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Digital twins of the Earth with and for humans

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Digital twins of the Earth are digital representations of the Earth system, spanning scales and domains. Their purpose is to monitor, forecast and assess the Earth system and the consequences of human interventions on the Earth system. Providing users with the capability to interact with and interrogate the system, digital twins of the Earth are decision support systems for addressing environmental challenges. By informing humans of their impact on the Earth system, digital twins aspire to promote new pathways moving forward. By answering causal queries through intervention analysis, they can enhance evidence-based policy making. Existing digital twins of the Earth are primarily technological information systems that represent the physical world. However, as the social and physical worlds are intrinsically interconnected, we argue that humans must be accounted for both within and outside digital twins of the Earth: Within twins to represent human impacts and responses that are integral to the Earth system; and outside twins to govern access and development and to guide responsible use of information acquired from twins. Incorporating human interactions in digital twins of the Earth represents a transformative frontier, promising unparalleled insights into Earth system dynamics and empower humans for action.

Humans are unequivocally causing climate change, while simultaneously being vulnerable to its impacts[1,2] (see Table 1 with a glossary for further definition of keywords and concepts described in this paper). The effects of global climate change are now relevant at the individual level, impacting both lives and livelihoods. This is particularly clear in the case of intensifying and more frequent extreme weather events[3], which increases hazards and vulnerability. The impact of these events depends not only on their physical nature, but also on the organization of society and its institutions, the level of disaster preparedness, and the effectiveness of responses. As the climate changes beyond the range of past experiences, so will the impacts[4]. Climate action is therefore urgent to enhance resilience and mitigate expected damages.

The importance of climate change, its implications for the planet and human well-being, and the urgent need to respond to it is well recognized beyond the scientific community. In the policy realm, the Paris Agreement in 2015 was a landmark, legally binding treaty in which nations agreed to limit global warming to two degrees above pre-industrial levels. Climate action is also an integral part of the UN sustainable development goals. Beyond global climate policies, the practical implications of climate change are already impacting human activities. Decisions must therefore be made on how to increase resilience globally and locally. These decisions are often accompanied by wider sustainability challenges of just and fair societal transitions aimed at preventing—and ideally reversing—growing social and geographical inequalities[5].

As individuals are already directly experiencing the impacts of climate change, understanding human values and responses is as relevant for climate change information as understanding physical climate change. For example, accurate local information can stimulate bottom-up societal

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Table 1 | Glossary of keywords and concepts related to humans and digital twins of the Earth

Keyword/Concept	Definition
Acceptance	The willingness of individuals and society to adopt and integrate new technologies or practices.
Accountability	The responsibility and transparency associated with the actions, decisions, and information produced by digital twins of the Earth, ensuring that users can trace and understand the outcomes.
Actionable information	Information that can be used to make informed decisions and take specific actions.
Agency	The feeling of control over actions and their consequences.
AI (Artificial Intelligence)	A field of computer science dedicated to creating systems or machines capable of performing tasks that typically require human intelligence, such as learning and problem-solving.
Calibration	The process of adjusting the performance of a device or instrument to correspond with a certain standard and diminish uncertainty and error.
Causal inference	The process of deducing and understanding causal relationships between variables based on observed data and evidence.
Cause-Effect Estimation	The process of quantifying the relationship between a potential cause and its effect, often using statistical methods to estimate the magnitude of the effect.
Climate change	Long-term changes in temperature, precipitation, and other climate conditions, primarily caused by human activities.
Climate change information	Timely and relevant guidance based on data and other sources to inform responses to mitigate climate change and adapt to the impacts of local and regional climate change.
Climate information	Data and insights related to climate change, including both current conditions and projections.
Climate models	Mathematical representations of the Earth's climate system used for simulations, reanalysis, predictions, and future projections.
Co-creation	Design process with participation of the stakeholders, ensuring that all needs of the object to be designed are being considered.
COP	Conference of the Parties: The decision-making body of the United Nations Framework Convention on Climate Change. The first annual COP meeting was held in 1995.
Copernicus Climate Change Services	An ambitious initiative contributing to climate information assimilation and dissemination.
Decision-making	The process of making choices or reaching conclusions, often informed by data, evidence, and information.
Deep uncertainty	Significant uncertainty in predictions, especially in the face of unknown future events or developments.
Democratizing	Making the information in digital twins and use of digital twins accessible to everyone; ensuring that all people have equal access or participation.
Destination Earth (DestinE)	A European program building on the Flagship proposal for Extreme Earth, aiming to create digital twins of the Earth for extreme weather and climate change decision-making.
Digital representations	Graphical or interactive depictions of Earth and its systems in the digital realm.
Digital Twin Earth (DTE)	A comprehensive conceptual framework involving interactive digital representations of the Earth, supporting decision-making, exploration, and understanding of the Earth system dynamics on various scales. The conceptual framework also emphasizes the human dimension and the interconnection between multiple digital twins addressing different user demands.
Digital twins	Concept derived from industrial applications. Digital twins are digital representations of a process or a system (also a single object or living being), in many cases continuously being updated using observations of reality. Digital twins empower decision-making by predicting the behavior of the represented process or system in diverse scenarios. Users can impose these scenarios on the twin to explore the ensuing consequences. Such scenarios can consider, e.g., interaction of the system with other systems or human intervention.
Distal	Situated further away in time or space from a certain reference.
Earth system	The interconnected physical and social systems of the Earth.
Evidence-Based Policy Making	Policy decisions informed by empirical evidence and data to inform decisions, aiming for effectiveness, efficiency, and positive outcomes.
Equitable	Treating everybody fairly and impartially
Extreme weather events	Unprecedented and impactful weather occurrences such as heatwaves, fires, floods, and droughts, often defined by statistical measures.
Fair use	Ethical and equitable utilization of information and resources, ensuring just outcomes for all stakeholders.
Fairness	The ethical consideration and equitable treatment of stakeholders in the development, access, and use of digital twins.
Global warming (cf. climate change)	The phenomenon of increasing average temperatures on Earth, primarily caused by human activities.
Governance	The system of rules, practices, and decision-making processes applied to the development, use, and access of digital twins, ensuring responsible and ethical handling of information.
Granularity	The scale or level of detail present in certain information, a set of data, or analysis.
Human dimension	The inclusion of human impacts and responses.
Human in the loop	The integration of human input, decision-making, and expertise within the digital twins of the Earth, emphasizing the active role of individuals in generating and using information.
Information practices	Methods and approaches used in providing and managing climate change information.
Interaction	The dynamic engagement and collaboration between humans and digital twins, involving feedback, (causal) queries, and iterative processes to enhance understanding and decision-making.

