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How models represent target systems in the world, and how we (need to) communicate this

Maarten G. Kleinhans[1]

[1]Universiteit Utrecht, Descartes Centre for the History and Philosophy of the Sciences and the Humanities, and Faculty of Geosciences, Department of Physical Geography, Princetonlaan 8A, 3584 CB, Utrecht, the Netherlands

Correspondence to: Maarten G. Kleinhans (m.g.kleinhans@uu.nl)

Abstract. Humans are a representing species: we construct conceptual, numerical and material models that represent the world in certain respects. However, how scientists communicate about how their models represent the world, sometimes reflects that it is unclear by what virtue models can represent and can be used to make claims about the world. This becomes most apparent and problematic when models are used to make claims about a target system in communications between scientists, the public, and consultants.

After introducing four example models of different kinds from one geoscientific discipline, recent accounts of model representation from philosophy of science will be summarized and exemplified. Some of these centralize the representational relation between models and their target phenomena, whereas others centralize the role of the modellers in the process of using the model as representation for the target. The latter group of accounts convincingly demonstrate the role of the scientist, their skills and their background knowledge in the representation. This works in both ways: the modellers and other experts put trust in their models, not because the models are perfect, but because they have background knowledge and experience. However, the receiver, with different expertise, does not have this.

Following examples from the geoscientific literature, suggestions emerge how more nuanced claims can be made with models, and which background assumptions on both the modelling and the target systems, and the role of required skills, need to be explicated. While scientists may worry that putting a scientist in the picture could reduce the trust in their model, for effective communication the target audiences need understanding at a level that links to their background and training to be able to evaluate the model results and integrate these with their own experience and knowledge.

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1 Introduction

Geoscience modellers often cite a statement by George Box that "*all models are wrong, but some are useful*" in their papers, presentations, PhD theses and in the aims and scope of the Geoscientific Model Development journal (accessed August 2026). This statement is wrong in both parts. First, models often represent a target system in the world in certain respects but never in its entirety, and sometimes represent something that does not exist in the world. Second, in practice all models are made for use, which is always a useful learning experience, and many models are informative and therefore useful. The modellers citing Box oversimplify an important practice of science that deserves a refined description. Furthermore, many earlier expressions of the sentiment that models cannot be perfect, complete copies of the world exist, such as John von Neumann's reputed statement that "*truth is much too complicated to allow anything but approximations*". The masterful modelling of animal motion in cave paintings made by palaeolithic artists shows that humans have always been a representing species.

Here I address the more interesting questions of how we use models for scientific understanding, explanation and prediction of target phenomena in the world, and by what virtues such models represent and allow us to draw inferences about the target phenomena. This is not to say that models represent, explain and predict the target phenomena on their own, regardless of the user, because that would overstate the role of the tool in science and underestimate the role of experts and expertise. I will therefore also focus on representing by modelling in practice and the roles of scientists in it (while avoiding the false conclusion that "*all scientists are wrong, but some are useful*"). The aim of this paper is to describe model representation such that we can critically reflect on our practices and avoid platitudes. To this end, I will apply theories from philosophy of science to example models of the geosciences. This will require a certain degree of simplification, which can eventually be remedied through improvement of our curricula (Kleinhans, 2021) and the provided references to more accessible philosophical literature.

Various kinds of model representations are included. Figure 1 illustrates several kinds of representations used in the geosciences, namely 'image data' of lion behaviour (Fig. 1a), a sketch modelling the motion of hunting lions (Fig. 1b), a conceptual model for provoking lion behaviour (Fig. 1c), a mostly harmless material scale model wherein a model lion can be manipulated under controlled conditions (Fig. 1d), a modifiable model of a feline animal in an underdeveloped stage, namely a cat embryo (Fig. 1e), here representing linear stability analysis of periodic pattern formation in their initialization stage, and a visualization of a numerical model of provoked lion behaviour (Fig. 1f). All these models represent lions in certain respects, which enables us to use models to mediate between abstract theory and the target phenomenon in order to make inferences about the target(s).

First, I will introduce four different kinds of models to use as examples throughout the paper. Second, philosophical accounts of model representation are briefly explained, grouped by the role of the modeller in the model-target relation, from which implications follow. These are then used as a lens to look at how geoscientists communicate about model representation in publications and in society, first with the example models and then with a small set of papers from several different

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geoscientific disciplines. Finally, conclusions are drawn with implications for reflecting on, and communicating about models.

