nature portfolio

Peer Review File

Digital twins of the Earth with and for humans

Web links to the author's journal account have been redacted from the decision letters as indicated to maintain confidentiality

Decision letter and referee reports: first round

27th Mar 24

Dear Professor Hazeleger,

Your Perspective manuscript titled "Humans and Digital Twins of the Earth" has now been seen by 2 reviewers, and we include their comments at the end of this message. They find your synthesis article interesting, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. In particular, please carefully consider and implement where possible the reviewers' suggestions to broaden the scope beyond climate change, and to deepen the discussion of the practical implications of your vision.

Please highlight all changes in the manuscript text file.

We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the referees' comments (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and the completed checklist:
[redacted]
** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

We hope to receive your revised paper within six weeks; please let us know if you aren't able to submit it within this time so that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Heike Langenberg, PhD
Chief Editor
Communications Earth & Environment

On X(Twitter): @CommsEarth

EDITORIAL POLICIES AND FORMATTING

We ask that you ensure your manuscript complies with our editorial policies. Please ensure that the following formatting requirements are met, and any checklist relevant to your research is completed and uploaded as a Related Manuscript file type with the revised article.

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• Life sciences
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You can download the form here:
https://www.nature.com/documents/nr-reporting-summary.zip

Furthermore, please align your manuscript with our format requirements, which are summarized on the following checklist:
Communications Earth & Environment formatting checklist

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*** DATA: Communications Earth & Environment endorses the principles of the Enabling FAIR data project (http://www.copdess.org/enabling-fair-data-project/). We ask authors to make the data that support their conclusions available in permanent, publically accessible data repositories. (Please contact the editor if you are unable to make your data available).

All Communications Earth & Environment manuscripts must include a section titled "Data Availability" at the end of the Methods section or main text (if no Methods). More information on this policy, is available at http://www.nature.com/authors/policies/data/data-availability-statements-data-citations.pdf.

In particular, the Data availability statement should include:
- Unique identifiers (such as DOIs and hyperlinks for datasets in public repositories)
- Accession codes where appropriate
- If applicable, a statement regarding data available with restrictions
- If a dataset has a Digital Object Identifier (DOI) as its unique identifier, we strongly encourage including this in the Reference list and citing the dataset in the Data Availability Statement.

DATA SOURCES: All new data associated with the paper should be placed in a persistent repository where they can be freely and enduringly accessed. We recommend submitting the data to discipline-specific, community-recognized repositories, where possible and a list of recommended repositories is provided at http://www.nature.com/sdata/policies/repositories.

If a community resource is unavailable, data can be submitted to generalist repositories such as figshare or Dryad Digital Repository. Please provide a unique identifier for the data (for example a DOI or a permanent URL) in the data availability statement, if possible. If the repository does not provide identifiers, we encourage authors to supply the search terms that will return the data. For data that have been obtained from publically available sources, please provide a URL and the specific data product name in the data availability statement. Data with a DOI should be further cited in the methods reference section.

Please refer to our data policies at http://www.nature.com/authors/policies/availability.html.

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

I am pleased to review the manuscript titled "Humans and Digital Twins of the Earth" by W. Hazeleger et al., assigned the reference number COMMSENV-24-0421. The paper underscores the significance of incorporating human behavior into the development and utilization of digital twin of Earth, advocating for these digital twins to endorse responsible human actions while fostering climate-resilient societies and sustainable development goals. I commend the authors for their diligent research efforts, and I generally agree with the conclusions drawn in the manuscript. However, I recommend substantial revisions before considering it for publication. Below, I provide specific feedback and suggestions for improvement:

Major Points
1. The authors should clarify how this paper distinguishes itself from existing literature, particularly emphasizing its unique contributions compared to other studies on digital twin of Earth.
2. It is advisable for the authors to further elaborate on the theoretical underpinnings of the framework and elucidate its practical applicability in detail.
3. The paper introduces a framework for digital twin of Earth that integrates human behavior. I suggest the authors delve deeper into the theoretical foundation of this framework and expound on its practical application.
4. If feasible, the authors should provide empirical research or case studies to illustrate the practical applications and impacts of the digital twin of Earth.
5. The manuscript discusses the technical implementation of digital twin of Earth but lacks in-depth technical details. Authors should furnish more specific information on technical implementation, data processing, and model construction. The discussion on the technical implementation of digital twin Earth lacks depth in technical details. The emphasis should shift from "what should be" to "how to do."
6. The article touches upon the governance framework for a digital twin of Earth, a crucial topic. I suggest the authors further explore the specifics of the governance structure and how issues concerning data privacy, intellectual property, and fair use are addressed.
7. The conclusion should highlight the main findings and recommendations of the study. It is advisable for the authors to summarize the key contributions of the study in the conclusion and propose directions for future research.
8. The introduction and the chapter of 'Current climate information practices' both delve extensively into climate-related content. While I acknowledge the significance of these topics as primary motivators for the development of the digital twin of, it is too many in the title of Humans and Digital Twins of the Earth.

Minor Points

1. L144 – L145: Li et al., (2023) have summarized the methodological and cyberinfrastructure advances in Big Data that have advanced the progress towards a digital twin of Earth.
2. At the conclusion of the document, the author includes Figure 1. However, I find it challenging to discern the purpose and contents of this figure. Instead, I suggest incorporating a technical framework or conceptual model for digital twins of Earth that include human behavior. This would provide a clearer visualization of the proposed approach and enhance understanding for readers.

Reviewer #2 (Remarks to the Author):

The manuscript argues that existing digital twins of the Earth (DTE), which essentially are used as climate change models should be upgraded from numerical models into into central decision-support tools by including human action on the Earth into the DTEs, and increasing human interaction with these DTEs.

Wild futuristic scenarios are envisioned, such as:
l338: "the use of digital twins of the Earth is not limited to Earth system prediction, but they will be used to explore societal options and pathways, explore non-linearities, and how can we empirically verify if they reflect reality, for instance using trends and social cross-sectional data from the (recent) past."

This is good in that academic authors should be able to present their vision. Here however, what is missing, is the relation of these DTEs to current city planning processes. And to the city digital twin techniques serving these processes.

The following phrase has a connotation that the climate digital twins truly are disconnected from the planning processes.
l138: "The innovation of our work is to consider humans and their institutions both within and outside digital twins of the Earth."

The key issue here is that the "digital twins of the Earth" are seen as a monument, the Ziggurat, and

that for them to become omnipotent, only lack the interaction with people. Especially, the introducing humans 'inside the core of the DTE' may be
understood it this manner. Meanwhile, city planning processes have considered environmental factors at large, among other important factors, for quite some time.

Should DTEs serve the decision making processes related to city planning, processes that have been in place and developed during centuries, instead of trying to become like them?

Would DTE then start to compete with the city planning methods? Try to override them? Or would they instead better be adjusted to improve and serve the current planning processes?

What if DTEs do not become omnipotent?
In Bauer et al (2021), the undesired version of the desired digital twin is seen to be a data atlas.
A data atlas provides statistics upon query, but lacks the predictive qualities that may be used to guide the human action.
But perhaps this could be the best way to connect DTEs to serve city planning processes?

Perhaps the climate digital twins should be a more integrate part of the city planning process, and not isolated
models that are discussed in separate clubs. Therefore, I would recommend the authors to include considerations on
how the proposed DTs could be a part of the already existing city DTs used in decision making, e.g. https://doi.org/10.2148/benv.46.4.501

Digital twins have been around for longer than since Bauer et al (2021), in several fields of science, including the concept of digital Earth. The manuscript could better elaborate the origins of digital twins to display a trajectory from where the concept originates to where the development is leading.
e.g. The idea of harnessing the digital twins to serve city needs, where most of human population is living, has been studied in
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The authors acknowledge that Bauer et al already argued that
l213: "high degree of interactivity such that humans can interrogate the information system and get accurate, falsifiable, and traceable answers to their (causal) queries."
It is unclear what is the added contribution of the authors, apart from the visions that need to be better connected
to city planning and the scientific state of the art.