Table 1 (continued) | Glossary of keywords and concepts related to humans and digital twins of the Earth

Keyword/Concept	Definition
Intervention Analysis	Examining the effects of human actions on the Earth system through digital twins. A method used to assess the impact of interventions or actions on a system by analyzing the causal relationships and outcomes associated with the interventions.
Just	Based on or behaving according to what is morally and ethically right and fair.
Knowledge gap	The lack of specific understanding about future climate conditions, particularly in the Global South, hindering adaptation and risk assessment.
Machine Learning	A branch of artificial intelligence that focuses on developing algorithms and models enabling computers to learn and make predictions or decisions from data.
NWP (Numerical Weather Prediction)	Computationally intensive model systems, based on numerical representations of physics of the atmosphere. When initialized from observed data NWP systems generate weather forecasts with uncertainties.
Paris Agreement	A legally binding international treaty that aims to limit global warming to two degrees above pre-industrial levels and ambition to one and a half degrees above pre-industrial levels.
Power	The capacity or ability to direct or influence others' outcomes or the course of events.
Proximal	Closer or nearer to the point of reference or origin.
Resilience	The ability to withstand, recover from, and adapt to adverse conditions, such as the impacts of climate change.
Societal transitions	Shifts in society to achieve just and fair development, often related to sustainability challenges.
Specificity	The quality of belonging or relating uniquely to a particular subject.
Standardization	The process of creating uniform practices and standards to improve collaboration and communication in climate science and modeling.
Sustainable Development Goals (SDGs)	Goals established by the UN to address global challenges, including climate change, resource scarcity, and urbanization, with a focus on broader societal well-being. These goals, adopted by the UN members in 2015, form an urgent call for action by all countries in a global partnership.
Systematic biases	Systematic under- or overestimation of physical quantities by models due to inaccuracies and limitations in models systems.
Technological information systems	Information systems enabled by innovations in data-driven methodologies.
Transformative frontier	A boundary pushing toward significant changes and advancements, particularly in the interaction with digital twins of the Earth.
Trustworthiness	The reliability and credibility of information, particularly in the context of digital twins.
Twin	In the context of this work: see "Digital Twin".
Uncertainty	Lack of precision, predictability or knowledge, particularly in the context of climate change models and outcomes.

initiatives in support of climate action, which can trigger cascading coordination effects by the actors involved[6] and promote the effectiveness and stability of policies to respond to climate change[7].

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. These, in combination with the expected actions, will inspire anthropogenic interventions[8]. These practices can be problematic because of systematic errors in climate models[1], with cascading uncertainties from global physical climate change to local societal impact. Additionally, uncertainty in the societal response is as important as physical uncertainty, yet not well quantified and uncommunicated[9]. Similarly, the likelihood of extreme events that have not been observed (e.g., the collapse of the West Antarctic ice sheet) cannot be well estimated. Under such deep uncertainty, providing actionable and accurate climate-related information to humans to support their responses and empower them at global and local scales is challenging[10]. To address this challenge, our current climate information practices need to be innovated to include questions of sustainability, equity, and just societal transitions.

The need for a substantial improvement in the quality of climate information, in addition to new scientific and technological developments, has led to the concept of interactive digital representations of the Earth[11]. These so-called "digital twins of the Earth" aim to inform and support decision making on climate change[11]. Digital twins have been developed originally in the context of industry[12] and since then they have evolved and have been applied as decision management tools for many sectors such as city planning[13].