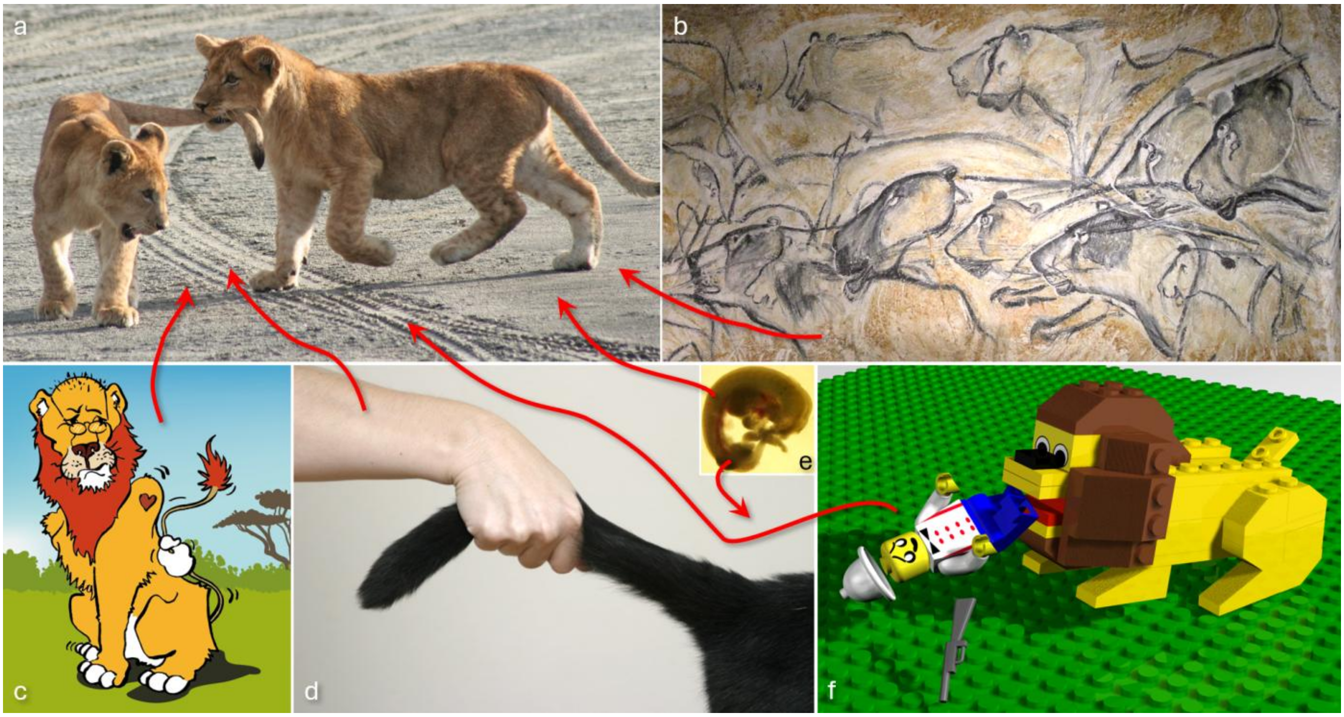

Figure 1: 'To twist the lion's tail' and observe what would happen, as a method of empirical science, is not advised for earth systems because it is dangerous. Instead, we twist tails of model representations of lions (after Kleinhans et al. 2010). (a) image data representation of lions twisting tails in the mating season, (b) sketched representation of hunting lions in a replica painting of the Chauvet Cave art created around 36,000 years ago (source: Wikimedia), (c) conceptual model representation of a lion (misrepresenting the author in certain respects), (d) scale model representation of a lion (care was taken not to hurt the domestic cat), (e) scale model representation of a feline animal in an embryonic stage (after Pieri et al. 2015), (f) numerical model representation of a lion (also representing the author in certain respects). The arrows are curved to emphasize that representation is not straightforward.

2 Kinds of models and some examples

Models are instruments of science that enable interventions (namely, poking the cat/lego/'lion') which would be impossible in their target systems in the world. As such, models enable us to gain understanding, explain and predict behaviours and infer causes of phenomena, to reason about existing theory and to aid in theory development. Simply put: models enable us to play with a surrogate for the target. Unlike the phenomena in the world, we can afford to change the model, break it and so on, from which we learn more easily than we can learn from abstract and mathematical theory on which models are only partly be based. A model is more than a theory made numerical: models can intermediate in many ways between theory and the world and also are a source of knowledge in their own right (Morgan and Morrison, 1999).

