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# Viewpoint: Composing complex earth system models

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ABSTRACT

Models of complex systems are built and used to gain understanding of target system properties and dynamics and to mediate between linked theories and observations. Models are particularly useful for earth systems including ecological processes, which have complex properties such as feedbacks, path-dependence, downward causation and tipping points that are not meaningful from the perspective of classic linear causal relationships. In composing such models, how do modellers carve nature at its joints, that is, decompose their complex, multilevel systems into processes, interactions, components and their organization? Two examples illustrate two strategies. The first is to limit the range of spatiotemporal scales by parameterising the smaller-scale processes and by imposing the larger-scale processes in the initial and boundary conditions. The second is to separate physical, biological and other levels. This allows control on the causes, processes, their interactions and organization in order to explore, explain and predict their effects.

## 1. Introduction

What is it we do when we build complex models of earth systems with ecological processes? What do we accomplish with such models? These are deceptively simple questions about the practice of ecology and earth science. It is important to ask them in order to be able to reflect critically on the scope of modelling results, the claims of causation, explanation and prediction. It is also important to address these questions in the education of new generations of modellers. This requires that we have the philosophical skills and concepts to address them (Frigg and Hartmann 2020). Here, I look at models through a particularly useful lens for educational purposes (Kleinhans 2021): the conceptual apparatus of complex systems that we decompose in order to comprehend parts of the world. This will shed light on what parts of the world modellers include and how they deal with what is kept outside the model.

## 2. What is a complex system?

A system is more than systematically ordered knowledge or a system of mathematical equations: it has behaviour and it produces phenomena. A complex system is an ensemble of many elements which are interacting in a disordered way, resulting in robust organization and memory (von Bertalanffy 1950; Ladyman et al., 2013). The persistent activity of a system creates a robust, or resilient order out of the disorder of the environment. Its emergent properties and dynamics cannot directly be inferred from the properties and dynamics of its components, but the order at a certain spatial and temporal scale is what makes it possible to distinguish such a system easily from the jumble of the world (Wimsatt 1994). Without organization and the order emerging from disorder, a system may be merely complicated, such as a gas at equilibrium, which can be studied by statistical mechanics and thermodynamics. Complex systems are open in the sense that matter, energy or information is exchanged with its environment. Having a model allows a degree of control over putative causes and components that cannot be achieved in nature, which allows epistemic access to the cause-effect relationships and dynamics at a higher level of organization without having to model all the small-scale processes (Green and Batterman 2017). As such, models mediate between observable phenomena and theories, such as the Navier-Stokes equations for fluid flow, which produces phenomena that are not accessible without the brute computational force that the models have (Frig and Hartmann 2020).

How to compose a model is to ask what part of the world is to be included in models. In biology, a living organism is a natural spatial scale for which to conceptualise a system, but there is not such an obvious organisation in levels of scale in earth systems or ecosystems. While most present-day earth systems would not exist without interactions with lifeforms, earth systems do not accomplish homoeostasis

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like organisms, but are more obviously driven, or forced, by ‘outside’ influences, or initial and boundary conditions (Schumm and Lichty 1965). Identifying appropriate boundaries for an earth system and its relevant levels of organisation is part of model building practice.

A useful concept for describing such model practices is that of near-decomposability proposed by Simon (1962; further developed by Wimsatt 1994 and Bechtel and Abrahamsen 2010). Decomposition is the breaking down of a system into its working parts, which also clarifies the system’s organization. In a nearly-decomposable system, the interactions amongst the sub-systems are weaker than within, but not negligible. They are weak (hence ‘nearly-decomposable’) in the sense that the short-term behaviour of each of the component sub-systems is approximately independent of the short-term behaviour of the other components. This argues against a bottom-up, physical reductionist approach. Where interactions are weaker, nature can be carved at it seams (see Kyker-Snowman et al., 2022 for a workflow that fits this notion). With decomposition, modellers achieve control by setting a complex system apart from the rest of the world and subdividing the system in parts that produce the phenomena of interest (Wu and David 2002; Bechtel and Richardson 2010). In terms of graph theory, parts can be seen as groupings of linked nodes in a network structure of causal interactions within and between system components (Wimsatt 1994; Bechtel 2017). The parts of the network with fewer links are the seams of nature where scientists can fruitfully carve out a system and decompose it into parts further, but how earth scientists do this in practice if the levels of scale are not obvious, is not clear (Katzav and Parker 2018).