Empowering humans by interacting with data directly, for example by enabling exploration of the consequences of different climate actions, digital twins of the Earth also aspire to enhance decision-making[11]. Various institutions worldwide pursue such a framework, including the European Commission's Destination Earth[14], NASA's Earth System Digital Twin[15], and NVIDIA's Earth-2[16]. These programs have a strong technological focus. We argue that, in order to empower action on climate change, digital twins of the Earth must be extended to consider humans, their behavior, and their institutions.

The need to be mindful of humans when developing and using digital twins is consistent with the aspiration for their use to support responsible decisions on climate change. Furthermore, it reflects the notion that human behavior is both a factor influencing and influenced by climate change. In order for humans to co-create information using digital twins, rather than only being objects represented in the system, they must be engaged in generating climate information[17]. When considering humans interacting with digital twins in practice, questions arise concerning governance, access, trustworthiness, acceptance, responsibility, values, and fair use of the information both used and produced by digital twins[18].

This article presents an overview of how climate change information is typically provided to humans, in addition to the advancement that digital twins are anticipated to bring. There is a large body of literature on digital twins for various sectors and applications, but digital twins of the Earth are a more recent innovation which focuses mostly on the natural Earth system and their representation through digital technology. The innovation of our work is to address the social context. We consider humans and their institutions both *within* and *outside* digital twins of the Earth. While there are many relevant societal actors for digital twins of the Earth, for instance their developers, professional users of climate information, and the general public, the reference to humans is made in a broad sense. Our emphasis on the human dimension builds upon existing work on digital twins of the Earth, including Bauer et al.[11]. who introduced the concept of Digital Twin Earth and who focused on new levels of information quality and interactivity, and on Bauer et al.[19] who introduced human interactions from a technological perspective. We also build upon Li et al.[20] and Hoefler et al.[21], who addressed their functional components. In contrast to digital twins that represent purely technical systems, we consider a digital twin of the Earth to be part of an interconnected ecosystem of functional or modular digital twins, a system of systems, capable of addressing diverse user demands. Here, we focus mostly on decision making in the context of climate change as an application of digital twins of the Earth.

Current climate information practices

While processes for transferring knowledge from scientific climate research to society are in place, their impact is often limited to support humans from global to local levels to address climate change. For example, the IPCC has been instrumental in providing authoritative scientific knowledge to decision-makers via Assessment Reports[2]. Institutions worldwide translate and customize the compiled information, and incorporate relevant local knowledge, to enhance climate services aimed at assisting humans to address climate change[22–24].

This relatively slow and rigid process can be viewed as an upstream-to-downstream mechanism[25,26]. Projecting future climate change often starts with global numerical climate model simulations that provide information on future climate under a variety of plausible storylines of future societal development and associated emissions[27,28]. Global climate data, with uncertainties accompanied by both explicit and implicit ambiguities and gaps in knowledge, cascades to regional and sectoral models. This process aims to generate regional and sectoral data on future climate change based on the global change scenarios, resulting in large uncertainties. It can take up to a decade for data and knowledge from the upstream scientific basis to flow into human action, hindering rapid responses to climate change. Hence, there have been calls to operationalize and accelerate this process[29].

Humans consider multiple perspectives when responding to climate change, and physical climate change may not be the most dominant priority. In order to generate information that best supports decision-making, participatory methods have been proposed to collaboratively information involving both the scientists generating the data and the end-users of such information[17,30]. However, many climate services only consider co-production in the last part of the knowledge exchange chain[8]. Digital twins promise to facilitate collaborative design by enabling users to influence the initial generation of information and by prioritizing timely access to that information.

When starting from the needs and values of humans, co-creation and interactivity can occur naturally. This is because the climate information generated is a direct response to human demands, explicitly reflecting the context and values of all those involved. Furthermore, local context and interdisciplinarity are ensured early, as human needs and values are, in practice, contextual and multifaceted. The benefits of this approach on co-creation between scientists and stakeholders are widely recognized[31–33]. This reversal of the data and knowledge exchange towards a downstream to upstream mechanism makes it immediately clear that humans are key and at the core of any climate information system design.

Regardless of the direction of data and knowledge flow, there is huge demand for accurate and reliable climate data[34]. Despite advances in observing systems and climate modeling, important physical processes that shape the global climate, such as boundary layer processes, clouds and convection, are not explicitly simulated. This leads to the persistent presence of systematic errors and biases in the representation of climate and weather extremes[35]. Similarly, sectoral models, such as those related to water, agricultural, and energy systems, face challenges in representing the systems they simulate[36,37]. Relevant data at the human scale is often parameterized, unimodal with a focus on the physical system only, and biased by systemic and cascading errors. Improving models and increasing the spatial resolution will partially remedy this concern[38–41]. However, in spatio-temporal simulation models, moderate improvements of resolution can increase computational costs by orders of magnitude, potentially hindering substantial further improvement. At best, conditional probabilities of climate change at regional and local scales will be better estimated.