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Some models are constructed to represent a specific situation in the world as accurately as possible, such that the effects of an intervention in the initial and boundary conditions or in the mechanisms at play can be used to quantitatively predict the effects of the same kind of conditions, or interventions at a local to global scale, in the specific target system. Alternatively, models are constructed to represent *a kind of* target system, such that effects of imposed conditions or interventions (i.e. causes) can be inferred about multiple target systems. Models can also misrepresent phenomena and behaviours that are unlikely or impossible in the world, for example a flat Earth climate model, or a model of a 'river' delta that receives its water and sediment from a central point source, such that it builds out in 360° by channel displacement in a roughly circular shape. This is possible in a simulation model and in an experiment, but in the world sediment does not rain out of the sky in one location that persistently.

There are many different kinds of models. A helpful classification already shown in Figure 1 covers a breadth that is useful for our exploration of model representation, namely physical (material) models, computer models and conceptual models, which can be qualitative and mathematical models that can analytically be solved. The computer models group is quite diverse, for example with numerical models strongly linked with theory and rule-based simulation models such as cellular automata and agent-based models. To make the issues of representation concrete and clear, I introduce four different models in some detail. All four represent morphology of estuaries for practical reasons (my expertise), and obviously it would also have been possible to select such models representing anything else under study in the geosciences, for example, plate tectonics, ocean currents, lightning, mountain slope ecosystems, glaciers, tube-building worms, and the Jovian moons.

The first case is a numerical model solving hydrodynamics, sediment motion and morphological change on a grid from physics-based and semi-empirical relations and boundary conditions, such as the amplitude and period of tidal water level fluctuations on the seaward end of an estuary and the river discharge on the landward boundary (Baar et al., 2023). The model was developed in the Delft3D suite to represent in an idealized way a kind of estuary with freely migrating bars and channels. The authors studied the morphological effects of different combinations of river discharge, tidal amplitude and initial width. The results were shown as maps of the morphology, timeseries of measures for bars, plots of such measures in relation to the imposed boundary conditions, and a conceptual plot qualitatively summarizing the system behaviours.

The second model reduces an entire system to a set of mathematical relations that can numerically be solved (Townend et al., 2016). The authors call it an aggregated model and it could also be called a reduced complexity model. It is conceptually built on a mass balance of a few compartments with elevations defined relative to the low mean tide and high mean tide, such as 'channel', which is subtidal, 'tidal flat' and 'ebb delta', which are usually intertidal, and 'salt marsh', which is supratidal. These compartments are in a near-equilibrium state and exchange water, depending on the storage space between high tide and low tide, and sediment, depending on the degree of morphological disequilibrium and on the water flux. The physical relations used in the model are in part the same as those in the first (model). The model was applied to the Humber estuary on the east coast of England and compared well in volume with the partial infilling during part of the Holocene as reconstructed geologically. This was shown in a figure as a timeseries.

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The third case is a conceptual model for the development of tidal systems under changing conditions, which was inferred from reconstructions of Holocene tidal systems and literature (de Haas et al., 2018). The models is presented as a causal loop diagram of processes and feedbacks, that depend on the coastal and fluvial boundary conditions, the paleo-relief before development, presence of floodplain-forming mud and plant species, and human interference. It is intended to enable qualitative explanation of the possible development paths that a tidal system can follow, and as such explains similarities and differences between the different kinds of tidal systems of which reconstructions were discussed.

The fourth case is a physical model for the development of experimental estuaries in a laboratory setup at a scale of 1:2000 (Kleinhans et al., 2022). To obtain alternating currents characteristic of tidal currents, the flume, called the Metronome, was tilted periodically. The aim of the experiments was to determine the system-scale effects of floodplain formation in a kind of estuaries, namely sandy with bars and channels and situated in coastal lowlands. The materials were tap water, coarse sand, and, added for floodplain formation, added crushed nutshell in one experiment and plant sprouts in another. This kind of material model could be called analogue model or scale model though several classic engineering scale model rules are violated, the effect of which the authors discuss. The results show a positive feedback between floodplain formation, channel- and bar morphology and the overall estuary dimensions and the authors argue that this confirms the long-term development in the presence of mud and plants as hypothesised in de Haas et al. (2018).

3 Model representation

Here we employ philosophical accounts of model representation. Philosophers of science debate representation in order to unearth what scientists do in practice, and what is defendable, and as such produce a useful but under-used complementary science. For our purpose it suffices to distinguish between two groups of accounts of model representation (see overviews in Frigg and Nguyen, 2021; Nguyen and Frigg, 2022). The first group interprets representation in terms of some correspondence relation between the target system in the world. Such relations can be, for example, dynamic similarity in experiments and isomorphism of mathematical equations describing alternative stable states of complex systems. The second group grounds the representation in the modeller, who has a purpose with the model and uses it in a representational relation with the target. This may involve recognizing features in the model and the target and mapping these between model and target. In this section, both groups of model representation will be explained and illustrated. As philosophical debates rarely get settled on a final answer, the purpose here is not to enter the debate, or to determine which account geoscientists should adhere to, but to learn from the breadth of these accounts how to be more nuanced in our claims about models and their targets in the world.

