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PERSPECTIVE

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Bring digital twins back to Earth

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Abstract

We reflect on the development of digital twins of the Earth, which we associate with a reductionist view of nature as a machine. The projects of digital twins deviate from contemporary scientific paradigms in the treatment of complexity and uncertainty, and does not engage with critical and interpretative social sciences. We contest the utility of digital twins for addressing climate change issues and discuss societal risks associated with the concept, including the twins' potential to reinforce economicism and governance by numbers, emphasizing concerns about democratic accountability. We propose a more balanced alternative, advocating for independent institutions to develop diverse models, prioritize communication with simple heuristic-based models, collect comprehensive data from various sources, including traditional knowledge, and shift focus away from physics-centered variables to inform climate action. We argue that the advancement of digital twins should hinge on stringent controls, favoring a nuanced, interdisciplinary, and democratic approach that prioritizes societal well-being over blind pursuit of computational sophistication.

This article is categorized under:
Climate Models and Modeling > Earth System Models
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KEYWORDS

digital twins of the Earth system, ethics of quantification, machine learning, mathematical modeling, sociology of quantification

1 | INTRODUCTION

Over the last years there has been an increasing interest in what has been named as digital twins (DTs), virtual models that aim at mimicking with a high degree of accuracy a wide range of phenomena. Recently, the journal *Nature Computational Science* channeled this momentum into a special issue titled "increasing potential and challenges of digital twins," in which the challenges, advancements and opportunities involving DTs were explored across domains: from optimizing product life-cycle management in manufacturing systems to

> … biomedical sciences to climate sciences and social sciences. For instance, DTs could enable improved precision medicine, more accurate weather and climate predictions, and more informed urban planning. (Anon, 2024)

In blending of the tested (DTs in manufacturing, in medicine and biomedicine) to the possible (DTs in longer term weather prediction, in urban planning) to the untested (DTs for climate change mitigation and adaptation), the special issue presents the DTs of the Earth as a natural evolution of present-day science and technology. By integrating Earth system simulations with information from satellites, drones, undersea cables, buoys, crop sensors and mobile phones, DTs of the Earth are purported to provide a scientific basis for decision-making in the Anthropocene (Bauer et al., 2021; Li et al., 2023; Rao et al., 2023).

The longing for products that faithfully reproduce the minutiae of the empirical world is not new. Both Carroll (1893) and Borges (1998) wrote fictional stories about nations whose maps became so detailed as to be large as the territory itself. As a result, these maps were regarded as useless and were consigned to oblivion. Regardless of the relevance of these tales to DTs, it is important to distinguish between closed and open worlds, or in decision theory terms, between small, stable worlds and uncertain, unstable ones. Complex modeling may work for closed worlds, but not necessarily for open-ended systems like climate and the environment.

The development and application of mega-models such as DTs of the Earth should not occur without extensive discussion of their scientific limitations, the societal risks they pose and what knowledge they might provide (and what knowledge they do not) to inform policy-making. While Earth system modeling has potential to inform policy making within certain domains, we contend that as a practical matter, a DT of the Earth raises several important concerns. This critical perspective is offered as a safeguard to premature policy closure by acknowledging what is often ignored: the fundamental ignorance associated with modeling.

2 | PHILOSOPHICAL STANCE AND HISTORICAL CONTEXT

The vision sustaining the DTs project is an optimistic understanding of the potential of science and technology in shaping our future toward human progress. According to Bauer et al. (2021, p. 80):

> By combining this new class of models with advances from past investments in Earth system prediction and observations, digital twins promise to close substantial and recalcitrant gaps in our ability to look into the future […] An exciting aspect of a digital twin is the potential to break the paradigm of classical Earth system prediction models with fixed and static flows of information managed by layers of experts. Here, the

challenge will be to design a digital twin that allows users to intervene, extract information and influence the system trajectory across time and space, as done—albeit often unwittingly—in the real world.

