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Digital Twins of Planet Earth

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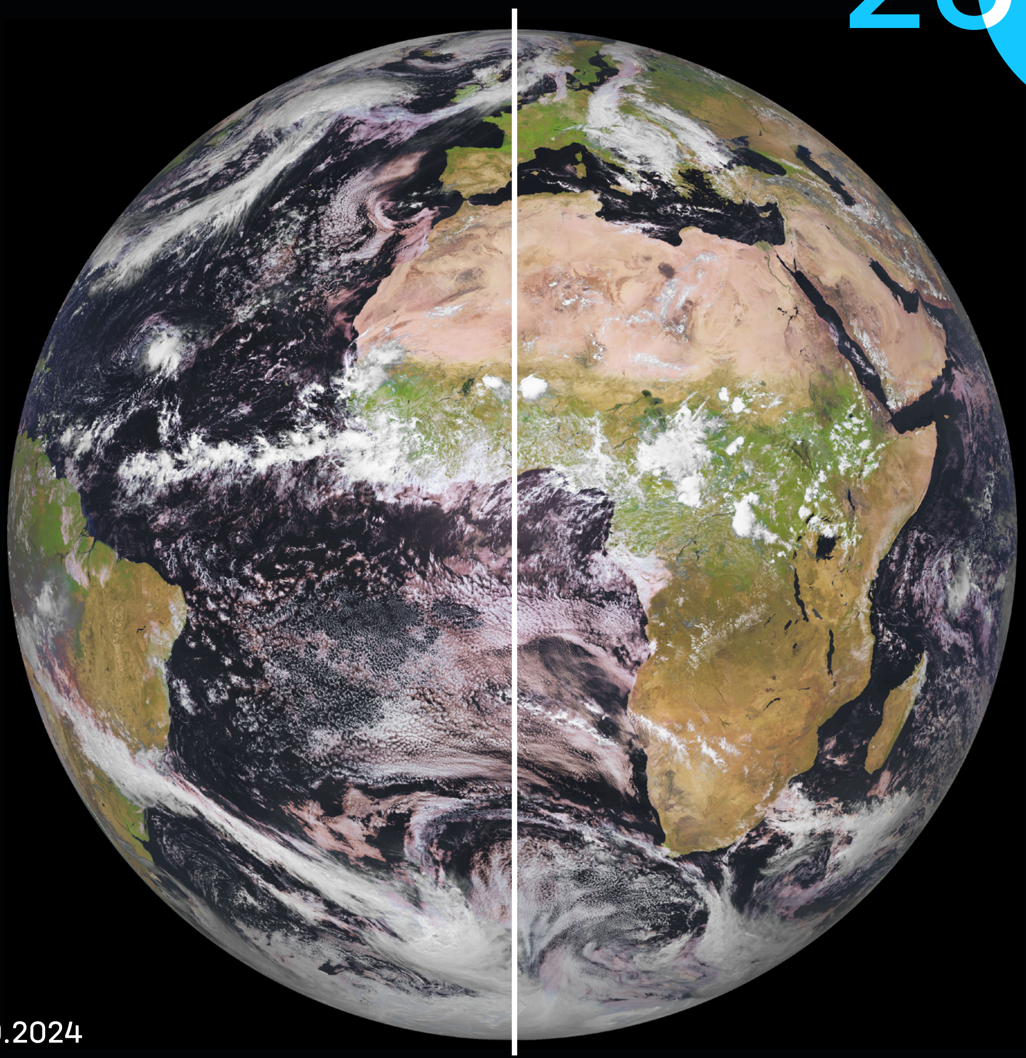

Digital Twins of Planet Earth

Sabine Attinger, Thomas Jung, Martin Visbeck, Franz Ossing

Peter Braesicke, Jean Braun, Sascha Brune, Mauro Cacace, Holger Gohlke, David Greenberg, Judith Hauck, Marie Heidenreich, Harrie-Jan Hendricks-Franssen, Corinna Hoose, Marion Jegen, Patrick Jöckel, Joana Kollert, Stefan Kollet, Eric von Lieres, Klas Ove Möller, Annemarie Müller, Magdalena Scheck-Wenderoth, Martin Schultz, Beate Slaby, Joanna Staneva, Claas Teichmann, Stephan Thober, Jan Vanderborght, Harry Vereecken, Sergiy Vorogushyn, Wolfgang Wiechert