Here I will show by two typical examples that modellers decide what to include in complex models by at least two decomposition strategies. The first is to focus on a window of spatiotemporal scales and exclude the smaller and the larger. This strategy is often made explicit. The second is by disciplinary division between physical, biological, economical and other processes. This strategy often remains implicit and is fraught with the issues of physical reductionism. The example will also make explicit how modellers deal with what is excluded, and what they can accomplish with their models.

## 3. Ecological processes coupled to an earth system model

The meandering river system model of van Oorschot et al. (2022) couples an existing physical model (Delft3D) to a new model for eco-engineering species that interact with the physical processes. As such, the system is composed by coupling of physical and ecological levels (Fig. 1). This model exhibits complex pattern formation and dynamics and has been used to explain why observed meandering patterns hardly emerge without riparian vegetation.

The physics-based model solves the equations of shallow flow on a grid to calculate the flux of sand caused by the flow, and to change the morphology by erosion and sedimentation from the mass balance in each grid cell. The changed morphology modifies the flow pattern in a feedback loop. The model was run for a few centuries with typical time-steps of minutes. Local morphology changes noticeably over days during flood conditions, but formation of bars and cut-off of meander bends takes decades in this river. Small-scale processes of turbulence on flow friction and of sediment movement are deemed unnecessary and computationally expensive details at the level of the emergent meanders and are parameterized, which avoids the problems of micro-reductionism (Kleinhans et al., 2005; Green and Batterman 2017). Ascertaining that such details are indeed unnecessary requires other research. Initial and boundary conditions, such as the valley slope and river discharge peaks, were loosely based on measurements in a real river and on characteristic dam operation regimes. Imposing these conditions avoids having to include the larger-scale hinterland processes, human interference including restoration, the longer-term tectonics and valley formation from the model components, and the rest of the planet (Schumm and Lichty 1965; Bokulich 2021).

In a separate code, functional tree species with eco-engineering properties are modelled. Ecosystem engineering species create and maintain habitats by modulating the availability of resources to their own and other species (Jones et al., 1994; Corenblit et al., 2007). Settling, growth and mortality are affected by physical processes such as inundation duration over the past month. Settling is modelled in spring on surface area where flood water (and assumed propagules) reached.