The simultaneous accuracy, transparency, and desirability of this new class of models correspond to what has been termed a "socio-technical imaginary" (Jasanoff & Kim, 2015). The vision is mainstream among the institutions advocating DTs, see the DestinE project by the European Commission (Bauer et al., 2021; Nativi et al., 2021) and analogous undertakings in the United States (Rao et al., 2023), for example the NASA Earth Science Technology Office's investment in the pilot development of an Earth System Digital Twins (ESDT). In this culture, science possesses a privileged position in the attribution of meaning to human affairs (van Zwanenberg, 2020; Wynne, 1993), and it is the natural sciences in particular that determine our understanding of the world, with all its attending conflicts and inequalities (Lövbrand et al., 2015). The promise of progress purportedly rests on technological innovation (Eversberg et al., 2023).

We argue that underlying the Twins' ambition there is also the metaphor of "nature as a machine" (Lent, 2017), a cultural imaginary deeply enmeshed in the so-called Cartesian Dream of prediction and control of man over nature (Pereira & Funtowicz, 2015). This is the idea that higher-resolution representations and data will help us decode real-world complexity by exposing its internal machinery of cogs and gears, allowing us to forecast the future course of our planet. This understanding is at odds with the modern scientific conception of nature as a web of interconnected self-organizing structures displaying emergent behavior, a view championed by scholars like Rachel Carson (ecologist), Ilya Prigogine (chemist), Gregory Bateson (anthropologist), Humberto Maturana (biologist and philosopher), Francisco Varela (biologist), and Niklas Luhmann (sociologist). We return to the problem of high-resolution modeling in the next section.

DTs of the Earth presuppose that computational power will endow us with the "God's Eye view," or a "view from nowhere," an understanding independent from history, values, ideology, or ethics. These visions, which have been termed "post social" and "post-political" (Lövbrand et al., 2015), are unrealistic and ignore the fact that the inception of projects spearheading the DTs concept is already a happenstance: if the standard in Earth System research had been one of "biological" (Rosennean, deriving from Robert Rosen) rather than "physical" (Newtonian) complexity, DTs would have been regarded as a futile pursuit given that systems that reproduce themselves, such as the Earth, cannot be algorithmically instantiated (Rubin & Crucifix, 2021). DTs of the Earth are thus a historical contingency arising from a mechanistic and reductionist view of science and human affairs, compressing the complexity and uncertainty of open systems. We can predict when Haley's comet returns because the heavenly bodies create a stable world (relative to our short lives). But we cannot predict the flu, exchange rates, the stock market, and most phenomena where humans have their hands on. Climate change falls in this latter category.

Plans such as DestinE in Europe and ESDT in the US embrace the datafication value chain and a global data-driven economy, where software platforms become engines of innovation. For example, with DestinE it is promised that the offer will create its own demand, bringing together data owners, data analytics companies, skilled data professionals, cloud service providers, companies from the user industries, venture capitalists, entrepreneurs, research institutes and universities (Nativi et al., 2021). All without considering essential societal aspects.

3 | SCALING

Notwithstanding doubts from within the modeling community (Famiglietti et al., 2021; Trenberth, 2010), the DT pursuit assumes that Earth's complexity can be tamed by diving deeper into its underlying physical dynamics. With reductionism already entrenched in notions such as the "global mean temperature" (a singular, static index for planetary climate control (Stirling, 2024)), a DT of the Earth envisages further idealized categories to characterize an intrinsically plural and dynamic relational complex. These take the form, for example, of (sub)kilometer-scale modeling to uncover the "true" numbers needed to characterize deep convective cloud systems and ocean mesoscale eddies, two key processes that boost or decrease the warming effect of CO_2. This is claimed to facilitate multi-decadal prediction of extreme events and their socio-economic impacts on marine, urban, or agricultural ecosystems (Slingo et al., 2022). DTs of the Earth thus assume that higher resolution will help us get the physics right.

