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Digital Twins of the Earth Between Vision and Fiction

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Abstract
Digital replicas (or twins) of the entire planet and of its inhabitants are being actively proposed by the research community for a variety of purposes, with a focus on climate adaptation and mitigation. Since mathematical modelling is at the core of this digital enterprise, we undertake to explore the possible limits of models in creating twins of the Earth by recalling some of the existing visions about the nature and function of mathematical models. We thus discuss what models are, what their function is in relation to the production of knowledge, and how one can question if a model is fair, by keeping the digital twins as the focus of our analysis. This leads us to discuss the way models intervene in the democratic process and orient power toward those who wield the models, and what these artifacts represent in the context of governance of science itself.

Keywords Sociology of quantification · Ethics of quantification · Mathematical models · Simulation · Modelling · Governance · Democracy

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Introduction

A definition of Digital Twins (DTs) is offered by IBM, for which (IBM 2021):

> A digital twin is a virtual representation of an object or system designed to reflect a physical object accurately. It spans the object's lifecycle, is updated from real-time data and uses simulation, machine learning and reasoning to help make decisions.

The journal Nature Computational Science has devoted in March 2024 a special issue to DTs (Editorial 2024). The editorial, entitled "Increasing potential and challenges of digital twins", spans the myriads of applications of DTs, from the classic applications to process and product optimization in manufacturing to new uses in aerospace technology, biomedical science, urban planning, earth sciences and climate change. More accurate weather and climate predictions achieved thanks to DTs of the planet itself are an important motivation for this special issue, due to several ongoing projects designed to link mathematical modelling of oceans, atmosphere, biosphere and humans with their economy via sensors, buoys, mobile telephones, realizing the ultimate model that will allow detailed prediction of climatic impact on the environment, health and the economy (Bauer, Stevens, and Hazeleger 2021; Rao et al. 2023).

Mathematical models can be extremely successful in solving both theoretical and practical problems, following what physicist Eugene Wigner called "the unreasonable effectiveness of mathematics". While Wigner's mind was on quantum mechanics and particle physics, there is no human endeavour where models cannot find their way (Rockmore 2024), with results at times both surprising and momentous. And yet, with every success comes the risk of abuse. '*Any artifact will have: intended use, creative new use, incompetent misuse and malevolent abuse'* in the words of philosopher Jerome R. Ravetz (2017). Where do the DTs of the planet fall in this rudimentary taxonomy?

In a recent work (Saltelli et al. 2024), a group of authors from different disciplines take issue with the transition from weather forecast to climate change, prediction and mitigation, all developments presented as natural by the advocates of DTs of the Earth. We extend this critique by recollecting to previous works on responsible modelling, where it was argued that models can be 'overinterpreted and underexplored' (Saltelli and Di Fiore 2023). We perceive elements of overinterpretation in the way the project is being presented by its proponents, and feel that not enough public debate has been had on the topic. Therefore, we propose to follow a philosophical trajectory moving from the ontology of models (what they are) to the epistemology of models (how they are or ought to be used to generate knowledge), and finally, to the ethics of models (how they are or ought to be used for some form of common good). It is evident that an enterprise as momentous as the creation of digital twins of the planet cannot be without consequences on the balance of power for the involved humans. Korenhof *et al.* (2021) note that the twins are not just descriptive of the system, as alluded to by the proponents with adjectives such as 'high fidelity', but predictive and prescriptive, orienting the action of the actors on the system. For these authors, addressing the present ambiguity should reveal the non-neutrality of the artifact; as steering devices with potentially cybernetic features, DTs are likely to favour some actors and disfavour others. Who does the steering becomes an important question. Like artificial intelligence, which is invoked as a component of the twins, DTs risk to favour technocratic forms of prediction and control that are antidemocratic (McQuillan 2022).

What are Models? Implications for Digital Twins

Through literature and fiction, we know that models inform our collective socio-technical imaginaries, understood as visions that a society holds about the relationship between technology and social life, and how these visions shape expectations about progress (Jasanoff and Kim 2015). Models modify power relations, which is paradoxically obscured when the epistemic authority of models is ascribed to their neutrality. Models represent - in the context of scientific activity - a case on its own, where communal norms of verification and control appear more problematic than in other areas of scientific endeavour (Saltelli and Puy 2023).