Instead of building the Ziggurat, the DTEs could be adapted serve and improve the existing processes:
l152: "While processes for transferring knowledge from scientific climate research to society are in place,
their impact is often limited"
Providing PDFs (Assessment Reports) through "an upstream-to-downstream mechanism" is indeed a limited way of transferring knowledge.
What would be needed? Perhaps computational information that could be plugged in a multi-objective optimization when city planning is
conducted using DT techniques, e.g. https://doi.org/10.1016/j.ecolind.2021.107540
What is the level of data integration? https://doi.org/10.1016/j.jag.2023.103440

The text flows well in the manuscript. However, the citations should offer a wider view to digital twins than just the climate modeling. The above-mentioned narrowness of thought is a challenge, as is the following disconnection with the state of the art.

Other comments:

General theory of systems may be considered to demonstrate the challenge of including the human interaction.
Including human factors necessitates the overall system dynamics to be modelled in a fundamentally different way.

Would DTEs just be based on numerical simulations or could there be, e.g., ontological or other models also?

Here, DTEs are lifted over all other state of the art DT techniques:
l385: "The use of DOE generate a social innovation that is initially not part of the digital twins themselves and,
hence, needs to be included retrospectively."
Why should this be the case? Has such social innovation not been already realized by other DT techniques?

Please elaborate the precision and accuracy of the data used in these models:
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Also, please elaborate the accuracy/precision and/or limitations of the data available for the human interaction part.

Author responses: first round

Reviewer #1 (Remarks to the Author):

I am pleased to review the manuscript titled "Humans and Digital Twins of the Earth" by W. Hazeleger et al., assigned the reference number COMMSENV-24-0421. The paper underscores the significance of incorporating human behavior into the development and utilization of digital twin of Earth, advocating for these digital twins to endorse responsible human actions while fostering climate-resilient societies and sustainable development goals. I commend the authors for their diligent research efforts, and I generally agree with the conclusions drawn in the manuscript. However, I recommend substantial revisions before considering it for publication. Below, I provide specific feedback and suggestions for improvement:

We thank the reviewer for these comments in support of our Perspective paper and for recognizing the significance of incorporating humans in developing and utilizing digital twins. We respond to the comments point by point below.

Major Points
1. The authors should clarify how this paper distinguishes itself from existing literature, particularly emphasizing its unique contributions compared to other studies on digital twin of Earth.

The digital twin literature is expanding rapidly (see, for instance, the special issue recently in Nature Computational Science, March 2024 that is relevant for this Perspective paper). Incorporating human behavior in digital twins is not new, but it has seldom been discussed in the context of digital twins of the Earth. A recent paper emphasizes the technological aspects of humans interacting with digital twins of the Earth (Bauer et al 2024). Our Perspective paper is unique in the breadth of considering human behavior represented within digital twins of the Earth and in the governance and utilization in these digital twins. Moreover, the paper emphasizes limitations in codifying human behavior within digital representations of the Earth system. Hence, it concludes that governance is crucial for the implementation of the twins in support of just sustainability transitions. To aid in the development of appropriate governance, we suggest a code for governance of digital twins of the Earth, as described in the text box in Section 4B.

We identify several levels of governance: from that at the development of twins (primarily the software infrastructure), to the one concerning data and software, and the one involving accessibility and use of the digital twins. Considering the latter, we draw upon recently developed concepts in the context of algorithm-generated information. The ELSA (ethical, legal, societal aspects) concept has been a source of inspiration (van Veenstra et al 2021), as well as theoretical concepts of design studies (Friedman and Hendry, 2019).

In the Introduction of the manuscript and at the end, we elaborated further on these aspects. We added this discussion to Section 4B as well because these governance aspects have not been addressed yet regarding digital twins of the Earth.

2. It is advisable for the authors to further elaborate on the theoretical underpinnings of the framework and elucidate its practical applicability in detail.

We recognize that our work builds on a legacy of digital twin developments in industry, city planning, and other applications. This provides a (conceptual) theoretical basis for our work related to digital twins. In addition, we build on a legacy in Earth system observations, predictions and projections, and climate adaptation and mitigation research.

