple viewpoints and multiple methods for causation is thought to provide stronger evidence of causation (Johnson et al. 2019, Pagliarin – this volume). Many methods were used to study river meandering in the past, exemplifying that geoscience often combines various methods and disciplines (Currie 2018; Bokulich 2021). However, how do geoscientists connect probabilistic and mechanistic causation with cross-disciplinary findings in practice? Many cases can be found, but the meandering case is interesting because the connection is at best partially made. The literature review for river meandering by Kleinhans et al. (2023) suggests that the recent debate on linking the emergence of meandering river deposits in the rock record to the evolution of land plants over 400 million years ago is colored by ignoring or overemphasizing evidence inferred from data, numerical modeling and experimental studies showing that river meandering can arise from other, alternative causal pathways. This leads to the question of what kinds of evidence are acceptable to these different disciplines, and whether such acceptance is related to familiarity with certain methods. Furthermore, Kleinhans et al. (2023) suggest that these alternative sets of causes are INUS conditions for meandering, but at the same time leave open the question which other causal models are implicit in practice in different scientific communities and different disciplines. In other words, it is unclear how researchers integrate in practice between findings from different disciplines, different methodologies, and different spatial and timescales of interest, and what mosaic of causal theories is implicitly laid (Illari and Russo 2014).

Where the example of meandering research focused on a pattern and its dynamics while using reconstructions of past systems, other examples can be found that aim for reconstruction of past climate conditions while using insights from extant systems, models and experimental research. For example, the study of the surface of planet Mars has soared on high with many successful missions in the past decades. A large number of satellites have collected various kinds of global data at as high a resolution as on planet Earth, which sprouted ideas about flowing water on the surface of ancient Mars. Large data are now publicly available (and easily accessible to the public through applications such as Google Mars), but the classic geological dating methods used on Earth remain impossible for dearth of different kinds of data from outcrop studies, fossils and sample analysis (Canali and Ratti – this volume). Robotic landers have tested the waters for various hypotheses about the presence, quantity and timing of fluid water. Much of the interest of the public and science was in fact spiked by the question whether there ever was life on Mars. A lot of research therefore focused on extant channels and deltas likely formed by fluid water, which is thought to be a necessary condition and sometimes even wrongly stated to be a sufficient condition for life. This focus oversimplifies the questions on the origin of life, which differ between scientific disciplines and lead to different approaches (Malaterre et al. 2022). A key factor in the debate on the possibility of extant life is the duration of past hydrological activity because the emergence of life on Earth is thought to have required at least a million years. The latest NASA lander, the Perseverance rover, is currently active in a past deltaic environment (Salese et al. 2020, Mangold et al. 2021). The easily observable size and morphology of the deltas and their upstream feeder channels can be used to infer duration of past hydrological activity, using physics-based models for water flux and sediment supply to deltas. Estimates for the lifetime of deltas in the literature range from months to millions of years, depending on the kind of evidence: that from the aforementioned modeling, from a dating technique based on crater size-density statistics and from the use of analogues on Earth (Salese et al. 2020). This example also indicates a great variety of methods, disciplines and implicit concepts of causality, and controversy regarding the timescale of hydrological activity.

These examples show a need for philosophical reflection on what the roles are of theory, models, analogues on Earth and laboratory experiments in inference and as evidence for hypotheses. What do the knowledge claims imply about what is considered sufficient (combined) evidence to support a causal hypothesis on extraterrestrial phenomena occurring billions of years ago? How are causal inferences and their implicit causal models linked to the disciplines and methods therein of the different geoscientists? The interests and scopes of the institutions to which the researchers are affiliated, such as NASA, may also be relevant in view of the large budgets and great public interest in space aviation and in the question of life on other planets.