Visions of models are offered by practitioners, historians, and sociologists. We briefly and selectively mention a few, and discuss how these relate to the development of Digital Twins of the Earth.

The World in the Model – The World in the Twins

As noted by Mary S. Morgan, describing what models are is not an easy task (Morgan 2012). For Morgan, models constitute an epistemic genre apart. Model creation and model use involve a double process of discovering 'the world in the model' – how the parts in the model act in relation to its characteristics, and 'models of the world', where the world is looked at through the lens of the model. Morgan is especially concerned with models used in economics, and the models discussed in her work lend themselves to be looked inside (the world in the model step). One can appreciate how crucial this looking inside the model is for the same modellers – economists in Morgan's case, by reading how Ricardo's model farm and Edgeworth box – two among the earliest models – came into being (Morgan 2012: 44–135).

According to Bauer et al. (2024), in order to make sense of the immense petabyte output generated by DTs, users may resort to pretrained-machine learning tools such as chatbots, to interrogate them using natural language. The world in the DTs would thus be illuminated with machine learning algorithms – one obscurity shedding light on the other. For Brian Wynne (1984: 311):

> Whether deliberately conceived and used in this way or not, big modeling can be interpreted as a political symbol whose central significance is the diseducation and disenfranchisement of people from the sphere of policymaking and responsibility.

Models as Cultural Artifacts

In her foreword to a volume on the politics of mathematical models, Wendy Espeland suggests that we look at models as cultural forms (Espeland 2023), following the theories of Georg Simmel. We can thus see models as subject to the tragedy of "modern life: a dialectical relationship between our capacity to produce a dazzling array of cultural forms, and our inability to assimilate them in ways that enrich our lives and cultivate our humanity". Models are after all a relatively 'new' fashion. "Mathematical model" as an expression to mean something related to mathematics and software was first seen in the 30's according to (Morgan 2012), and boomed in the public language around the late 50's early 60's, possibly in conjunction with the diffusion of mainframe computers. Still in 1951, a very popular book entitled 'Mathematical Models" was in fact about *physical* models (e.g. of paper or card) of geometric solids (Cundy 1951). Also within the sub-domain of mathematical models, cultural forms are recognizable: a clear geography of science is visible in the popularity of different models in different parts of the world (Addor and Melsen 2019). Also, the Digital Twins of the Earth, although intended to simulate the whole Earth, have a geographic bias and are dominated by institutes in the Global North, and, even within the North, distinct geographies of science are at play when discussing global climate (Mahony and Hulme 2018).

DTs can undoubtedly be seen as new and as a fashion, where the distance between the twins and their purported users is such to preclude meaningful "reciprocal domestication between models and society" (Saltelli, Puy, and Di Fiore 2024). Unlike a digital twin of a human heart, that can be realized as to customize medical treatment to different hearth typologies (Coveney and Highfield 2023), one fails to see how the users (which users?) can get any meaningful proximity to these planetary behemoths.

Models as Distant

Both modellers (Jakeman, Letcher, and Norton 2006; Padilla et al. 2018) and philosophers (Baudrillard 1990) have noted the distance between the environments where models are constructed and those where they are used. For Baudrillard (op. cit.: 92):

> One 'fabricates' a model by combining characteristics or elements of the real; and, by making them 'act out' a future event, structure or situation, tactical conclusions can be drawn and applied to reality. It can be used as an analytic tool under controlled scientific conditions. In mass communication, this procedure assumes the force of reality, abolishing and volatilizing the latter in favour of that neo-reality of a model materialized by the medium itself.

In large global models, such as the integrated assessment models (IAMs), and a fortiori in Digital Twins of the Earth, the distance between modellers and the simulated environment is high. The potential of these DTs to distort the real is hence also important.