Not all representations are model representations. For example, figures, statues and three-dimensional maps are, in this sense, not models. They represent certain phenomena but do not allow interventions, which I foregrounded in the previous section as an important property of a model. For example, the plots summarizing causes and effects in the model runs of Baar et al. (2022) are not a model in themselves, because neither the conditions nor the mechanisms can be intervened upon

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to produce different phenomena. Likewise, the timeseries of palaeogeographical maps of the coastal lowlands based on geological reconstruction, which de Haas et al. (2018) use for their conceptual model construction, is not a model. Of course, when one runs water over a three-dimensionally printed elevation map to explore, for example, fluvial and coastal flooding in a low-lying country (such as the Netherlands), then the map is used as part of a physical model, which includes the water supply (preferably controlled by primary school pupils for more fun). A digital twin is not clearly a model, because, while it enables interaction with a dataset representing a select set of phenomena, the data do not change upon intervention unless the digital twin has a working model embedded. To be pedantic, the term digital twin is an oxymoron, because a limited, digital representation of the world cannot be a twin of the world (with which the higher authorities George Box and Douglas Adams would undoubtedly agree). Representations that are not based on models are therefore left to the side in the brief summary of philosophical accounts below.

3.1 Model-target correspondence by similarity and isomorphism

Dynamic similarity is established by showing that a certain set of dimensionless ratios of relevant forces that characterizes the dimensions and behaviour of the two systems, is quantitatively the same (within a certain range) in the model as in the target system (Sterrett, 2002; 2017; Weisberg, 2013). For example, cats and lions have disproportionally different weights and bone diameters, such that the ratios of bone strength and pressure needed for fracturing are similar. Likewise, the ratio of the force (per unit area) of the flow and of the gravitational force on the sand particles in the experimental estuary is the same as that in the target estuaries. Note that such similarity does not imply that the target system's materials must be used in experiments. For example the suspended mud of estuaries is represented by crushed nutshell in the physical model case. Dynamic similarity is accomplished in a dimensionless sediment mobility number for the suspended mud, based on its submerged weight and the force of the flow. Likewise, material models for mantle flow and lava flow use viscous material with a much lower melting point than in the target systems, such as candle wax, and are scaled by a dimensionless ratio, the Reynolds number, of inertia of flow over viscosity. The dimensionless ratios, including the relevant length scales and timescales, are used to calculate dimensional quantities deemed valid for the target from the outcomes of the model.

Exact similarity is in practice often not achievable, notably when the same important variable occurs with different power in different dimensionless parameters that cannot both be kept the same at the small experimental scale. In such cases, choices are made which parameters are prioritized and other parameters not considered causally relevant are ignored. However, scale effects arise: some force ratios are not identical between model and target system, and the resulting deviations can be accounted for in many engineering scale models (Weisberg, 2013; Sterrett, 2017). In this sense, it is useful to describe in what respects, and to what degree, the similarity holds, also because model design should account for the aims of the modelling (Giere, 2004). The degree of similarity could be cause for academic debate, but the often-cited review of material models by Paola et al. (2009) was mounted as a defence against criticism and even rejection built on dogmatism in a community using engineering scale models. In another community, namely tectonics, analogue modelling is considered on equal footing with numerical modelling.

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The representational relation between model and target is different for mathematical models, such as the numerical estuary model case (Baar et al., 2023) and linear stability models for periodic morphological patterns such as estuarine sand bars. These are essentially mathematical structures. There is nothing essentially physical about these models, except when the results are interpreted for the target. The model represents the target by having an object for each object in the target and by having mathematical relations between all objects. Having corresponding objects and relations makes the model isomorphic to the target. A classic example is a Newtonian representation of the solar system used to calculate positions and speeds of the planets, where the planets are the objects linked by a mathematical relations derived from Newtonian mechanics. The second model case (Townend et al., 2016) is also a clear example, with the compartments, e.g., 'channel' and 'tidal flat' being the objects and the mathematical relations representing fluxes and masses linking them. The conceptual model of de Haas et al. (2018) likewise has objects and relations, though here the relations are not in the form of mathematical structure but as a graph. A numerical model is obviously different from the mathematical structure. Numerical models such as the solver of flow, sediment transport and morphology of the first case, are computer-run algorithms based on mathematical relations such as the shallow flow equations representing the object 'water' as a continuum, but adapted for numerical discretization, numerical stability and efficiency on a grid.