Yet historical evidence reveals numerous challenges when translating reductionist approaches into high-resolution modeling. The higher the resolution (i.e., the greater the localization), the more non-physical feedbacks emerge as relevant, whether it be the micro-climatic effects of forest stands or the albedo micro-patterning of slush ponds on ice sheets. Scale change often brings about non-trivial shifts in complexity and governing principles, and finer-grained scales may reveal deterministically-driven chaotic behavior (Levin, 1992). A different resolution may require different, perhaps yet unknown, process descriptions. This is a challenge well-recognized in hydrology, a domain that should be captured by a DT of the Earth. Here, higher resolution is unlikely to eliminate the need for effective parameters to describe heterogeneity in soil, topography, and vegetation properties. "Zooming in" just opens up new challenges of parametrizing these processes (Beven et al., 2015; Beven & Cloke, 2012). To achieve one's "Twin" ambition for one's model, one may end up with more parameterizations, not fewer.

Second, increasing resolution may not necessarily translate into more accurate climate predictions. The accuracy of multi-decadal estimates on climate sensitivity may be highly dependent on cloud feedbacks (Zelinka et al., 2020), which are not conditioned by model detail. Inherent climatic variability due to the large-scale chaotic atmospheric and oceanic circulation patterns also occur over periods of 50 years, setting strict limits to how much more accurate predictions can get through hyper-resolution (Deser et al., 2012).

Third, research entails delving into the unknown, and as one source of uncertainty is reduced, others tend to emerge (Sarewitz, 2000; van der Sluijs, 2005). In model-based research, finer-grained resolution introduces new uncertainties that compound existing ambiguities, often resulting in expanded output uncertainties due to a higher effective dimension of the model (more parameters influencing output uncertainty and higher-order effects) (Saltelli, 2019). Consequently, more complex models tend to become more dominated by interactions among uncertain parameters/structures, further amplifying output uncertainties (Puy, Beneventano, et al., 2022). Proponents of DTs suggest that this uncertainty-complexity trade-off does not apply to models focused on fluid and energy flows, and illustrate this assertion with the example of weather prediction models, whose increasing resolution has gone hand in hand with higher accuracy. Yet this argument neglects that, unlike short term weather prediction, predicting multi-decadal futures calls for DTs to deal with non-linear and reflexive feedbacks with multi-scale biological life and human societies. Even though DTs aim to integrate Earth and human systems, they fail to embrace the reflexive features of human societies and biological feedbacks. These systems cannot be understood solely through physical laws: think forests, crops, marine biology, microbial systems and more, all of which are subject to evolutionary responses in reaction not only to future climate, but also in response to future human systems, technologies and behaviors. The repercussions of climate change and of mitigation policies on socio-economic systems depend on contextual factors that are impossible to predict by a DT of the Earth.

4 | GOVERNANCE BY NUMBERS

As part of the broader theme of the politics of numbers (Mennicken & Salais, 2022), there is a political economy of mathematical modeling whereby epistemic authority is purchased via recourse to large models. At times, these models end up objectifying or depoliticizing political issues, making them appear determinable and hence solvable via an impersonal objectivity (Saltelli & Fiore, 2023).

For instance, during the COVID-19 pandemic, model-based policies were implemented under the "follow the science" banner, often by ignoring uncertainties in crucial model parameters (Miller, 2022) and biases from modelers' lifestyles and work habits. The parallel with the DTs of the Earth is clear: complex political problems related to climate change and the environment are reframed as technical issues, solvable by developing powerful diagnostic tools. In reality, these models provide policymakers with convenient instruments for justification and control. It is imperative that questions are asked about the presence of political bias in purportedly scientific and value-neutral global models (Keepin & Wynne, 1984). Models thus volunteer themselves as the answer to Lövbrand et al.'s (2015) question of "Who speaks for nature?"

