Digital Twin Earth

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Scientific

The main aim of this workshop was to develop a new interdisciplinary research agenda on Digital Twins of the Earth. The proposed agenda will feed into European and other research programs, such as the science plan of Destination Earth.

The workshop brought together scientists from three communities: climate science, computer and data science and social sciences. Each of the three domains is of importance for digital twin development for environmental sciences and policies.

Key moments

1) The first key moment was the introduction of representatives of four communities (climate, climate impacts, social sciences, computer/data sciences), where each community could express their expectations at the beginning of the meeting. Pitches helped to clarify the scientific perspectives of each domain.
2) The second key moment was a reflection on the above after three days into the meeting. Where did we end up after three days of interacting?
3) The final key moment was the last day where we concluded that with each specific take on the problem, the common open issue was where and how humans are represented in digital twin Earth.
4) Socially, the meetings at Lorentz and the dinner led to very productive interactions.

Key debates

1) How do humans interact with digital twins, what questions are asked from the twin (note, we were amidst ChatGTP discussions)?
2) What is part of the twin in terms of modular components? What is included in these modules and how do they interact? Is this (computationally) scalable?
3) What is the role of AI in emulating processes in the Digital Twin Earth?
4) How humans are represented within digital twin Earth?
5) How is interactivity designed?

Outcome(s)

1) Key points summary (see attachment).
2) Perspective paper in preparation
3) Input for major strategic climate science meetings:
    a. EVE summit Berlin July 2023 (world wide activity on vitual earth engine for climate)
    b. DestinE scientific programming, input Scientific Advisory Board meeting in Brussels 29th of March (presentation of results of this workshop) and input for next Horizon calls.

Organization

See program of the workshop
https://www.lorentzcenter.nl/digital-twin-earth.html

Summary of workshop results

1. Digital Twin Earth

1.1 Why Digital Twin Earth?

* With the continuing warming of the Earth leading to potentially severe consequences for human-made and natural systems, there is an urgent need for actionable information to support decisions for optimal pathways towards climate resilient societies. Understanding and identifying these pathways involves multiple aspects of the earth system, from the atmosphere, lithosphere, hydrosphere, cryosphere and biosphere, and their complex interaction with the social, economic and political processes. These processes are connected across a large range of spatial and temporal scales.

*Computational models are a mainstay of climate science, but existing numerical climate models are not optimized to link to domain-specific climate impacts from global to local scales, as well as coupling to social systems. While there are currently computational models that address these processes they are generally executed and implemented in isolation, with only a few ad-hoc examples of coupling.

* Existing climate and climate impact data resources are not developed to be queried by users interactively to support their decisions. In order to evaluate optimal pathways in a holistic manner, we need a way (system) to couple models that capture multiple processes across different spatial and temporal scales in order to be able to make better decisions.

A Digital Twin Earth is the name given to the system designed to fill these gaps. The system will deliver trustworthy and actionable climate information with a much larger degree of interactivity and with a larger fidelity than current climate information systems can provide. This system should be accessible and designed in a way to aid decision makers and help them explore multiple potential pathways, assess their feasibility and understand their uncertainty.

1.2 What is a Digital Twin Earth?

* A Digital Twin Earth is a digital replica of the Earth system, including natural and human components, designed to allow users to: (i) monitor the state of the system, (ii) forecast with uncertainties, and (iii) interact with the Earth system to explore its response to a broad range of interventions (or not) at different scales. Forecasting under given conditions (scenario's) is envisaged with a high accuracy, the latter often achieved by a high spatial and temporal resolution.

* The core of the Digital Twin Earth consists of data resources from Earth system observations, simulations (from numerical and AI learned models) as well as simulators (numerical models and emulators) and combinations thereof such as data sets in which observations are assimilated or fused with simulators (e.g. Earth system reanalysis data).

* The core of Digital Twin Earth encompasses the full Earth system and is a networked, modular system of connected data resources and simulators, connecting global and local scales and various key components of the Earth system. The twin components are interoperable, guided by the FAIR principles, and open source.

* Digital Twin Earth contains our best possible representation of the trajectory of the state of the Earth System subject to estimates of past, and projected future changes, with more fidelity and greater accuracy than current model systems.

* Digital Twin Earth can be queried by multiple classes of users, all with different roles, all leading to different use cases which should be accommodated (see examples at the bottom).

* Digital Twin Earth should possibly have a natural language interface (ChatGTP-like) to query the twin.

* Digital Twin Earth offers full accountability, traceability, and transparancy of its output, including uncertainties of the output.

Digital Twins are tools long used in industry to help manage and operate complex and vital infrastructure. Nothing is more vital and complex than the Earth System. Our current tools are suboptimal and a Digital Twin Earth is thus an essential tool for sustainably caring for our planet.

2. The human dimension of Digital Twin Earth

2.1 Human dimension in the Digital Twin Earth

* Humans are represented in the network of data resources and models that are part of the digital twin. Their collective behaviour can be mimicked as well as individual behaviour of interacting agents.