48.3 Which parts of past and present planet Earth?

Reconstruction of the past and explanation of the patterns and dynamics must go hand in hand. Earth systems that exhibit hysteresis and tipping points have in practice an intractable history. The development path of complex systems must be recorded or reconstructed from the scant evidence preserved in the rock record, which is what historically oriented geosciences such as geology focus on. One meaning of 'contingency' used in geoscience (e.g., Kleinhans et al. 2005; Phillips 2018) is that today's conditions depend for some aspects on yesterday's and for other aspects on the previous century's conditions, where the latter may be a legacy of very different processes. This legacy effect is far from negligible because the Earth system is sensitive to conditions at the arbitrary point where our path of interest starts. Given slightly different conditions, the Earth system could have developed in many other ways. This is a second, related meaning of 'contingency' (Inkpen and Turner 2012; Phillips 2018): a system's development depends in part on previous states. This partial path dependence is opposed to an isolated system, or a living system, that develops towards some equilibrium state at which it is no longer dependent on its history. For example, a mammal may develop a fever and lose weight, but will, upon recovery, return to its usual body temperature and weight, such that all traces of its illness and its dependence on previous conditions are lost (Simon 1962).

One consequence of contingency and (partial) loss of dependence on historic states is that retrodiction from known causes is impossible and the past must be reconstructed by tracing and combining pieces of evidence (Kleinhans et al. 2005; Currie 2018). The ongoing debate about the existence of tipping points in Earth systems is precisely about sensitivity to conditions around tipping points. This is, for instance, relevant for local ecosystems on the coast or along rivers that may collapse under sea level rise (Thoms et al. 2018). It is also relevant for the global climate system, which has been launched on a path towards an alternative 'stable' state to which humans are not adapted (e.g., Steffen et al. 2020). Unlike lifeforms, Earth systems do not exhibit homeostasis but may have one or multiple quasi-stable states. Geoscientists reconstruct the Earth's contingent history, and closely monitor it through multivariate data collection and analyses to explain how the phenomena came about, and to predict how they may develop.

This leads to the questions whether and how researchers integrate in practice between causes identified in theoretical and experimental research and causes of patterns inferred by geological reconstruction. To address this question, history and philosophy of the geosciences in practice could look at the intersection of experimental and historical approaches to causation of specific phenomena, such as river meandering. The temporality and historicity of such complex systems need not be unique for the geosciences: similar ranges of scales and path dependence may be found in the biological disciplines ranging from cell chemistry to ecology and evolutionary biology (El-Hani et al. – this volume) and in the physical sciences from nuclear physics to astronomy and cosmology (Beisbart – this volume).

48.4 What can complex Earth systems do?

The conceptualization of a part of the world as a system, such as a meandering river, involves putative causes of the patterns and dynamics of interest. By conceptualizing a system and by creating a numerical model or scale experiment, the researchers obtain a representation of an isolated part of the world where they have control over the causes unlike in the real world, for example, the conditions that are relevant to the patterns and dynamics. How the identification of the relevant causes and organization of systems depends on previous knowledge, on various combined methods of causation and on the context and purpose of the research, requires philosophical and historical reflection.

Not only geoscientists are in disagreement about what a complex system is. The philosophical notions of complex mechanism and complex system are related and overlap. A mechanism for a phenomenon consists of entities and activities organized in such a way that they are responsible for, or cause, the phenomenon (Illari and Williamson 2012, Kaiser and Krickel – this volume). Here, Illari and Williamson cover the common ground of alternative previous accounts of mechanisms. The phrase 'responsible for a phenomenon' does not necessarily imply deterministic regularity but can mean diverse things, such as control, behaviors and homeostasis. Mechanisms have feedbacks and inter-level interactions, which are also attributed to complex systems. Indeed, Glennan's preferred definition for mechanism links the two: 'A mechanism for a behavior is a complex system that produces that behavior by the interaction of a number of parts, where the interactions between parts can be characterized by direct, invariant, change-relating generalizations' (2002, p. S344).

Not only philosophers are in disagreement about the meaning of concepts. Geoscientists often call systems and their models 'complex', but a recent questionnaire revealed that geoscientists have no consensus on what they mean precisely by complexity (Baartman et al. 2020). The number of explicitly included processes and their interactions, or feedbacks, are deemed most important characteristics of complex models, followed by processes that 'act over multiple scales', 'number of input variables' and 'nonlinearity of processes' (2020, Figure 3). What 'multiple scales' and 'nonlinearity' mean is usually not clearly stated, let alone causes of the system's organization. On the other hand, the mere complication in the spatiotemporal resolution or the number of equations and output variables are not seen by the majority as characterizing complexity. It is perhaps significant that Baartman et al. (2020) entirely avoid the word 'chaos', often associated with complex systems, pattern formation and nonlinearity, but at present burdened with many other connotations and therefore not considered useful.