Contemporary literature describes digital twins as systems of systems, networked, or ecologies of twins, in particular when digital twins are virtual representations of real complex systems (see e.g. Batty et al 2024, Nature Computational Science). Earth is a complex system consisting of physical and social worlds that interact. The theoretical underpinning of the overall framework of digital twins of the Earth is conceptual and has been described in Bauer et al 2021 (Nature Climate Change). This framework of digital twin Earth is embedded in overall digital twin conceptualization, often attributed to product life-cycle management, originally published by Grieves (2005; Product Lifecycle Management: Driving the Next Generation of Lean Thinking. New York: McGraw-Hill; see also National Academies of Sciences, Engineering, and Medicine. 2024. Foundational Research Gaps and Future Directions for Digital Twins. Washington, DC: The National Academies Press. https://doi.org/10.17226/26894).

The computational and data management underpinnings for digital twins of the Earth are grounded in computer science. They are described in further detail by, for instance, Li et al (2023, Nature Computational Science) and by Hoefler et al (2023) in the context of Earth Virtualization Engines. Digital twins of the Earth will rely on proven IT frameworks and infrastructures, such as high-performance computing systems and cloud infrastructures. They should swiftly respond to the inputs of users exploring data and performing simulations. Orchestration of computing workloads and data transfers within high-performance computing systems and across the firewalled high-performance computing boundary thus become paramount and will be based on work of e.g. Parodi et al (2020). Workflows would have to be executed fast and in a controlled manner. This will require cross- and intra-system orchestration and task-scheduling frameworks (see e.g. Manubens-Gil et al 2016).

The theoretical underpinning of the subsystems of the Earth that are part of digital twins of the Earth are domain specific. For example, the first principles of physics underpin global weather and climate models. Theoretical insights in geochemical

and water cycles and vegetation dynamics underpin, for instance, vegetation models, while behavioral theories and models underpin socio-economical models.

Finally, conceptual theories on human-machine interactions provide a basis for the design of digital twins of the Earth. This has been explored for other digital twins within other sectors such as for energy systems and health (see below for references).

We now start section 3 with these theoretical considerations, showing that this work builds upon various relevant strands of research and development.

The second request of the reviewer is to elaborate on the practical implications. Since the development and application of digital twins of the Earth is occurring in a scientific area that is in rapid development, the practical implications are only recently becoming clear, often in use case studies of particular questions and issues raised by societal stakeholders. The Destination Earth program demonstrates through use case studies the capabilities of digital twins of the Earth: The utilization through these use cases is clear (see Use Cases Catalogue Archive - Destination Earth (destination-earth.eu)). However, these use case studies also highlight issues to be developed and that are described in this paper related to human dimension within and outside the digital infrastructures.

We now refer to these pilot use cases in section 3.

3. The paper introduces a framework for digital twin of Earth that integrates human behavior. I suggest the authors delve deeper into the theoretical foundation of this framework and expound on its practical application.

This comment is similar to the previous comment, so we refer the reviewer to our response above.

4. If feasible, the authors should provide empirical research or case studies to illustrate the practical applications and impacts of the digital twin of Earth.

These use case studies are in development, such as in the Destination Earth project. We refer to the use cases as practical examples: Use Cases Catalogue Archive - Destination Earth (destination-earth.eu) (see response above).

5. The manuscript discusses the technical implementation of digital twin of Earth but lacks in-depth technical details. Authors should furnish more specific information on technical implementation, data processing, and model construction. The discussion on the technical implementation of digital twin Earth lacks depth in technical details. The emphasis should shift from "what should be" to "how to do."

The reviewer is correct that this paper, as a Perspective paper, takes a forward look. We appreciate the remark on the 'how to do' and in response refer to very recent papers, partially from co-authors, that address the technical aspects of digital twins of the Earth. This includes the implementation of components considered to be in the core of digital twins of the Earth (Li et al 2023 and Hoefler et al 2023) and the implementation of the interface of humans querying twins, e.g. using large language models (Bauer et al 2024).

At several places in the paper we refer more explicitly to these papers when considering the 'how to do' now. Thanks.

6. The article touches upon the governance framework for a digital twin of Earth, a crucial topic. I suggest the authors further explore the specifics of the governance structure and how issues concerning data privacy, intellectual property, and fair use are addressed.