Models as Thoughtless Bureaucrats

Models can act directly in life (Lane 2014), e.g. in issues of policy or governance, or in the form of algorithms. For Dan McQuillan (2022), lacking intent, an algorithm cannot be held accountable. He reconnects this to Hannah Arendt's concept of thoughtlessness (Arendt 1963) to say that a machine's thoughtlessness is automatic. In other words, if a functionary in a bureaucratic machine can be thoughtless, a fortiori this can be the case for an actual 'machine'. There is thus an algorithmic thoughtlessness. Hannah Arendt herself notes elsewhere our incapacity to process the products of new technologies (quoted in Schiff 2013):

> And if 'knowledge and thought have parted company for good', two consequences follow. First, 'we would indeed become the helpless slaves, not so much of our machines as of our know-how, thoughtless creatures at the mercy of every gadget which is technically possible, no matter how murderous it is'.

This reconnects models to the 'cultural forms' discussion above: McQuillan's considerations made for algorithms can easily be extended to models, given the blurred boundaries between different categories of quantification (Popp Berman and Hirschman 2018; Saltelli and Puy 2023); models are thus themselves in the family of Arendt's 'gadgets' with which we must coexist. As we shall discuss in The Ethics of Modelling and Implications for the use of Digital Twins, what kind of policy might be 'science-based' because of the DTs, and what controls will citizens have on it?

Models as Instantiation of a Cartesian Dream

Mathematical models can lend themselves to instantiate the Cartesian dream of prediction and control of humans over nature (Davies and Hersh 1986; Pereira and Funtowicz 2015). More specifically the sociological critique of models targets model-based distortions known as economicism (Drechsler 2000; Reinert 2000), reductionism (Scoones and Stirling 2020), justificationism, and decisionism (Majone 1989).

In Millgram's (2015) book 'Great Endarkenment', modernity is seen as facing a period of endarkenment because of our inability to understand the functioning of our own world. Interestingly one of the examples offered by Millgram is that of models used in finance, where not even their developers master their inner workings (p. 29) as modellers 'don't remember' how they did them:

> […] The process of constructing and validating [value-at risk] models is time consuming and detail oriented; normally even the people who produced the model will not remember many of the assumptions incorporated into it, short of redoing their work, which means that the client cannot simply ask then what went into it.

This difficulty to recollect the assumptions is not limited to models used in finance (Melsen 2022). Similar pitfalls will occur for Digital Twins of the Earth, which consist of an assemblage of highly complex models for which extensive sensitivity and uncertainty analyses – that help modellers to come to terms with their assumptions (Saltelli and Di Fiore 2023; Reinecke, Pianosi, and Wagener 2024) – are hardly feasible. Furthermore, multiple data, software, coding and domain-experts are involved in the development of each sub-module, thereby diluting the understanding of the functioning of the overall model.

Models as Metaphors

For Jerome Ravetz (2023), models can be metaphors of how we perceive the world. They express "in an indirect form our presuppositions about the problem and its possible solutions". Baudrillard's (1990) models as simulacra come pretty close to this presupposition. An archaeologist of the future may learn a good deal about us by looking at our models. A different use of the term simulacra in relation to mathematical modelling is offered by Nancy Cartwright, to signify that scientific models are not direct representations of reality, but rather simplified and abstracted representation tailored to a research objective (Cartwright 1983). The DTs do not aim to be a metaphor relative to a piece of the real; in a sense their ambition is to imitate it and substitute for it. If anything, the DTs can allude to a mythical dimension, that of a Promethean project endowing mankind with a life-changing innovation, bringing 'climate to our fingertip' in the words of one enthusiastic politician (Frost and Symons 2024).

Models as Natural Divination

We borrow the last vision about models from Francis Bacon's 'The New Atlantis'. Published in 1627, one year after the death of the author, this novel possibly created a new science fiction genre. In a section entitled *Magnalia Naturae* (Bacon 1627), the protagonist is recounted by a wise exponent of a more advanced civilization the wonders of human progress brought about by natural philosophy – today's science. The list is too long to quote here; it starts with

> The prolongation of life; The restitution of youth in some degree; The retardation of age; The curing of diseases counted incurable; The mitigation of pain; More easy and less loathsome purgings;

and ends with

> Natural divinations; Deceptions of the senses; Greater pleasures of the senses; Artificial minerals and cements.