The problem of defining complexity is discussed in, e.g., Ladyman et al. (2013). They reviewed characteristics associated with complex systems in the philosophical literature and measures for complexity in the scientific literature. Ladyman et al.'s tentative definition for a complex system is an ensemble of many elements which are interacting in a disordered way, resulting in robust organization and memory. As also implied by von Bertalanffy (1950, 140), the robust, but not static, organization of an open complex system at a certain spatiotemporal scale allows epistemic access to cause-effect relationships between components of the system and between the external conditions and the system's dynamics. But how do geoscientists decide in practice what is part of the system, and what is outside?

When geoscientists identify a system, the causal interactions with the environment are set apart and are apparently considered of lesser importance for the system properties and behavior than the mechanisms within the system. These are the joints where systems are carved out of nature, but how scientists do this is not clear (Kleinhans 2023, Beisbart – this volume, El-Hani et al – this volume). In part, the selected scale of a pattern or timescale of a phenomenon are different from the spatiotemporal scale of the phenomena excluded from the system, including conditions that vary much more slowly, such as tectonic uplift of a valley in which a river meanders, and phenomena that vary much more rapidly, for example, turbulent fluctuations in the channel flow. Where the physical boundary of a living system offers a natural spatial scale, namely, an organism's size and the size of its components and the timescales of its dynamics up to its span of life (Simon 1962), no such an obvious spatial scale exists for Earth systems such as geomorphic systems (Schumm and Lichty 1965; Howard 1965). Earth systems do not accomplish homeostasis but are more clearly open to influences from the surroundings. This implies that the entity that is distinguished as an Earth system has already been decomposed from its greater environment in timescale and spatial scale before it is pried apart by analytical decomposition of its parts (Wimsatt 1994; Bechtel and Richardson 2010). How to draw the boundaries has already been recognized as one of the outstanding philosophical issues in climate science (Katzav and Parker 2018) but the problem has broader scope as it applies to all Earth systems (e.g., Kleinhans 2023): it begs the question whether and how robustness of system organization, dynamics and causation play a role in how geoscientists conceptualize their systems.

Not surprisingly, geoscientists identify, conceptualize and represent their systems of interest with a certain goal, such as explanation or prediction of patterns and dynamics at a certain scale. Research interest, previous knowledge and previous identification of said patterns and dynamics already may limit a conceptualized system. All this may make the causation goal-dependent, which leads to the question whether such systems have a general ontological status that exists beyond the conceptualizer's practice, and whether geoscientists believe their systems to have such general status.

48.5 Conclusion

The geosciences have comparatively little been studied in philosophy of science, except for simulation models in climate science (e.g., Katzav and Parker 2018) and reconstruction in geology and archeology (Inkpen and Turner 2012; Currie 2018). In general, geoscientists strive to find causes of patterns in time and space by various different methods and 'experimental' approaches. Causal hypotheses are in part developed by integration of theory, models, analogue situations, laboratory experiments and by conceptualizing parts of the world as complex open systems. The historicity of the structure and behavior of systems, going back in time to the formation of the solar system and the origin(s) of life, is reflected in the second, 'historical' approach of the geosciences: reconstructions of past causes of radical changes and relevant conditions for phenomena. Two case studies illustrate a large variety of methods and approaches, and that confusions and disagreements amongst geoscientists in different disciplines are rife. This indicates that a variety of implicit conceptualizations of causation exist in parallel. Yet the geosciences are not studied in the causality literature.

The tremendous range of spatiotemporal scales of the patterns and dynamics studied by geoscience and the great variety in approaches, methods, interdisciplinary practices around systems approaches provide a fertile soil to address questions about methods for causal discovery, validation and prediction and about implications of the focus on complex systems. First, confusions amongst geoscientists due to unclarity about terms and concepts could be alleviated by development of the complementary function of history and philosophy of the geosciences. Second, philosophical questions are raised about the context-dependence of implicit conceptualizations of causes and of systems, the context- and scale-dependence of integration between different kinds of data, methods and evidence as illustrated in the case of river meandering, and the possible role of financing of geosciences as suggested in the case of water and life on Mars.

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