We thank the reviewer for this comment. Indeed, a reflection on governance is a crucial and specific contribution of this paper. We address governance in the box regarding societal norms and values, providing a set of criteria that can be used as a framework for governance of Digital Twins of the Earth. When worked out further, this should include data privacy, intellectual property rights and fair use. We propose that the latter are aspects of a wider ethical, legal and societal oriented socio-technological assessment perspective (see below).

Drawing from expertise from some authors in digital twin frameworks within the Destination Earth program, we remind readers that the regulatory aspects are governed by law, such as the GPDR in Europe, addressing data privacy issues. IP is generally arranged in contracts between developers and owners. We stress the need for open licenses for data and software to ensure the widest accessibility and possible. The current lack of equity on data access (see, for instance Westerlaken (2024), where the case for biodiversity data and information is made) needs to be addressed in the governance.

In general, the governance of new technological innovations such as digital twins is supported by accompanying socio-technical research on the ethical, legal, and societal aspects (ELSA), as it has been pioneered in ELSA research on the human genome project (Zwart & Nelis, 2009) and in health care (Matheny et al 2020), and is now, for example, done in ELSA labs addressing the impact of AI (van Veenstra et al., 2019). An important aspect is to gauge the societal acceptance of the innovation (e.g., Wüstenhagen et al., 2007) and to understand how people adopt, and are affected by, the innovation, from the micro-level of individuals to the macro-level of society (e.g., Greenhalgh et al., 2017). Related research efforts involve citizen science, technology co-creation processes with stakeholders, and human-centric and value-sensitive design approaches (e.g., Friedman & Henry, 2019). We

recommend applying the same design and research principles to the development of digital twins of the Earth, to create an evidence-based and democratically enacted basis for a regulation and governance.

We expanded the paper on these governance issues, in particular at the end of section 4.

7. The conclusion should highlight the main findings and recommendations of the study. It is advisable for the authors to summarize the key contributions of the study in the conclusion and propose directions for future research.

We summarized more concisely our findings.

8. The introduction and the chapter of 'Current climate information practices' both delve extensively into climate-related content. While I acknowledge the significance of these topics as primary motivators for the development of the digital twin of, it is too many in the title of Humans and Digital Twins of the Earth.

We appreciate the comment and shortened this part. However, we would like to emphasize that the motivation for this paper, and digital twins of the Earth developments are based on climate models and Earth observations or that form a backbone of many policy decisions regarding climate change and sustainability. We identify that human behavior and use by humans should be considered more.

Minor Points

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We agree and emphasize that now.

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We appreciate the remark. There are many technical and conceptual frameworks schematized in flow diagrams published already, and we do not want to duplicate those schemas. Given that recent literature already provides such diagrams (Bauer et al 2024, for instance), we choose to expand on issues beyond such technical

frameworks. Thus, we indicate the limitations and need to expand current frameworks. We clarified the caption and the reference to the figure in this respect.

Reviewer #2 (Remarks to the Author):

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The text flows well in the manuscript. However, the citations should offer a wider view to digital twins than just the climate modeling. The above-mentioned narrowness of thought is a challenge, as is the following disconnection with the state of the art.

We thank the reviewer for these comments and appreciate the comment that digital twins of the Earth build upon the legacy of digital twins that have been developed

before. Clearly, these include urban digital twins, which have a clear policy relevance. We elaborate on the foundations of digital twins in the paper in more detail now and refer to relevant literature. Papers mentioned by the reviewer (e.g. (Lethola et al 2020, Jeddoub et al 2023) and a recent paper by Batty (2024) address digital twins of cities, and also take a wider perspective on digital twins.

Because of the impacts of climate and environmental change across and between sectors, digital twins of the Earth have many applications. We see digital twins of the Earth as a system or ecology of twins that are interoperable and not one centralized system. These will include other twins. So, we don't foresee a singular twin of the Earth, but rather a system of systems. Second, interactivity of users with these systems is key, and this is why we stress co-creation and design principles on the development and use of digital twins of the Earth.

We adapted and elaborated on the view of digital twins of the Earth as a system of systems in the introduction and conclusions, to clarify that we don't foresee a singular digital twin of the Earth and that these twins will build on the legacy of other digital twin developments.