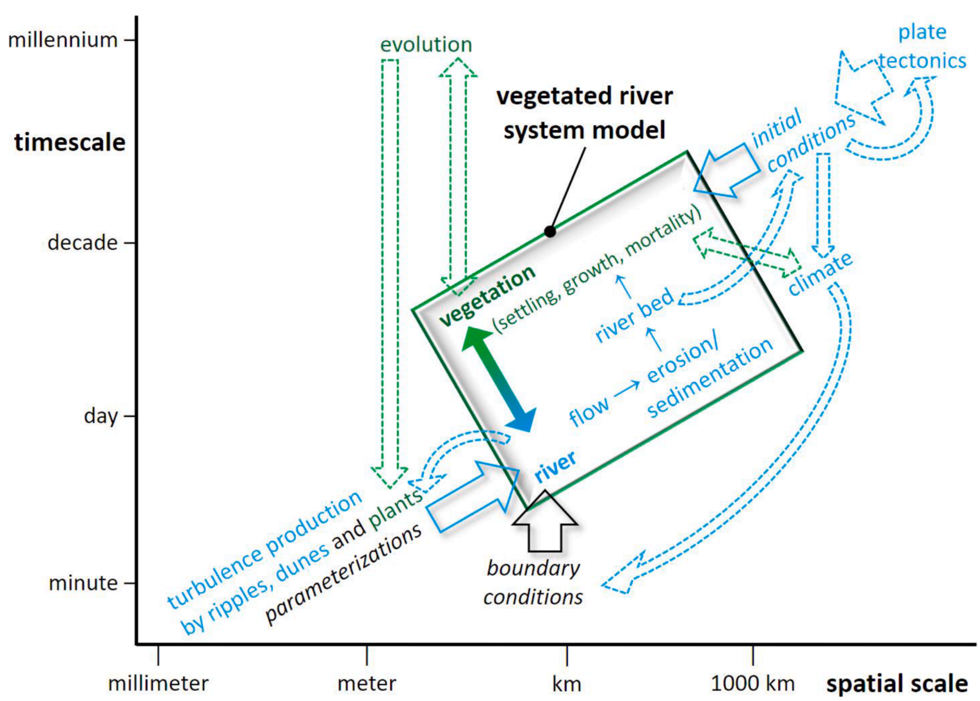


**Fig. 1.** A window of spatiotemporal scales around a bio-geomorphological river system model. Arrows within the window are modelled interactions. Open arrows with drawn lines are causal influences imposed as parameterizations, initial and boundary conditions (in italic terms). Open arrows with dashed lines are feedbacks that were windowed out (see text).

Plant life stage-dependant mortality depends on the flow and on excavation or burial of the roots, and senescence. The ecological model is coupled back to the physical model through flow friction determined by tree cover fraction and size. Flow resistance, caused by sub-grid turbulent flow separation and blockage on stems is parameterized as drag per life stage and added up as parallel resistors in each grid cell. As such, ecology is not reduced to physics, but only physical effects of trees are fed back to the physical model. Thus the river model has two interacting feedback loops: the hydromorphic loop and the eco-engineering species loop (van Oorschot et al. 2022). Collectively, this organisation leads to complex dynamics and alternative river pattern states with eco-engineered habitats, depending on model settings and the chosen boundary conditions.

An analogous, but much more complicated analysis can be done for the Community Land Model 5 (CLM5) component of the Community Earth System Model (CESM) (Lawrence et al., 2018). CESM is used, for example, to hindcast and forecast coupling between plant communities, fertilisation and climate change (Fisher et al., 2019). The CLM5 is composed of twenty-eight complex sub-sub-systems with physical, chemical, biological or human aspects. For example, the sub-sub-system of terrestrial ecosystems was composed separately as the 'Functionally Assembled Terrestrial Ecosystem Simulator' (FATES, Lawrence et al., 2018, section 29.1). FATES simulates the general vegetation type, structure and dynamics; not at the level of species but in a generalized form sufficient to produce the physical effects that are then fed back to other model components. Such generalization allows a global application despite all the smaller-scale differences between vegetation types.

## 4. Conclusion

The examples illustrate the two strategies in practice: the large and small spatiotemporal scales are put outside the scale window of interest, and the physical and ecological levels are separated and further decomposed. The first strategy is often explicitly recognized, but the second is usually implicit. Thus a part of the world, conceptualised as a complex system, is isolated in a model such that it includes the most relevant causal interactions and components for their purpose: studying the target phenomena and dynamics. All models are made with a certain purpose in mind, but they are iteratively improved after comparisons with data, experiments and other models, and conceptually or even numerically connected to, or nested in, models at other scales. Many models also have some redundancy of components and interactions which allows for exploration and discovery of unsuspected effects and application to somewhat different target systems in the world.

The strategies allow for separate control on processes imposed in the model components and their interactions, on parameterised subgrid processes, on causes specified in the boundary conditions, the choice of species and other model interventions that are hardly possible in the real world. Modellers then use this kind of models in various exploratory, explanatory and predictive ways. In the model example above questions were addressed how riparian vegetation or dam removal possibly affects river systems, how global vegetation possibly interacted with atmospheric chemistry and climate change.

The conceptual apparatus of near-decomposability reviewed here can be modified to other kinds of models and will help to teach, communicate and debate views on what models are, what is imposed as cause and what is explained, what we learned from the model construction and application, what they can accomplish and whether it is fruitful to make them increasingly complex, or simplify them further.

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## Declaration of Competing Interest

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## Data availability

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