Depending on how the count is made, the list may include some 36 discoveries or inventions. A good case can be made that all items on the list are in use today – if anything Bacon failed by omission, as he did not predict space flights nor a virtually interconnected humanity. 'Natural divinations' refers to predicting the future without the use of magic or divine powers. A case can be made that mathematical models do offer the kind of 'natural divination' dreamt by Bacon. This case can likewise be contested, precisely to the extent that we know better today the limitations of the 'divination' element of the prophecy, from our understanding of quantum mechanics and complexity theory. DTs are thus tools for modern science-based divination, but models' extraordinary success in many fields should not be thought of as extending to DTs without reflecting on these limitations.

Struggling Practitioners

As a new and sophisticated cultural form, models escape not only the comprehension, and thus the proper use, of the lay publics, but appear difficult to tackle even to practitioners themselves; natural scientists are notoriously resistant to accept constructivist accounts of their craft (Eker et al. 2018; Lane 2014), while only a rarefied cluster of sociologists and historians of science dispose of the needed palette to investigate them, as one can realize by reading the multi-author book of (Morgan and Morrison 1999); see (Saltelli and Puy 2023) for a discussion. Although the DTs of the planet have a clear holistic ambition, it is unlikely that their implementation will bring different epistemic communities closer. As noted in (Westerlaken 2024), DTs will be realized in what is now defined as federation of entities, but is, in reality, a puzzle work of different funding arrangements given the colossal ambitions of the project. The predominance of physics in this construction is unlikely to be seriously challenged by other disciplines (Saltelli et al. 2024). Different modelling communities have different understanding of what would constitute model validation (Padilla et al. 2018), and there are historical precedents in hydrology to the effect that large models – let alone huge ones – cannot be validated (Konikow and Bredehoeft 1992).

Epistemologies of Models and its Implications for Digital Twins

In this section, we explore the epistemological value of models in general, and Digital Twins of the Earth in particular. Morgan & Morrison (1999) refresh the well-known expression from George Box "All models are wrong but some are useful" by reconnecting models to technology: like for a technology, we cannot judge of the quality of a model 'in theory' but only under conditions of 'use'. In the same volume, Morrison & Morgan (1999) discuss of models as mediators between theory and world. This fluid, intermediate state is what ensures the extreme versatility of models. One more author in the same volume (Boumans 1999) expands the dialectic world-theory to encompass a broader array of ingredients, including theoretical notions, mathematical concepts and techniques, stylized facts, empirical data, policy views, analogies and metaphors. When we call models 'mathematical', we are probably giving a very partial view of their nature.

Can Models be Falsified?

In the philosophy of science, the Duhem-Quine thesis (Quine 1951; Duhem 1991) posits that it is impossible to test a single hypothesis in isolation, because any hypothesis relies on a network of assumptions, background theories, and auxiliary hypotheses. Therefore, when an experiment fails to confirm a hypothesis, it's unclear whether the failure is due to the tested hypothesis itself being incorrect or if it's due to one of the auxiliary assumptions or background theories being incorrect. Mathematical models – when used to predict – are ideal subjects for this critique. As noted by Oreskes (2010), models are an amalgam of theoretical assumptions, holistic preconceptions, measurement devices, and physical equations. When 'model' and 'world' disagree, we do not even know, in principle, if we need to make the world simpler – e.g. in mechanics eliminating some of the frictional forces – or the model more complex – e.g., staying with the example, making the model to include frictional forces, see Ernan McMullin quoted in Suárez for a discussion (1999).

Models as Mediators

Seeing models as mediators (Boumans 1999; Morgan and Morrison 1999) offers a proper antidote to conceiving mathematical models as mathematics. It also moves the discussion about models from the world of absolutes (true, false) to that of quality, where the judgment on the quality of an artifact becomes relative to the task it has been assigned and by the constituencies involved in its use and construction. A move in this direction was advocated by post normal science that suggested moving the emphasis from the truth content of different scientific propositions to the quality of a scientific process of generation, including with the use of pedigrees, specifically conceived to deal with any form of quantification involving numbers (Funtowicz and Ravetz 1990b; 1990a); see (Parker 2020) for a more recent discussion.

Looking at DTs through the lenses of a 'models as mediators' epistemology (Morgan and Morrison 1999), one may ask what mediation is taking place here; since the twins have the ambition to be the digital replica of the real, the real *in silico*, they seems to be intended to replace the real more than mediate between it and theory, so much so that the replica are purportedly designed to provide instructions for operations to mitigate or adapt to climate change (Korenhof, Blok, and Kloppenburg 2021).