Alternative climate modeling approaches are developing to improve coarser Earth system models with machine learning[42], which are computationally cheaper and lead to reduction of systematic errors[43]. Although the representation of local climate is likely still insufficient to directly drive sectoral models.

It has been argued before that two additional innovations are needed to deliver actionable climate information: 1) a leap in information quality from the global up to the human, experiential scale; and 2) a high degree of interactivity such that humans can interrogate the information system and get accurate, falsifiable, and traceable answers to their (causal) queries[11,19]. Here, we argue that this implies that humans and their institutions must be integral to such an information system. The existing conceptualization of digital twins already foresees the fast provision of digestible information for local and timely responses, with potential to seamlessly integrate information back into the digital twin and thereby close the feedback loop between users and digital twins. Below, we reason that the interaction of humans with digital twins and their context, such as location and culture, should also be considered.

Digital twins

Building upon domain-specific theories and concepts from a range of applications, such as industry[12] and city planning[13,44,45], the weather and climate community is developing digital twins of the Earth. The theoretical underpinning of the framework of digital twins of the Earth is conceptual[11,19]. This framework originated from more generic digital twin conceptualization, often attributed to product life-cycle management[12]. The computational and data management underpinning for digital twins of the Earth is grounded in computer science[20,21]. Digital twins of the Earth will rely on proven digital 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 and across high-performance computing systems thus become paramount[46]. Workflows would have to be executed fast and in a controlled manner. This requires cross- and intra-system orchestration and task-scheduling frameworks[47]. The theoretical underpinning of the subsystems that are part of digital twins of the Earth are domain specific. 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 are the basis of the human interactions with digital twins of the Earth. This has been explored for other digital twins within several applications, including energy systems and health[48,49].

Digital twins of the Earth are built on the wealth of Earth observations, in combination with enhanced weather and climate modeling capabilities and data assimilation approaches supported by machine learning approaches. The aim is to achieve a leap in the quality of information and enhance interactivity. A key characteristic of digital twins is the twinning of a physical entity such as the Earth system which can include human society, with one or more virtual entities, where data flows from the physical to the virtual entity and feeds back to the physical entity[50]. Digital technologies have the potential to provide global data with local granularity, in a way that facilitates human interaction with the data[51]. Digital twins of the Earth should allow multiple human perspectives to be considered and provide information that is not limited to the few pathways generated by climate models but, rather, integrate data from societal and ecological domains. By integrating and generating new data, digital twins could provide information that is better suited to informing decisions that individuals need to make within their specific contexts.

Digital twins of the Earth are designed with the goal to allow users to: 1) monitor the state of the system; 2) forecast with uncertainties; and 3) interact with the system to explore the response (or lack thereof) to interventions from global to local scales and at different temporal scales. They allow humans to interrogate the digital twin and interactively ask "what if" questions. In this way, tailored, accurate, and actionable information is presented. Engaging with digital twins empowers individuals through direct involvement and establishing a direct connection to the user's specific question context, thereby supporting them in decision making.

Digital twins monitor the impact of interventions either in the real world, being updated by data in near-real-time, or virtually to develop "what-if" scenarios of human interventions that affect future climate development. Digital twins have been developed representing environmental systems at various scales and with various levels of complexity: from geospatial digital twins of cities using geoinformation systems technologies that support spatial planning decision making[45], to digital twins of river basins for supporting water management[52], up to the European Destination Earth digital twin[14] that has the ambition to represent the global Earth system. Under the Destination Earth program, a digital twin that integrates high-end global weather and climate models and data with information on weather and climate impact (related to e.g., water management, energy, flooding and health) is in development. Several use cases studies within the Destination Earth program pilot the practical implication of a digital twin of the Earth for extreme weather and climate adaptation.

In social sciences, digital twins are being introduced and used to describe and model social interactions. In this case, the "physical entity" twinned is the social construct we call human society. Such digital twins have already been used to assess the factors and behaviors that influence the spread of infectious diseases[53], or that influence economic inequalities[54]. In a similar vein, digital twins could help to assess how the behaviors of communities impact climate, as well as the influence of climate change on human behaviors.

Given the scope and scale of the problem, it is neither likely nor feasible for all humans to interact with a full digital twin infrastructure using traditional computational models. Therefore, digital twins of the Earth are envisaged to largely consist of machine learning models or emulators of subsystems of the Earth system that are interconnected. In this respect, it is useful to differentiate between scientific users and developers of digital twins, professional users employing the information for decision-making, and the general public.

Developers and scientific users will have access to high-end computational infrastructures, in addition to the competencies to fully use and interact with digital twins. Conversely, professional users and the public may not have these capabilities. Instead, they will need to query digital twins and explore options with low latency and without direct interaction with models and data. This is envisaged to be accomplished through the usage of machine learning models and the provision of access to digital cloud infrastructures. Additionally, visualization and the application of natural language models could allow for human-computer interaction[19]. This distinction of users, although driven by practical considerations (e.g., limited computational capabilities, technical and scientific competencies), raises questions on governance that will be discussed later in this paper.