3.2 Model, target and the scientist in the picture

So far our cat, and the cat embryos, would seem to offer an optimal combination of material similarity and dynamic similarity with the lion, allowing experimenters control on small genetic and conditional differences, causally interact with many replicates, test hypotheses and thus represent feline species. What emerges in this toy example is that the modeller's purpose of what particular respect the model animal is to represent, determines which respects, both material and dynamic, may be relevant in its design and use and therefore matter for the representation (Giere, 2004; Suárez, 2024). Geoscientists, whose hands are not that invisible in Figure 1, have to make many design decisions on material composition, which causal variables and what physical theory to select, which dimensionless parameters to quantify and where to allow concessions in the dynamic similarity. Likewise, they designed numerical models for specific purposes on which many choices depend concerning inclusion of mechanisms, feedbacks and conditions as well as parameterizations and numerical aspects. The absence of the actor/modeller makes the dynamic similarity and isomorphism notions of representation too restrictive.

The second group of notions of representation clarify how the agents that make the decisions partake significantly in the representational process (Frigg and Nguyen, 2021; Suárez, 2024). This may seem obvious but it has wide-ranging consequences. For one thing, it portrays knowledge not as a thing stored in papers, but as a process that involves agents.

The simplest version states that a model represents a target when 1) a model *denotes* a target, 2) an agent *demonstrates* something with the model, and 3) the results of this demonstration are *interpreted* to apply to the target (Fig. 2). These three steps, denotation, demonstration and interpretation (DDI), are best illustrated with the second case: the conceptual-analytical model of Townend et al. (2016). First, Townend et al. denote the Humber estuary with their model. Second, they used the model to demonstrate (D) a response of the depth distribution and the sediment balance between the model compartments to

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imposed sea-level rise. Third, these results are interpreted (I) to apply to the Humber, for which the changed depth distribution of tidal channels, flats and saltmarshes is calculated. The role of the modeller in this third step is to interpret the model outcomes for a claim about certain properties of the estuary.

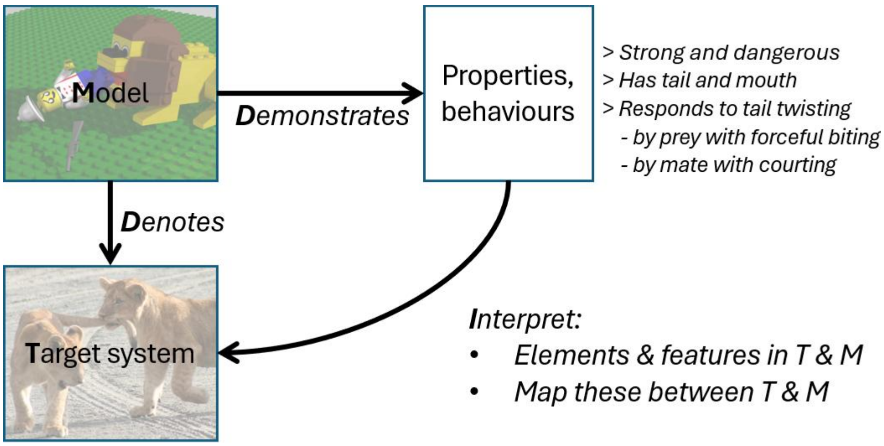

Figure 2: Illustration of model representation foregrounding the roles of the modeller.

A more recent account is that of Frigg and Nguyen, who argue that the interpretation step in the DDI needs further work. For them, a scientific model represents a target if four relational conditions are satisfied: denotation, exemplification, keying up of properties, and imputation (DEKI). The estuary model *denotes* the Humber estuary because its properties *exemplify* some properties of the estuary that are *imputed* to the target through a *key* that translates (or maps) the exemplified properties of the model to properties that can be ascribed to this target. Like the DDI account, the representational process is not only about dynamic similarity or isomorphism, but also about exemplifying, mapping and ascribing by an agent. It is the modeller who turns the model into a representation of an estuary by interpreting selected morphological properties as properties of the estuary. Compared to the DDI, the DEKI specifies the interpretation and inference in terms of imputation through a key (see Frigg and Nguyen, 2021). This key is best illustrated with the fourth case: the experiments of Kleinhans et al. (2022), which has no exact material correspondence between the mud flats and saltmarshes in estuaries. Instead, crushed nutshell is used to represent mud and sprouts of plant species that prefer dry habitats are used to represent saltmarsh vegetation. This is not to say that the experimenters believe that mud and vegetation are represented in all respects (that would be, well, nuts). The key used to map bars, channels and shape of the model on the target system is the geometric scale number. The key used to map nutshell deposits and vegetation cover of the model onto the target system is the relative location, not only along the model and target estuary but also relative to high water levels in the model and the high tide level in the target. These 'mud' and 'plant' properties are demonstrated, and not designed before the experiment, because their eventual effect in the experiments depended on complex interactions between several processes. The experimenters had good reasons to expect these effects

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based on earlier experiments with meandering rivers and on auxiliary experiments wherein mud and plants were studied in isolation from the hydrodynamics and the channel and bar dynamics.