DTs and Biodiversity

As discussed in (Saltelli et al. 2024), biodiversity offers an interesting case to show how with DTs a reductionistic scientific logic espouses and reinforces an economicist logic. For (Westerlaken 2024), the discipline of biodiversity can be severely damaged by a DTs-based approach. By construction, DTs will focus on those species that DTs' sensors can capture, against the quest in the field for new species to be protected. Again, this will favour researchers in the global North where the DTs are physically located against the researchers in the global South where most of the biodiversity of the planet is stored. This path of development with technology at the forefront privileges the feasible (e.g. what data are accessible) over the needed (e.g. what groups are vulnerable), creating a host of legacy effects that will then restrict the spectrum of available policies (Westerlaken 2024).

Concepts such as 'ecosystem services' are used to direct and manage through an impersonal digital environment, while reshaping, thanks to the seductive and performative properties of numericization (Merry 2016), the very subjects being addressed.

The Ethics of Modelling and Implications for the Use of Digital Twins

While for McQuillan (McQuillan 2022) algorithms live in a state of exception, the same can be said for mathematical models (Saltelli, Puy, and Di Fiore 2024). Dangerous as algorithms, models escape more easily than algorithms the inquisitive gaze of sociology of quantification, maintaining in general their discrete charm and epistemic authority (Davies and Hersh 1986), bar when – under exceptional circumstances – they are brought to the limelight, as was the case during the recent pandemic (Saltelli et al. 2023). COVID-19 offered to models unprecedented visibility (Saltelli and Di Fiore 2023). Both media (Pielke 2020; Samuel 2023) and academia (Rhodes and Lancaster 2020) have become concerned with the power entrusted to models. Cases of model-generated harm or risk are discussed in (Pilkey and Pilkey-Jarvis 2009; Qi 2024; Scoones and Stirling 2020; Wilmott and Orrell 2017); a review is in (Saltelli, Puy, and Di Fiore 2024). Irrespective of any ontological or epistemological account, models have ethical implications. It is also interesting to note that the introduction of these large technologies of computation, such as DTs and artificial intelligence, has generated an auxiliary narrative by nuclear energy advocacy, with major high-tech companies investing in nuclear power plants to support their data centres (Wong 2024). Current estimates suggest that these centres, which will be crucial to DTs and AI operations, could account for between 4.6% and 17% of U.S. electricity consumption by 2030 (Hiller 2025).

Models and Reductionism

It has been written that quantification can be an ingredient of a technocratic approach to governance (van Zwanenberg 2020). For scholars of sociology of quantification, numbers such as those provided by algorithms, indicators and models may promote inequality and contribute to undermine democracy (Bruno, Didier, and Prévieux 2014; Mennicken and Salais 2022). This may be achieved via "justificationism", where the objective of a number is to justify a policy. Numbers also promise objectivity, and hence the purported neutrality of numbers may be used to defend the 'facticity' of facts against ideological resistance (Porter 1995). Finally, numbers may help with reductionism, whereby complex socio-political dilemmas are reduced to choices driven by straightforward metrics, suppressing uncertainty and ambiguity (Scoones and Stirling 2020).

Models can be functional to all of these strategies. For sociologist Luhmann's science is often called to 'deparadoxify' policy decision – i.e. to make them seem the result of a rational decision instead of the outcome of a negotiation among competing interests (Saltelli and Di Fiore 2023). The COVID19 pandemic has seen this mechanism at play (Saltelli et al. 2023). Our future will see negotiations or disputes arising from the use of land, water and natural resources in a context of climate adaptation. How will the availability of the twins play in those contexts? Will they play the same role as the AI's criticized by McQuillan (2022) in favouring bureaucratic forms of governance that exclude even the possibility of an appeal (Brauneis and Goodman 2018; O'Neil 2016)?