For a user to trust information from digital twins of the Earth, the reliability of the information, transparency regarding data quality, and acknowledgment of uncertainties are crucial. Relevant uncertainties are associated with the quality of data, the epistemic uncertainty associated with the mathematics-based representation of the physical and social components of the Earth system in models, the stochastic uncertainty of represented processes, and the uncertainty in future societal and climate developments where these different types of uncertainty are compounded[55]. Here, and while we do not elaborate further, we acknowledge that meaningful mathematically based estimates of uncertainty cannot always be made, particularly under deep uncertainty[56] and ignorance and ambiguity[57]. Alternative techniques, such as storylines and futuring, have been suggested[10,58–60].

Humans and digital twin Earth

Existing characterizations of digital twins of the Earth have primarily focused on digital technology and the representation of the natural world in data and models[20]. In most studies, humans are perceived as users that are external to the digital twin. The prevailing viewpoint is that the lack of climate information prohibits improved decision making. This deficit view is technocratic, formed at a time when natural sciences dominated the field of climate science. While the importance of more accurate models and data of the physical Earth system is undeniable, improving both the context and trustworthiness of such information is essential. This includes considering the human element in interactions with digital twins, such as factors like the location, culture, and background[61]. Therefore, when developing digital twins, it is necessary to consider both the social and physical worlds. Social worlds are not only impacted by physical worlds, but also contribute to shaping what future worlds are possible. Humans are part of the system that the digital twins of the Earth replicate, and human behavior feeds back to those systems.

The position of humans inside the core of digital twins of the Earth

Human components can be included within digital twins of the Earth. Some sectoral models have already been implemented into physical climate models through a two-way coupling, enabling feedback loops. For example, dynamic vegetation models have included agriculture and land use, which are driven by human activity and on which climate responds[62]. More commonly, a one-way coupling is used, wherein data from climate models and observations serve as a boundary condition to sectoral models to assess the impact, conditional on physical climate change. When feedback between social and physical systems is strong, interactive coupling should be considered[63]. Current state-of-the-art models of social systems allow to account in detail for social strata with differing behaviors and preferences. Once calibrated, using data from official statistics for the economy, demography, and other relevant social indicators, there is a realistic prospect of expanding the scope of digital twins in this direction.

The complexity of digital twins of the Earth increases as more components are interactively coupled within the digital twin or when they are coupled to other digital twins within a system of systems[13], making computation, interpretation, and use more complicated and computationally expensive. A solution to the computational challenge is to replace components of digital twins of the Earth with data-driven models and emulators. These are typically far more computationally efficient than numerical simulations, although the training of these components can be expensive. Digital twins of the Earth can draw on recent advances in machine learning and causal inference to study the Earth system and climate change impacts[64].

By coupling multiple components, digital twins of the Earth can cover a huge phase space of options and pathways. It will be necessary to have transparency and provenance in how the digital twins produce the information. Interpretation and use will be more manageable in the process of co-production. If only information relevant to a specific action is considered, it will constrain the pathways to be considered. For instance, causal inference methodologies and Bayesian network approaches can be used to provide quantitative information on causes, effects, and uncertainties[65–68].

Compared to aspects of human impact on the climate, human behavior is poorly represented in climate models. In some models, aggregated behavioral aspects are included as part of the economy and certain strands of management and geography. Economic models are not explicitly coupled to allow for feedback in complex climate models, but they are an integral part of Integrated Assessment Models (IAMs) where a two-way coupling between societal sectors, economy, and climate is established[69]. However, due to their integrated nature, these models are coarse in their representation of the individual components of the climate system. This complicates the provision of meaningful information at regional and local scales.

While the full richness of social processes and the individual human experience have greater complexity than is feasible to simulate, more stylized models of social mechanisms are available and can be calibrated for use in numerical simulations. This level of detail would be appropriate for modeling the mutual interactions of climate change and human behaviors. In this way, social systems can be affected by the information created by digital twins of the Earth, leading to new social processes that could be integrated in updated versions of digital twins.

This implies that 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. So called 'natural experiments'[70] can be used to understand whether causalities and interactions correctly represented.

Detailed human interactions are often explicitly represented in digital twins of spatially smaller systems, such as cities. For instance, agent-based models simulate interactions between humans as agents through behavioral rules. Various social and socio-economic models and social data are used in such twins (e.g., economic forecasting agent-based models). These systems could be part of digital twins of the Earth, or at least interact with them, forming a family of digital interconnected twins. Furthermore, accurately simulating physical interactions at local scales can only be achieved in physical models with finer spatial resolution than that of global Earth system models that are currently foreseen in digital twin of the Earth programs.

The scope of social data is enormous. Uncertainties will depend on the relevant data and models that used to address a user question. We may generalize on social data at scales of groups of people. 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. Additionally, 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 use as backbone for a much wider variety of human interactions, with each other as well as with their 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 digital twins.