The examples illustrate that model representation, even by these accounts, do not solely depend on agents with intentions. Acceptable justification of inferences about target systems requires that the modellers have good reasons to think that the keys cover relevant similarities or isomorphism for their purpose. Moreover, the modeller needs informed and skilful judgement to recognize the relevant respects of similarity and draw inferences about the target from the model. In practice, the recognition by a modeller that a certain model can be used for representation often develops synchronously with the development and inferences from the model, as illustrated in the experiments case.

While the philosophical debate continues, an important conclusion for the geosciences already emerged: model representation involves agency of the modeller, which implies that the training, skills, background knowledge and purpose of the modeller are highly relevant. To what degree this is communicated, and what the consequences are for the practices of science and societal interaction, will be discussed next.

4 How we communicate about models

While most modellers know the limitations of their model representations, the communications about the models in conferences, publications and consultancy contexts often strongly suggest the model-target correspondence is justified by similarity or isomorphism alone. As a result, background knowledge that contributed to understanding and trust in the model for the modeller, may remain obscure for others. I will argue that this is detrimental to science, public engagement, public affairs and consultancy, but first I will present evidence of such communication lest the reader could argue that I have set up a strawman fallacy. In many coastal modelling papers best not referenced, I found sentences such as "*The model is shown to perform well in several theoretical, laboratory, and real life situations*" and "*The simulations show that the intertidal flats in the* […] *Sea are very sensitive to the sea-level rise rate*". In these examples, it is the model that performs and shows how 'reality' works. With the previous section in mind, this raises many questions, such as who sets the standards for performing well and for what purpose (e.g., coastal defence), are there conflicting interests with other purposes (e.g., ecosystem integrity), and by what virtues of the model do the modellers infer the effects (of sea-level rise) on the target system (which is much more complex than the model). Why academic geoscientists and other experts (such as in agencies and consultancies) communicate like this, I cannot address here, but it can be hypothesized that use of the passive tense is thought to impress that the agent's roles in modelling are marginal, suggesting scientific objectivity, which is at least problematic and likely impossible. If correct, then we can already improve communication by writing in the active tense.

4.1 Model representation in peer-reviewed publications

First, the four cases will illustrate how the model representation is often communicated in publications. (I disclose that I was involved in two of them and I am familiar with the others.) Townend et al. (2016) made a direct link between model and

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target with their aim: "*to explore the bulk morphodynamic changes (in terms of volume change) of large-scale estuarine and coastal systems over relatively long term*". They also suggest that "*Adding more complexity, these extensions widen the application possibilities of the model and make the model more realistic*", which implies a claim that it is already realistic without specification in what respects and to what degree.

Baar et al. (2023) also step over the representational relation by directly linking model results to their target, a kind of estuary: "*The results show that estuaries with a peak tidal-to-river discharge ratio higher than 10 can adapt to an increase in river discharge by adjusting the channel dimensions and braiding index to the combined tidal and river discharge.*". They report on the sensitivity of model results to a particular parameter value (A_{sh}): "*a lower* A_{sh} *value is needed in morphodynamic models to increase downslope sediment transport and thereby counteract unrealistic grid size-dependent incision*". This refers to a problem that for a physically valid value of the parameter (as determined by experimentation), the model misrepresents behaviours of the target systems. As such, the behaviour was calibrated for empirical adequacy using expertise and experience, on which the representational relation critically depends.

Haas et al. (2018) also make a direct link between model and target: "*a conceptual model portrayed as a causal loop diagram denoting the interaction between the most important processes and feedbacks controlling the evolution of tidal systems*". Here, the specification of relevant elements and features and how they are mapped onto the target is implicit and the result of abductive inference from geological reconstruction and literature.

Finally, Kleinhans et al. (2022) goes as far as to claim that the physical 'models' are in fact real estuaries, though at a very small scale: "*Three estuaries were formed in experiments in the Metronome*". Ignoring the interpretive steps in the representation altogether, they then draw a general conclusion about the kind of estuary represented in the experiments: "*Where the more protected flanks of the estuary fill up with fine sediment and vegetation, the tidal system is effectively constrained and reducing in dimensions as observed in reconstructions*". Here, the reconstructions is an explicit reference to their background knowledge such as published in de Haas et al. (2018). At the same time, the experimenters, like all modellers in the other cases, show awareness of respects in which the target is not represented in the model: "*In nature, the calm hydrodynamic conditions in salt marshes could be conducive to organic matter production and storage leading to organogenic rise of the bed surface*". This illustrates that the authors must have at least an inkling of the fact that the representational relation involves the modeller's agency.