Other comments:

General theory of systems may be considered to demonstrate the challenge of including the human interaction.
Including human factors necessitates the overall system dynamics to be modelled in a fundamentally different way.
Would DTEs just be based on numerical simulations or could there be, e.g., ontological or other models also?

We thank the reviewer for this comment. A complex systems approach is indeed fitting to the concept.

The incorporation of humans in the virtual representation as well as the utilization of twins, implies that digital twins of the Earth are not merely numerical models. Numerical climate models, or emulators of those, are part of the core of the system, but also agent-based models to simulate human behavior are included. It is foreseen that machine-learned models, including unsupervised learned models, will also be part of the system of digital twins.

Here, DTEs are lifted over all other state of the art DT techniques:
l385: "The use of DOE generate a social innovation that is initially not part of the digital twins themselves and,
hence, needs to be included retrospectively."
Why should this be the case? Has such social innovation not been already realized by other DT techniques?

We do not intend to lift digital twins of the Earth over other twins and acknowledge both the legacy of digital twin developments and that digital twins of the Earth are embedded in families of twins. While social innovation has taken place in relation to already existing digital twins, including industrial or urban twins, as mentioned above such a social innovation process has not been realized for digital twins of the Earth yet.

Please elaborate the precision and accuracy of the data used in these models:
l105: "In current climate information practices, the uncertainty in future change is estimated through assessing the likelihood of alternative climate states derived from global and regional climate models."

The phrase refers to the spread in output of ensembles of global climate models which is a compounded signal of uncertainty in model formulation (i.e. the virtual representation of the real word), internal variability due to nonlinear dynamics of the physical climate system and uncertainties in future external forcings (e.g. pathways of future greenhouse gas emissions, aerosol loading, land use changes, and solar variability; see e.g. Hawkins and Sutton 2009, BAMS). This spread is largely irreducible when coupling global models to regional and sectoral models and hence cascades through the system.

Also, please elaborate the accuracy/precision and/or limitations of the data available for the human interaction part.

The scope of social data is enormous. Uncertainties will depend on the user query and the relevant data for that used to address the query. However, we can generalize when it is about social data at larger scales. In a number of countries (including the Netherlands and the Scandinavian countries) there is the possibility, through the use of administrative register databases, to map out the formal network of contacts in society. For example, because of the needs of epidemiological modeling for dealing with the COVID-19 pandemic, in many countries surveys have been conducted so that the more informal and fleeting daily contacts between people are also possible to estimate. These data can be leveraged using statistical techniques, to be used as backbone for a much wider variety of human interactions, with each other as well as with the natural environment. It is an active topic of research to estimate potential biases in such datasets and their consequences for models. The finest granularity might only be directly accessible in a limited set of countries. However, all UN member states conduct regular censuses, which provide robust constraints. Combined with surveys covering behaviors, there is a good prospect that statistically reliable modeling can be done of the human component of DTs.

Thank you for this comment, we elaborate on this in Section 4A now.

References:

Batty, M. (2024). Digital Twins in City Planning. Nature Computational Science. https://doi.org/10.1038/s43588-024-00606-7.

Bauer, P., Hoefler, T., Stevens, B., and W. Hazeleger (2024). Digital twins of Earth and the computing challenge of human interaction. Nature Computational Science. https://doi.org/10.1038/s43588-024-00599-3

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Decision letter and referee reports: second round

11th Jun 24

Dear Professor Hazeleger,

Your revised manuscript titled "Humans and Digital Twins of the Earth" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment under the open access CC BY license (Creative Commons Attribution v4.0 International License).

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Heike Langenberg, PhD
Chief Editor
Communications Earth & Environment

On X(Twitter): @CommsEarth

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

I have no additional suggestions and recommend acceptance

Reviewer #2 (Remarks to the Author):

The authors have revised the manuscript according to comments, including adding the concept of system of systems to balance the text.

Please elaborate briefly on the system of systems concept, and how the authors understand that. E.g. How are humans represented in the system? How would the interface between the humans and the system be realized? Include examples, e.g. through the state of the art. Overall, this is a minor recommendation.