* In principle both data and models of social systems, including institutions, can be integrated within the digital twin. Traditionally the social and natural components have been decoupled - in the sense that climate model forecasts are provided as input to economic models, and socio-economic model forecasts are provided as input to climate models (e.g. Integrated Assessment Models produce scenarios that are input to numerical climate models).

* However, there are important aspects of climate pathways in which there are vital feedback loops between the human and earth systems.

2.2 Humans interacting with Digital Twin Earth

* Users, individuals and institutions, interact with Digital Twin Earth by querying the twin for information to explore and support decisions.

* Users can have different levels of technical expertise and interactivity. It is useful to differentiate between scientific users, policymakers, and citizens.

* Answers can include pathways towards climate resilience that work and identify pathways do not work.

* Answers provided to the users by the digital twin are transparant, traceable, and accompanied by an estimate of relevant uncertainties. Transmitting the concept of uncertainty itself is challenging, and the system should be expressive of it in a quantitative way, but also in the fact that some uncertainties are non-determinable - extrapolation - and would limit the value of an answer.

* Users, and their institutions, co-create the Digital Twin Earth, where a feedback between the answers of the twins and the user perspective can lead to further (co)development of the twin.

* Users, and their institutions, interacting with the digital twin should be made aware of ethical, legal and societal considerations, aiming for responsible use according to democratic values further defined by the governing body.

2.3 The governance of Digital Twin Earth

* The Digital Twin Earth is governed by the developers, and their institutions. They decide what is in the Digital Twin and what not. The exact governance model is to be exploited (e.g. Apache, Mozilla, ...).

* Digital Twin Earth should democratize research through the inclusion of new models and data and through increasing the accessiblity of the twin.

* Ownership and accessiblity of the data from the Digital Twin Earth needs to be explicit. The design of this element of goverance will require social scientists (e.g. legal scholars) as well as the humanities scholars (e.g. ethics scholars).

3. What is new?

Global and regional climate system models and sectoral impact models of e.g. the water system, agriculture, energy systems, have been around and used for decades. IPCC is an effective boundary organization. Regulations and policies are in place on future emissions. Societies are adapting to current and future changes. However, Digital Twin Earths are new by virtue of:

- Accessibility across a wide variety of users and stakeholders, from scientists, policymakers to citizens;
- Interactivity and user interfaces for (the simulation of) interventions - real time model simulations, constrained by data, based on levers and tradeoffs to explore sustainability pathways.
- Bringing together and reconciling disciplinary communities that deal with these interventions differently;
- A user-friendly and reactive interface for exploring options in a responsible way;
- Being interactive across a range of space and time-scales and domains, operating at the scale of climate impacts, from the human - experiential - scale to global scales;
- Enabling interoperability across domains and their full data space;
- Enabling co-development of the digital twin based on the interactions with the twin;
- Providing provenance of models and data (a DT result is not a copy!), being FAIR, transparent and traceable;
- Coupling interactively, multiscale, multimodel with much larger fidelity than current coupled climate models, Integrated Assessment Models and climate impact models do allow for exploring feedbacks across natural and social systems;
- Computational efficiency at scale enabled by AI and emulation;
- Networked architecture instead of centralized system(s).

Because Digital Twin Earths aim to make data visible in ways that are unprecedented, surpassing the current imagination, they also raise new ethical, legal, and societal questions that may arise from the broader use and implementation of the twin.

4. What new research questions are raised by Digital Twin Earths?

A multitude of questions arise from the points above that have not been addressed systematically yet. Here are some that were identified at the workshop:

* How will users interact with Digital Twin Earths?
* What goverance model(s) are suitable for (the maintenance of) Digital Twin Earth?
* How to embed the ethical, legal and societal considerations in the twin and its interface (e.g. privacy concerns)?
* What are the dangers and risks of such systems being manipulated in undesirable ways?
* How to engage stakeholders in the Digital Twin design and when interacting with the digital twin?
* How can such a system, through interactive feedback, be co-developed?
* How to integrate across various modelling paradigms, i.e., gridspace based models, agent based models, and inference from networked models?
* How to integrate across scales, from the micro scale to global/macro scale and across domains and time?
* What are feedbacks between natural and social systems across domains and scales?
* How can AI be used beyond the training sample? [name=FIS] [time=Fri, 03 Mar 2023 8:53] What is the role of causality for AI solutions, and DTE in a broader sense? [color=teal]
* How can context and uncertainty be communicated to users of Digital Twin Earth Systems?
* What are the optimal strategies for exploring the space of possible Earth system trajectories?
* How can information content be structured and managed at the foreseen high spatial and temporal resolution and foreseen increase of interactions?

This requires new research disciplines and / or interdisciplinary collaborations involving climate science, including climate impact science, computer science, data science, social sciences, including psychology and behavioral science, sociology, ethics, law, and communication science.

5. Some illustrative examples

1. Managing water resources for agriculture in Europe, anticipating droughts and floodings, as well as long term spatial planning governance.
2. Assessing the resilience of tropical rain forests to warming and deforestation
3. Verifying carbon credits and emissions.