An informal survey of some recent papers using modelling was conducted to assess how many recent studies formulate their representational model-target relation with and without modeller's agency. In total 52 extra papers were scanned for anecdotal evidence in a number of EGU journals, namely Geoscientific Model Development, Climate of the Past, Biogeosciences, SOIL, Earth Surface Dynamics, Solid Earth, in the AGU Journal of Advances in Modeling Earth Systems and in the Copernicus journal Wind Energy Science (see supplementary information). An in-depth discussion of different kinds of models and experiments is beyond the scope of this paper. Some papers model specific targets and suggest generalization of the inferences to other targets. Other papers model a kind of target. Some papers, especially those in the journals for model development, focus on model behaviour and sensitivity and also address results that they consider unphysical and not likely at all to occur in their kind of target system. All papers address shortcomings and future improvements. Furthermore, about three quarter of the set concerns numerical modelling, whereas one quarter concerns experiments. These are most frequently reported in the three journals Solid Earth, Earth Surface Dynamics and SOIL, sometimes combined with numerical models in a single paper. The two journals Soil science and Biogeosciences also had field experiments where some control was possible such as in mesocosms, that allowed for intervention, on conditions considered statistically representative for a large system.

Some relevant observations are as follows. All papers with numerical models appeared to use an isomorphic representational relation and all papers with experiments appeared to use similarity of physical or chemical dynamics. Formulations how inferences were made from the modelling about the target are often nuanced. In less than half of the papers, the authors apply their model inferences directly to the target, stating model objects and behaviours in the same terminology as the target. This happens more frequently in experiments, suggesting that the authors consider the representation through similarity sufficiently dealt with in the methods section. It also happens frequently in mesocosm experiments, suggesting that the authors consider a direct representational relation of their target by the experiment that is in fact situated within their target.

Most importantly, only two papers showed minor signs of communicated author agency: a case in hydrology (Reinecke et al., 2026) and one in coastal hydrodynamics (Li et al., 2026). The authors of the hydrological paper aimed to leverage global water and climate models through model intercomparison, intended to increase robustness of predictions and identify uncertainties for societally relevant issues and end the paper with a vision how they intend to accomplish this with their community. In the coastal paper, which is about interaction between two water bodies, such as mixing of saline and freshwater, the authors explicitly disclose their background knowledge in the conclusions section. This is not to say that other papers do not disclose this information, but there it is usually implicit in the citations of earlier work. As such, the communications are entirely focussed on model results, while background knowledge remains at best implicit and more generally opaque.

4.2 Model representation in public affairs, public engagement and consulting

Several papers scanned in the previous section mention a potential societally relevant application, for example in risk management. An analysis of consultancy reports is well beyond the scope of this paper and would also be risky, but here I believe we can proceed with experiences and literature. It goes without saying that models and model results are used often in public affairs, consulting for management and infrastructure, and also often play a part in public engagement (e.g., Lane, 2014; Reinecke et al., 2026). It does not go without saying that the audiences trust models: they may trust them too much or too little, as has been extensively researched for communicating climate model results (e.g., Akerlof et al., 2012). This is at least in part because they do not have the background knowledge and modelling skills to assess the respects and degrees in which model results are useful.

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I illustrate the lack of trust due to not having the skills with an anecdote. A decade ago I received an invitation for a parliamentary committee on environment and infrastructure to discuss the role of scientific models in national policymaking, starting with the statement "*As long as models are not complete representations of reality yet, they cannot be used for policymaking*". Basically the anonymous civil servant (often academically trained in the Netherlands) who prepared the meeting was not ready to believe in a scientific model unless it were a perfect representation of the world. If one took only the model as the carrier of knowledge, this is a fair point, because it would be like asking a religious person to believe that a statue *is* the god. Not even the Greeks and Romans, who were prolific god conceivers and statue makers, believed that (Gupta, 2014). The common position of this civil servant throws a strong lion baby out with the bathwater.