A picture emerges of digital twins of the Earth, wherein models and data illustrating the influence of human behavior on sectors and the economy, alongside agent-based models, constitute a network of interconnected Earth system components. These components are coupled to each other and the physical climate model. That is, human behavior will be represented within this interconnected system of systems that constitute the digital twin of the Earth. IAMs already have some of these capabilities, but they do not have the accuracy and granularity required at regional and local scales. Similarly, they lack the interactivity that is needed for a digital twin of the Earth, and they lack to provide the agency for humans to respond responsibly. Agency is envisaged to be provided by digital twins as networked systems of Earth system components represented with the help of machine learning, which humans can interact with, enabled by artificial intelligence.

Humans outside the core of digital twins of the Earth

The behavior of humans, including that of the organizations and institutions that are part of their distant and proximate worlds, is difficult to quantify from data and models[71]. Empirical studies explain human behavior related to climate and sustainability at multiple scales, but they cannot be generalized in a reductionist approach as with physical laws. The challenge of conceptualizing and modeling elements like human reflexivity and social concepts such as power, interest, and legitimacy, will be an important aspect for any digital twin. This makes it crucial to consider and guide the interaction of digital twins with society. In other words, the design of digital twins of the Earth must consider human aspects that cannot be captured in computer codes within the core of digital twins of the Earth.

The interactivity and democratization, that is, the access to a wide range of users of digital twins of the Earth, has the potential to empower humans. Humans who interact with the twins are subjects, rather than externalized objects, who have agency over how they use the information to inform their future actions and decisions. Humans construct meaning in their lives, inside and outside their social systems, and act on issues that are important to them. Digital twins should support humans to take responsibility for their knowledge about climate change, behavior, well-being, relationships, and roles within their local and wider communities. As a consequence, the social part of digital twins of the Earth must behave as an adaptive complex system.

The aspirations of digital twins of the Earth are normative. Ultimately, information from digital twins of the Earth aim to influence human action. It empowers humans to contribute to a climate-resilient society and advance wider sustainability goals. Such actions raise ethical questions that are not easily answered within the digital twins. The context of a human interrogating a digital twin is also important. Therefore, it requires insight into the values, norms, and ethical frameworks of users and developers of digital twins regarding the creation and presentation of the information these digital twins provide and how humans respond to that information[72]. The use of digital twins of the Earth generate a social innovation that is initially not part of the digital twins themselves and, hence, needs to be included retrospectively. This leads to a feedback loop between the digital twin and its users.

Acknowledging the human aspect of digital twins raises questions about who determines what is in digital twins of the Earth, who maintains and updates the twins, who gets access to them, and who takes responsibility for the consequences based on the information provided. More broadly, it asks how information from such a digital infrastructure is trusted and used in decision-making. Such questions have been addressed in the post-normal science literature before[73,74].

In institutionalized programs, such as Destination Earth of the European Commission, ownership and intellectual property rights are well defined within the context of the program. However, there has been less consideration for broader governance issues related to development of digital twins and responsible use by stakeholders (see Box 1). The initial aspiration of digital twins of the Earth – to enable and empower humans to achieve climate-resilient societies and meet sustainability goals – may serve as a guide for a governance framework beyond the data and software of the twin and potential legislation.

The aspiration is that a diverse range of users will be empowered, each within their specific contextual situations. Different levels can be considered, from the broadest level encompassing all of humanity to the smallest unit of the individual. Engaging users in co-designing digital twins of the Earth holds significant potential for democratizing the development and use. We therefore advocate for digital twins based on open science principles[75], with a strong emphasis on reproducibility aspects. In this way, local knowledge (e.g., through data and locally calibrated models) can be meaningfully incorporated into open software development and data sharing. The FAIR principles can be important guidelines for this process[76]. The link to a local scale introduces local knowledge and insights from the individuals using and contextualizing the information and data acquired from the digital twin.

Democratizing digital twins also means open and inclusive access. In existing digital twin Earth programs, the core of digital twins of the Earth involves sophisticated and complex software and high data volumes that can only be accessed and executed by scientists and experts on sophisticated digital infrastructures. This means that the development of digital twins has primarily occurred at knowledge-intensive institutions, predominantly situated in the global north. Meanwhile, the climate and sustainability challenges being addressed are interconnected globally. Therefore, and by adhering to co-development principles, efforts should be directed towards achieving broad access. Yet, the complexity of infrastructures and the limited computation resources result in limited access to technically advanced components of the digital twin infrastructure, such as high resolution global numerical climate models. Likewise, making huge datasets FAIR is a considerable challenge, and basic methods for this are still under development[77].

Accessibility is likely less of an issue for components built on top of these advanced models, and they could theoretically offer more specificity to the user needs and provide local granularity[19]. Nevertheless, constraints

Box 1 | Ingredients for governance framework of digital twins

Inspired by the work on digital public governance[74], a code for governance of digital twins of the Earth could involve three main components:

Democracy. Rules for (open) *participation* in digital twin development and access to use and access to information generated by digital twins, with attention for citizen engagement, inclusiveness, transparency and cooperation. Rules for *public value* of digital twins with attention for collective interest, sustainability, prevention of harm, and protection.