The Anthropocene describes our current time where the environment of our planet is significantly shaped by human activities. Rapid growth in human population and affluence have triggered sustainability challenges across all parts of the Earth system. At the same time, advances in Earth observations, system models, and digital technologies now enable us to create „Digital Twins" of the environment. Digital twins combine Earth system data and models to generate highly accurate digital representations of planet Earth, helping us explore consequences of human development scenarios and assess their impacts on the environment. As a result, digital twins offer decision-makers a powerful decision support tool to balance human development, sustainable resource use and environmental preservation.

This document introduces the concept of digital twins of planet Earth and summarizes key initiatives within the Helmholtz Association's Earth and environment research.

What are Digital Twins?

A digital twin is an interactive virtual representation of a physical object, system, or process that is continuously updated with real-world data (see Fig. 1). It allows for monitoring, performance analysis, outcome prediction, and better decision-making by simulating how a system will behave under various intervention scenarios.

Originally used in engineering, recent advances in computing and data storage now make it possible to create digital twins of parts of the Earth system, which represents an information system that exposes users to a digital replication of the state and temporal evolution of the Earth system constrained by available observations and the laws of physics.

Thus, digital twins of planet Earth and its compartments offer powerful tools for understanding and managing human impacts on the environment. To provide reliable information, digital twins must be validated against observations and show strong predictive capabilities, ensuring they can support decisions in close to real-time.