Furthermore, models can colonize the future by creating or reinforcing some socio-technical imaginaries (Jasanoff and Kim 2015) to the exclusion of others that remain foreclosed (Scoones and Stirling 2020). The appropriation of the future operated by models may take the form of an assault, such as in the case of models in finance (Walter and Wansleben 2020), or when narratives generated in the Global North are imposed or the Global South, as where, for example, migrants from Pacific islands are instrumentally labelled as already being ‘climate refugee’ (Farbotko et al. 2023; Farbotko and Lazrus 2012). As engines for traveling backward and forward in time, models hold important epistemic and ethical responsibilities. Are modellers ready for the task? Or are they ethically ‘insolvent’ (Becker 2023) in the sense that their ethical vision is focused on a value-neutral vision of technology whereby the problem of ethics can be solved with the right set of guidelines? Moving from a discourse about ethics to one about values opens the way to a reflexive and recursive process of analysis that touches on the beliefs and preferences that direct and orient individual and organizational work also in relation to what counts as a fact. In discussing the impossibility of a neat separation between facts and value (or between mean and ends) Christoph Becker (2023) quotes an entry from the Devil’s Dictionary (Bierce 2023):

> **models**, n. pl. (computing): the carpets under which, if we look carefully, we can find the human values, politics and moral decisions that have become code, features, qualities, documentation and other technological facts through the social practice we call systems design.

To stay with the similitude, DTs are thick carpets.

Models and the Governance of Science

We could also look at the DTs and their models in the context of the present governance structure of science. It has been written that science’s independence as portrayed by the classic works of Polanyi (1963) and Bush (1945) has underwent a process of decline that was feared by De Solla Price (1963) and boldly prophesized by Jerry Ravetz (1971), for whom the quality control arrangements of little science would collapse with big or mega science, leading to a process of internal corruption. The present crises (Ravetz 1971; Smaldino and McElreath 2016) vindicate this prophesy, while in recent years science’s own governance might have been further hijacked by scientific publishers, who push scientists to favour science that can be published rapidly over the one that takes long times and the slow accumulation of evidence (Neff 2020). Remaining with the case of biodiversity, ‘slow’ science would be represented by field investigation and taxonomical work, while the fast one is well represented by the modelling activity that goes into DTs. This is a self-reinforcing loop, because, when funding decisions are taken to support the DTs, journals are likely to be more favourable than critical. There will be losers among researchers who could possibly contribute the most to the cause of biodiversity, and who may happen to be in the global South, a region whose science, additionally, is not favoured by the present publishing regime of quasi-monopoly (McGill 2024). For Pierre Bourdieu (2004), science's most precious and defining attribute, that tells it apart from other human endeavours – such as for example art – is that each scientist's production is vetted by her or his rivals – who will be the most severe of critics. For the reasons described in the present work, we believe that the vetting of DTs work will remain partial at best. For Wynne (1984, p.314):

> Indeed, policy analysis, especially that conducted around large-scale modeling, tends to be structured in such a way that each modeling team is virtually its own peer group community.

Quantification's Double Dimension of Quality

The quality of a quantifications, including when carried out with a mathematical model, can be looked at with a double lens, technical as well as normative, as recommended by sociologist of quantification Robert Salais (2022). Salais makes reference to Amartya Sen's Informational Basis for Judgment of Justice (IBJJ) (Sen 1990): a system of measurement or analysis provides a fair, informed judgement if it helps individuals to achieve their goal, once their individual conditions are taken into account. This is Sen's well known capability approach, whereby a just society is not one where all have the same material means, but rather all have an equal opportunity to fulfil their aspirations once their starting condition is taken into consideration. For Salais (2022), lacking this normative dimension of quality, a scheme of quantification can contribute to deprive citizens of their agency, creating a system of a-democracy – a situation where citizens' participation is only an appearance. We do not think of these two dimensions of quality as independent, as no technique is ever neutral, and different methods of quantification are by design closer to different systems of values (Majone 1989; Saltelli and Di Fiore 2023).

Concluding Remarks

We have argued that models are recent cultural forms that can be used to mediate between world, theory and much more, and ought to provide defensible quantifications whose normative and ethical implications have not been left unquestioned. How did we apply these considerations to the context of models being developed in the various digital twins projects?