Rule of law. Rules for *procedural justice*, with attention for suitability, non-discrimination, explainability, user-friendliness, disputability and actionable and solution oriented approaches on climate action and sustainability challenges. Rules for *human rights* with attention for freedom of expression, privacy, human autonomy, and human dignity.

Governing capacity. Rules for *quality of governance* of digital twins, with attention for agility, knowledge, risk awareness, correction, security, efficiency and independence. Rules for *responsibility* with attention for accountability, verifiability, integrity, supervision, and human responsibility.

Many of these aspects can be encoded[8] in contracts of developers and users of digital twins of the Earth. These rules should be sufficiently broad to ensure responsible development and use of digital twins for the public good.

might arise, such as limited access to the internet. An open-access framework is needed for wider participation in co-developing these parts of digital twins and co-production of information. For the complex and computationally expensive parts of the twin, access will be limited by necessity, but users can still actively participate in the development process by expressing their needs and by having a representative voice in the development.

Such an inclusive approach poses technological challenges. It is difficult to anticipate which parts of the Earth system will need to be part of the information system, and at what scale. However, digital twin developers, in collaboration with users, do not necessarily need to make a choice beforehand. Flexibility could be built through an open and interoperable architecture, allowing developers to add and critically evaluate components. Open software governance models, such as those of Mozilla and Apache[78], can serve as inspiration, as can efforts - started in the last decade - to characterize and support proper Research Software Engineering[79]. Community, open, not-for-profit scientific software development institutions such as Numfocus[80] can also serve as an exemplar for scientific software development. FAIR data and similar open software principles[81] are already widely supported and should facilitate the interoperability of the data and simulators. Quality standards, as agreed upon in an international and representative community should be enforced, in addition to the establishment of a mechanism for admitting and integrating new components. These quality standards should cover technological software standards and consider values of openness and inclusiveness.

Information based on digital twins of the Earth is intended to support decision-making and lead to action. Therefore, ethical questions about the responsible use of the information will arise, but the responsibility of those accessing it is a matter of personal freedom. Transparency is needed in how the digital twins obtain information, and the quality of such information should be measurable. It should also be made clear that there is always inherent bias and subjectivity in the data and simulators that form the basis of such information[82]. Therefore, these uncertainties must be transparently presented to improve the trustworthiness of the knowledge and data communicated to users. Demonstrating competence, honesty, and reliability is needed for users of the information and usable evidence that allows others to evaluate the information. Explainable artificial intelligence methodologies can also inform humans how digital twins generate and integrate information internally.

All these aspects aim to improve the trustworthiness of the information from the twins and improve efficacy. Formulating guiding ethical principles for digital twin information can stimulate responsible use. Following a declaration by UNESCO on ethical guidelines for climate change policies, digital twins of the Earth should prevent harm through its information, follow a precautionary approach in case of serious threats or irreversible changes (even with incomplete knowledge), foster equity and justice, promote well-being and sustainable development, consider solidarity with vulnerable people, communities, and societies, and result in integrity in decision making based on scientific knowledge[83]. The work of COMEST, part of UNESCO, on core ethical principles for AI technologies inspires ethical principles for digital twins of the Earth by addressing a variety of aspects: proportionality and do no harm, safety and security, right to privacy and data protection, responsibility and accountability, transparency and explainability, human oversight and determination, awareness and literacy, sustainability, fairness and non-discrimination[84].

These principles depend on the context in which information is produced and used and can be reflected in the governance framework of digital twins of the Earth. Humans who steer the development of digital twins and users of the information generated by digital twins must deliberate on whether the information from the digital twins is consistent with these guidelines. The recent rise of AI has prompted a move towards ethical algorithms. However, given the complexity and interrelatedness of climate and sustainability challenges, we argue that it is necessary to have guidelines within the decision-making process where information from digital twins is used. Decisions and actions are embedded in power dynamics that can generate resistance, contestation, and conflict[85]. Therefore, understanding the context in which decisions are made is crucial, necessitating inclusive learning and deliberation involving both users and developers.

A global governance framework for digital twins of the Earth can address the issues above. The governance of digital twins must ensure that a diverse range of users and developers will be listened to and adequately represented during the development and maintenance of the twins. Global institutions, such as the World Meteorological Organization or other United Nations institutions, could provide the procedures and support to set up a governance framework of information systems, empowering the current and future generations to take action on climate change towards a more resilient and sustainable.

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[86] and health care[87], and is, for example, done in ELSA labs addressing the impact of artificial intelligence[88]. An important aspect is to gauge the societal acceptance of the innovation[48] and to understand how the innovation is adopted by, and affecting people, from the micro-level of the individual to the macro-level of society[49]. Related research efforts involve citizen science, technology co-creation processes with stakeholders, and human-centric and value-sensitive design approaches[30]. We recommend applying the same design and research principles to the development of digital twins of Earth, to ultimately create an evidence-based and democratically enacted basis for a regulation and governance structure.