The DTs represent a climate-ecological variant of what sociologists of quantification (Mennicken & Espeland, 2019) call "governance by numbers," whose rapid diffusion has caused concern for its noxious effects on democratic processes (McQuillan, 2022; Mennicken & Salais, 2022; Supiot, 2017; Zuboff, 2019). If the societal alarm sounded by several authors in relation to the domestication of life by digital technologies reaches the general public, will society accept that the care of the planet is turned over to Behemoth models to which people have no true access? According to Bauer et al. (2024), decision-makers and lay citizens may be able to interrogate using natural language the unyielding output of DTs via pre-trained machine learning tools (chatbots). But this creates precisely the sort of quantification by privileged communities that excludes sense-making, meaningful deliberation and democratic participation about what the model represents, why, and how.

The digitalization of the real has been called a "displacement" when operated with models (Wynne, 1992), an "escape into the non-things" in a broader philosophical context (Han, 2022). It also opens an avenue to the excesses of climatism, understood as a mono-causal explanation of all that is wrong with humanity and the planet (Hulme, 2023). The loss of sovereignty in favor of a specialized digital technocracy gives rise to "a-democracy," a system with the appearance of democracy but without the taste (Salais, 2022).

Although it has been promised (Rao et al., 2023) that "a diverse and inclusive community with broad representations of developers, users, domain scientists of both natural and socioeconomic processes, government and international organizations, and industry members" will collaborate closely, we believe that reliance on DTs is likely to reinforce technocratic dynamics by centralizing modeling activities that are currently distributed among many research organizations that are often in close contact with policymakers and local communities.

The DTs of the Earth reinforce a culture of economicism, favoring quantification before uncertainty and heterogeneity (Scoones & Stirling, 2020). 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.

In that regard, biodiversity scholars (Westerlaken, 2024) have been the first to articulate a concerned critique of how their discipline may end up flattened beyond recognition by a DT-based approach, as technologists and developers supporting the DTs zoom in on those species that their sensors can capture and quantify. Rather than building twins based on the need of specific species, DTs offer selective modeling driven by what is technically feasible. Another general point made in Westerlaken (2024), that extends beyond biodiversity, concerns the piecemeal way these projects are funded, by a myriad of different case specific "infrastructures, pilot projects, prototypes, hackathons, and other separated or outsourced segments that merely offer innovative showcases." The physics-based drive beyond the twins is further likely to fragment nature and focus on the presence-absence of measurable species rather than their web of entanglement. It also neglects the aspirations of less influential human stakeholders who may have deeper cultural and traditional connections with those species (Westerlaken, 2024).

Another example of how enthusiasm for innovative mathematical models can lead to trouble is when these models are used to link climate change, extreme weather, and expected losses to inform insurance policies, as advocated by DT proponents (Nativi et al., 2021). Biased risk estimates of extreme events can devalue properties exposed to those risks, potentially causing systemic effects already visible (Weinkle, 2024). The use of mathematical modeling in insurance (Johnson, 2020) and securitization (Salmon, 2009; Weinkle, 2024) has created unexpected and considerable problems before. These examples would suggest caution before deploying DTs-derived analytics on the market.

5 | A KINDER FUTURE

In our discussion thus far, we have argued that the plans for the creation of DT's (Nativi et al., 2021; Rao et al., 2023), and the echoing of such plans in the media (Frost & Symons, 2024), portray an imaginary that we find philosophically untenable and democratically questionable. Moreover, the fact that the evidence generated by models and the data on which they rely are historically situated (Morgan and Morrison, 1999), only lends greater credence to our findings. A more human alternative is possible. We suggest the following:

1. Fund the development of several model types by different independent scientific institutions to curb the "one model to rule them all" idea. These mixed models need not constitute a federation integrated in a single platform, such as that being planned and advocated by the proponents of the DTs. Adopting a constellation of various modeling approaches rather than a federation would ensure diversity, which would better match the complexity involved in the modeling of climate change than all-encompassing DTs of the Earth. It should also allow for the methodological intersection of different scientific perspectives and open up (rather than foreclose) debate.