Scientists, on the other hand may sometimes have too much trust in their models (also see Chamberlin, 1890). Oreskes et al. (1994) argued that models for complex open systems such as studied in the geosciences can at best partly be confirmed. This is because their results depend not only on boundary conditions, choices of relevant variables and parameterizations (also see Lane, 2014), but also on calibration which forces it to have empirical adequacy for the calibration conditions but offers no certainty that the model is verified and validated. Oreskes et al. raise the questions "*How much is based on observation and measurement of accessible phenomena, how much is based on informed judgment, and how much is convenience?*" and answer with the point echoed in this paper: "*In areas where public policy and public safety are at stake, the burden is on the modeller to demonstrate the degree of correspondence between the model and the material world it seeks to represent and to delineate the limits of that correspondence.*". Lane (2014) argues along similar lines for hydrological modelling, of which the level of uncertainty depended critically on historic data and a parameter that is conceptually impossible to determine from observation or physical principles alone.

Based on the accounts of model representation, it has become obvious that knowledge is not carried by the models, but by the scientists who use the models as tools in combination with background knowledge and other forms of expertise. Therefore it is necessary to communicate some of the background knowledge of the modellers on which their understanding and trust is based. This is, fortunately, not a novel idea but has been experienced in many science-society interactions. Lane (2014) recounted cases of hydrological modelling involving experts and previously flooded communities.

This paper needs a case in an estuary: the Ems-Dollard estuary, which has a major water quality issue of high mud concentration, in part due to channel deepening. A large governmental program has been developed in the past decade. Ideas to remove mud from the system were studied with a numerical model, but at the same time another question was also addressed by long-term modelling: how much of that mud is needed for sedimentation to keep up with future sea-level rise, in order to maintain valuable intertidal habitat area. The question persistently on the table was, of course, in what respects and to what degrees this model could be trusted to represent the estuary. The academically educated project leader for the government knew that models can also produce nonsense, but was unable to understand why certain choices were made that led the model to reproduce past estuarine developments acceptably to the modeller. Fortunately, in this setting of the hydro-sociological setting (in the sense of Lane, 2014) comprised of this specific estuary, the technology and policy of the region, the trust has been built up over considerable time by a large community of scientists in academia, research institutes,

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consultants and the governmental institutions responsible for the estuary and many other systems. Moreover, multiple kinds of models are combined and new measurements are conducted and some concrete plans and changes in policy begin to emerge. Regional managers of the estuary have worked on public engagement from the very beginning of the project. Both project leader and modeller (and myself as intermediator) knew much about the past developments, which enabled insightful debate where background knowledge was contributed, but the question of trust in the model ultimately devolved into a question of trust in expertise.

5 Conclusions

I conclude that the philosophical accounts of model representation offer the conceptual apparatus to improve reflection on, and communication about, model construction and model use in the practices of science and science-society interactions. In a nutshell, it is helpful to indicate precisely in which respects and degrees a model represents a target or a kind of target, because that indicates the scope and limitations. One could furthermore specify precisely which model properties are compared with what target properties in terms of similarity or isomorphism.

Moreover, the context and the roles of the modeller in the representation need to be highlighted. Some philosophical accounts of model representation pointed at the need for informed and skilful judgement of the modeller, which, while in itself unsurprising, highlights an extremely important aspect of model use. Know-how, namely skill in construction and use of all kinds of models grows with education, 'play' and experience. Likewise, being informed refers to relevant theory and observational experience in the target system. For example, in the cases of Townend et al. (2016) and Kleinhans et al. (2022) the comparison with geological reconstructions was essential for the representation and for gaining trust in the modelling. The conceptual model of de Haas et al. (2018) was to a large degree based on geological reconstructions and the case of Baar et al. (2023) was indirectly linked to geologic background knowledge through the literature references.

So far, this pertained communication within science, but the previous point easily extends to communicating model to other audiences, who have different skills and background knowledge. These should be taken into account in science communication by including the necessary background knowledge of the modeller that was needed for the modelling study. For example, such audiences may gain understanding of, and perhaps trust in, the experimental model and the numerical model when the process of modelling is illustrated and the results are shown to resemble the geological reconstructions sufficiently in relevant respects. This point is an extension of the well-known need to explain the concepts used in the communication because they may likely mean different things to audiences outside one's expertise (e.g., Venhuizen et al., 2019). It is also an extension of the empirical finding that acceptance of science communication increases with knowledge about the nature of science (Weisberg et al., 2021). Altogether, this analysis hopefully helps to improve our communications about model representation and the impacts this has.

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Supplement link

The supplementary material provides a spreadsheet listing the journals and papers scanned for section 4.1.

Competing interests

The author declares that he has no conflict of interest.

Ethical statement

The research proposal and protocol for this study was in line with the policies of the Utrecht University's Science-Geo Ethics Review Board. No human subjects were involved.

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Review statement

The review statement will be added by Copernicus Publications listing the handling editor as well as all contributing referees according to their status anonymous or identified.

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