Conclusion

Digital twins of the Earth, if well-designed, have the potential to engage and empower humans to respond to climate and sustainability challenges. By accessing reliable climate data from global to local scales and through interacting with data, humans can enhance their preparedness to adapt to

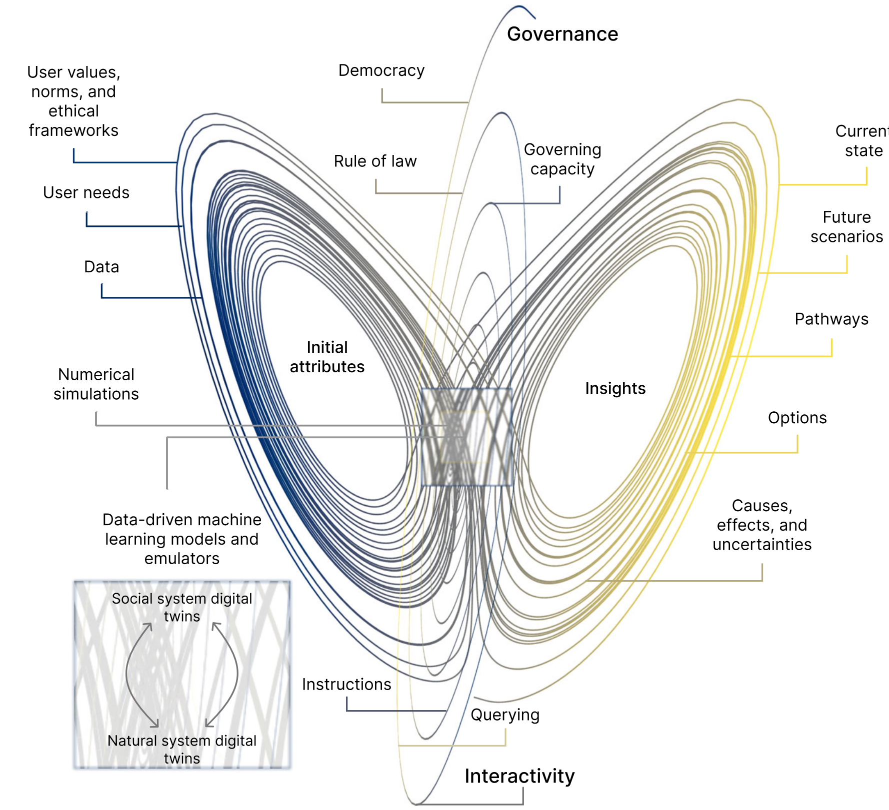

Fig. 1 | Artist impression of attributes related to humans and digital twins of the Earth. The left wing displays initial attributes, related to real physical and social worlds and the right wing shows the insights acquired from the digital twins of the Earth. The core of the digital twins of the Earth is in the middle, governance on top and the interactivity of humans indicated below. This schematic does not expand on the core of digital twins of the Earth, but emphasizes the human aspects to be considered when developing digital twins of the Earth.

extreme future weather and increase resilience. When digital twins of the Earth are designed and developed with users of the information in mind, and when they can deliver information aligned with the user's needs, context and values, they become a radical new concept compared to current climate information systems based on climate models and downstream cascading couplings. If digital twins are brought to scale, they can democratize the development and use of climate models and data and provide relevant information that can support action.

Aspects discussed in this paper are artistically represented as a (Lorenz) butterfly with interconnected 'wings', describing the initial attributes and information that can be acquired from digital twins of the Earth (Fig. 1). Most published schematized diagrams of digital twins focus on the technical and conceptual frameworks of the core of digital twins[19]. In Fig. 1 we extend to the human dimension discussed in this paper. Firstly, as initial attributes, we consider humans (users) and their needs, values, norms, and ethical frameworks guiding their actions as of primary importance, defining the observations, simulators, and other data utilized. Secondly, as information and insights, we consider representations of the current Earth system, possible future pathways and options to act, changes to these according to user inquiries, and quantitative information on causes, effects, and uncertainties. The connection between these 'wings' should be mediated by data, numerical simulations, data-assimilation systems, data-driven machine learning models and emulators using various social and natural system digital twins. Hence a digital twin of the Earth will be a system of systems which includes representation of aspects of humans. This system should be transparent and can grow using open scientific development principles under the guidance of a governing body consisting of all interested parties, including scientists, policymakers, and citizens and it should allow interactive steering by users.

We argue that governance is crucial for the implementation of digital twins of the Earth in support of just sustainability transitions. 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.

We conclude that digital twins of the Earth can only be effective if human aspects are considered in the design and implementation of the twins. Democratization and trust are key and will come from an open and inclusive framework accounting for humans, their actions, and their institutions.

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Author contributions
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Competing interests
All other authors declare no competing interests.

Additional information
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