Cole & Pavitt (1973)'s work 'Models of Doom' can help us with this illustration. Written by a group of scholars from Sussex's Science Policy Research Unit, the book offered a constructive critique of what we could call an antecedent of today's DTs: the so-called 'World models' or Models of Doom, developed by the system dynamics group at MIT (Massachusetts Institute of Technology) and published in (Forrester 1971; Meadows 1972). Here the view of the Sussex's team:

> The apparent detached neutrality of a computer model is as illusory as it is persuasive. Any model of any social system necessarily involves assumptions about the workings of that system, and these assumptions are necessarily

> coloured by the attitudes and values of the individual or groups concerned. For this reason too Cole and Curnow 1973 conclude that computer models should be regarded as an integral part of political debate, just because they may hide possible sources of bias. The model is the message. This is particularly important in relation to forecasting models. Subjective values and attitudes do influence forecasts, however much the individual may strive for objectivity. It does matter in considering forecasts of the future patterns of world energy demand and their implications for pollution whether the forecasters are working in the oil industry, the nuclear power industry or the coal industry. This does not mean that all forecasters are paid hacks or manipulate their data in a dishonest way but only that the environment in which a forecaster works influences his theoretical assumptions. His sources of data necessarily influence (often unconsciously) the form and presentation of a complex argument in which values are inevitably and inextricably involved.

It is difficult to say more. Modellers *qua* modellers, even if not working for corporate power or private interests, do inhabit communities (Robertson 2021; van Beek et al. 2022) and do have concerns, desires and world views.

Looking at the DTs through the lens of a 'double dimension of quality' – one technical and one normative – as discussed above, both dimensions appear elusive. Since we need an AI-agent to look at the output of a DT, the technical dimension escapes control. The second dimension, that of fairness and normative adequacy, is even more challenged, as per the creation of endarkenment and distances, but also because the DTs subscribe to a vision of humans and the planet where the narrative is dominated by climate change, as opposed to the ensemble of environmental and ecological planetary afflictions, not to mention important socio-and geo-political storms affecting the world. As discussed by Hulme (2023), we should resist 'climatism', not because climate change is not real, but because it cannot play the role it is presently attributed of 'master-narrative', whereby everything, from wars to migration, is made to descend from it. Such a master-narrative leaves many excluded, especially those that the master-narrative purports to defend, the weak and the powerless, the world's South, the victims of wars.

Our criticism of models of the earth system does not imply that all techniques of digitalization are to be regarded with suspicion. For example, digital technologies can be crucial for tagging, monitoring and preserving endangered species or combating overfishing. In a book that is aware of the risk imposed by digital technologies Karen Bakker (2024) argues that "it is not the digital nature of the technology that is critical, but the system of ownership, enterprise and governance in which they are enmeshed". For this author digital technologies can not only assist in the protection and restoration of ecosystems but strengthen our relationships with them by reconnecting ecologists, law enforcement agencies and affected communities in a common endeavour. Digital technologies can, potentially, be used to "regenerate the Earth".

If we insist on using DTs of the planet to inform decision-making related to climate change mitigation and adaptation, then we must be aware that we have taken the Cartesian path of human control and domination over nature, and of Bacon's natural divination. It is important to become aware that – however one might wish to call it

– important elements of faith and fiction animate these choices that are presented as science-driven, and have important implications for the distribution of power.

For (Becker 2023), the 'computing's critical friends' – meaning by this those who study the sociological and philosophical implications of quantification – need to be alert of value blindness, and offer antidotes such as feminist standpoint theory and critical system thinking where coders and modellers can reflect on their practices. Similar recommendations for using more intellectual frameworks to look at analyses and their computational devices are offered in (McQuillan 2022), not to mentions the many who studied specifically the pitfall of analysis and modelling, e.g. Quade (1980), and Wynne (1984). For the authors in (Saltelli et al. 2024) funding agencies need to promote diversity and plurality in both model building and data collection against the holistic vision of DTs. More plural approach including e.g. "the physical climate storyline approach, and Earth system models of intermediate complexity" are recommended by Pacchetti et al. (2024), while approaches based on sensitivity analysis and on the exploration of functional relationships underpinning our theoretical knowledge of the Earth's functioning is suggested by Reinecke et al. (2024). For society, a more cautious and circumspect attitude in the consumption of models is advisable that starts with not being blinded by the promises of DTs.

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Declarations

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