While Earth System DTs are supported by important institutions, many relevant others are left aside and may experience a lack of funding for basic climate research. Consequently, researchers might be led by their quest for funds to promote "digital twins" of everything—DTs of biodiversity (BioDT) and of extreme events (DT-GEO) are already in progress—thus overstretching the metaphor. We suggest more latitude in the work-program for a fruitful interplay with ecologists versed in complexity, as well as with humanities and the social sciences. For example, we note that societal concern with pollinator decline is attentive to phenomena of regulatory capture (Drivdal & van der Sluijs, 2021;

Robinson et al., 2018), seen as one of the causes of pesticide-friendly legislation. In the logic of DT's this political phenomenon is not considered (see project BioDT, 2024).

2. Explore the potential of simple, heuristic-based models in climate/environmental settings. We agree that models can indeed be powerful tools to make sense of the world, but their utility is not mechanically determined by their complexity.

Heuristics or rule-of-thumb strategies may be especially suited under conditions of complexity and uncertainty and often outperform the hyped models of "big-data analytics" (Katsikopoulos, 2020).[1] These strategies have been investigated and demonstrated to improve safety in other volatile, dynamic and uncertain situations, such as in health, finance and macroeconomics, and facilitate communication with end-users (Katsikopoulos, 2020; Katsikopoulos et al., 2022). Consider the recency heuristic that forecasts next week's influenza incidence to equal this week's incidence: this often disparagingly called "naive" heuristic halved the error of once bigdata "poster child" Google Flu Trends in predicting the incidence of flu-related doctor visits (Katsikopoulos et al., 2022). The same heuristic also predicted future demand in volatile and disruptive markets better than complex macroeconomic models that try to finetune on the past (Dosi et al., 2020).

As Puy, Sheikholeslami, et al. (2022) have shown in the case of global irrigation water withdrawals, simpler models can do the job of several complex models combined while better addressing key uncertainties. They are also useful to inform environmental action: they are especially tuned to function when an optimum solution is out of reach. Their parsimony implicitly acknowledges the computational intractability of nature and hence does not require a never-ending flow of data to foster action. Moreover, they are simpler to implement and understand, facilitating open and constructive deliberations among policy-makers and citizens and reinforcing democracy. DTs of the Earth are not designed with these standards in mind (Klinkenberg, 2023).

3. Invest in collecting and integrating data from divergent and independent sources, including traditional knowledge, such as for example that of Sámi reindeer herders discussed in Tyler et al. (2007). Moreover, some models in the last Coupled Model Intercomparison Project (CMIP6) offered too high climate sensitivities ($>5°$C), which became evident once they were crosschecked against paleoclimatic and historical records, simple models and basic theory (Sherwood et al., 2020). This corrective process may be unviable with DTs of the Earth due to the enormous stream of inputs and outputs and its internal machinery, which would hinder the identification of what has gone wrong in the simulations. Another aspect here is spatial justice: we should strive to offset the geographical imbalance of evidence, as discussed above for biodiversity (Westerlaken, 2024). In such cases, it has been shown that the understanding of how climate change affects different biota is limited by geographical study bias (Bennett & Classen, 2020). Therefore, it is essential that such imbalance is acknowledged and addressed.
4. Abandon a vision of the planet centered on physics and its variables as the principal focus for action against climate disruption. Instead, a stance of caring for a flourishing climate should be adopted (Stirling, 2024). This recognizes that what is currently being so devastated by polluting emissions, is not a singular, static, mechanistic categorical system, free from indeterminacy and subject to idealized mechanistic control. The Earth's climate is instead more accurately engaged with as a naturally fluctuating and irreducibly uncertain diversity of relational processes, both social and biological, warranting more pluralist and provisional practices of care. Fields such as political ecology, post-colonial studies and critical, interpretative social theorizing can help creating spaces for humility, immersion, and mutualism to contrast socio-ecological narratives of ecological modernization, green growth, ecosystem services and the like (Lövbrand et al., 2015). The imagination that arguably helped drive problems of environmental devastation in the first place cannot be the same used to solve them.

6 | CONCLUSION

DTs of the Earth espouse a reductionist scientific logic and reinforce an economicistic vision. This path of development with technology at the forefront privileges the feasible (e.g., what data are accessible, what processes can be simulated) over the needed (e.g., what groups are vulnerable, to what processes are outcomes sensitive). A host of legacy effects will then be created that will restrict the spectrum of available policies (Westerlaken, 2024).

Pushing the boundaries of scale will always have a place at the scientific frontier, but it is naive to think that bridging scales from high resolution processes will pave a path to meeting the needs of policy makers. There is the danger that measuring becomes a diversion from important policy goals (Mennicken & Salais, 2022), ultimately damaging policy itself. DTs of the Earth represent a single and limited viewpoint, but may end up being used as a political instrument for justification and control, eroding the basic principles of democracy. Political judgments risk being outsourced to the DT, but with modeling itself recognized as political, the exercising of similar standards to that of other political processes becomes necessary (Royston et al., 2023).

Due to the subjective nature of model assumptions, the question as to who is *not* involved in a modeling practice is more salient than the question of who *is* involved. This applies in terms of equity, particularly between the global North and the global South when addressing the impacts from and the mitigation of climate change (Stoddard et al., 2021, pp. 667–668). The fairness of such an ambitious regime of digitalization of the planet's future needs more discussion than what we see unfolding at present in both scientific journals and media, and more spaces for common deliberations where modeling is subject to a closer societal scrutiny (Saltelli et al., 2020; Saltelli & Di Fiore, 2023; Stirling, 2023). Humanity's care of the environment is not only a scientific but also a philosophical, ethical, legal, and ultimately a political matter. Bring DTs back to Earth.

AUTHOR CONTRIBUTIONS

Andrea Saltelli: Conceptualization (lead); methodology (equal); writing – original draft (lead); writing – review and editing (equal). **Gerd Gigerenzer:** Investigation (equal); methodology (equal); writing – original draft (equal); writing – review and editing (equal). **Mike Hulme:** Conceptualization (equal); investigation (equal); methodology (equal); writing – review and editing (equal). **Konstantinos V. Katsikopoulos:** Investigation (equal); methodology (equal); writing – review and editing (equal). **Lieke A. Melsen:** Investigation (equal); methodology (equal); writing – review and editing (equal). **Glen P. Peters:** Conceptualization (equal); investigation (equal); methodology (equal); writing – original draft (equal); writing – review and editing (equal). **Roger Pielke Jr:** Conceptualization (equal); methodology (equal); writing – review and editing (equal). **Simon Robertson:** Conceptualization (equal); investigation (equal); methodology (equal); writing – review and editing (equal). **Andy Stirling:** Methodology (equal); writing – original draft (equal); writing – review and editing (equal). **Massimo Tavoni:** Conceptualization (equal); formal analysis (equal); writing – original draft (equal). **Arnald Puy:** Conceptualization (equal); investigation (equal); methodology (equal); writing – original draft (equal); writing – review and editing (equal).

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study. The image provided to illustrate the text has been purchased from Shutterstock, enhanced license Order ID: CS-01E99-863A.

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ENDNOTE

[1] A formalism that can explain this phenomenon and delineate its boundary conditions is the bias-variance trade-off (Geman et al., 1992). The prediction error of a model can be decomposed as the sum of bias (discrepancy between model predictions and observations), variance (of the model predictions), and irreducible noise (which is the same for all models). Typically, complex models with more flexible mathematically forms and many parameters achieve smaller bias, whereas simpler models with more fixed forms and few parameters achieve smaller variance (Saltelli, 2019). Thus, a simpler model may predict more accurately than a complex model if (i) the simpler model can achieve low "enough" bias or if (ii) the complex model cannot achieve low "enough" variance. Conditions that lead to (i) include the presence of (approximately) dominating decision options or decision attributes, and conditions that lead to (ii) include the presence of scant, low-quality information or unstable, and undetected, data-generating processes (Katsikopoulos, 2023).

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