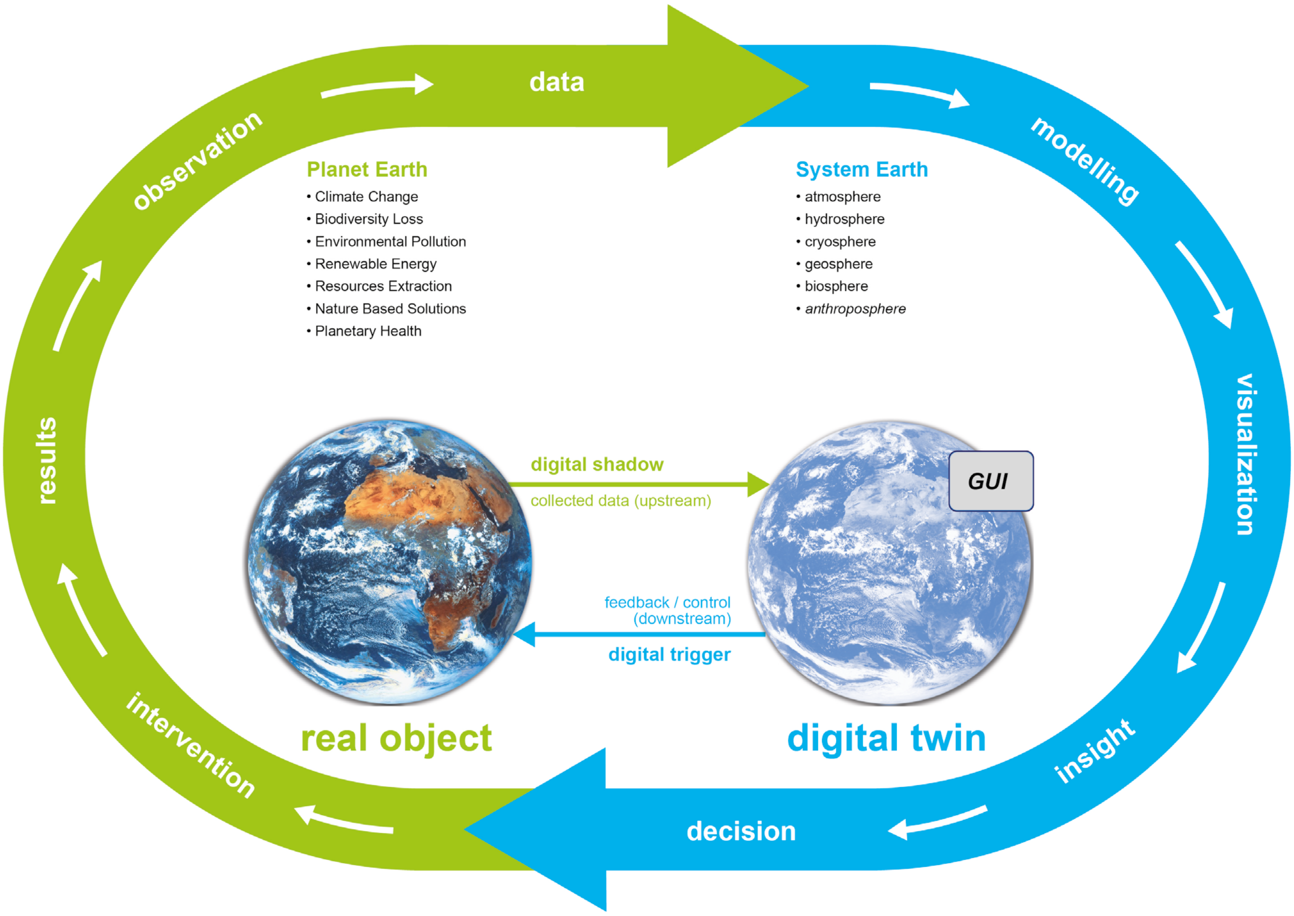

Fig. 1: Concept of the intervention-driven relation between a real Earth and its digital twin. (Graphics: G. Schwalbe/F. Ossing, GFZ, after Leopoldina Nationale Akademie der Wissenschaften (2022): „Zukunftsreport Wissenschaft. Erdsystemwissenschaft – Forschung für eine Erde im Wandel", Halle (Saale), 101 S., https://doi.org/10.26164/leopoldina_03_00590;ISBN:978-3-8047-4255-0).

Exploring „What If...?" Scenarios

Digital twins excel at answering „What if...?" questions by simulating the outcomes of different interventions. This enables decision-makers to explore potential consequences of actions and adjust management strategies accordingly. By continuously updating with new data, digital twins help monitor the interactions between human activities and natural processes. For digital twins to be effective, stakeholders and end-users need to be involved in the definition and co-development of the respective 'What if...' intervention scenarios.

Beyond actively engaging decision-makers, digital twins also provide opportunities for communication with a wider audience. A user-friendly interface (GUI) tailored to different stakeholders makes these systems accessible, while a flexible and interoperable architecture ensures that data systems are easy to use. This interface is critical for exploring the consequences of decisions and adjusting interventions as needed. By facilitating these interactions, digital twins contribute to achieving the United Nations Sustainable Development Goals (SDGs), particularly those related to sustainable resource management, climate resilience, and environmental conservation, ensuring their broader relevance to global challenges.

Digital twins enable users to test interventions, optimize management strategies, and mitigate unintended outcomes by customizing and coupling model parameters to define their own DT scenarios. A central element of the digital twin system is the data lake, a repository that stores all relevant data. This data must adhere to the FAIR (Findable, Accessible, Interoperable, Reusable) and CARE (Collective Benefit, Authority to Control, Responsibility, Ethics) principles. The FAIR principles ensure data is findable, accessible, interoperable, and reusable, enabling efficient sharing and integration. The CARE principles focus on the ethical use of data, particularly for indigenous and marginalized communities, ensuring that data serves collective benefits and respects community control.

What is the difference between a digital twin and a forecasting system?

The key difference lies in their purpose. Traditional forecasting systems aim to predict future states based on current data and the guiding dynamics of the system. In contrast, a digital twin not only generates forecasts. It allows users to interactively explore how predictions are changing when specific inputs are modified, e.g. accounting for the effects of human interventions or policy changes. This makes digital twins an ideal tool to provide a deeper understanding of potential outcomes under various intervention scenarios.

How AI will Improve Digital Twins

Artificial Intelligence (AI) has the potential to significantly enhance digital twins by enabling faster (real-time) data processing, predictive modeling, on-demand simulations, advanced visualization, and automated decision-making. In some cases, AI allows digital twins to continuously update with live data, providing immediate and accurate simulations of evolving conditions. This capability helps decision-makers to quickly test „what-if" scenarios and optimize strategies. AI-based emulators also offer faster, more flexible simulations compared to traditional models, while self-learning systems improve accuracy over time. Additionally, AI can automate decision-making by identifying optimal solutions, making digital twins essential for managing complex systems like climate resilience and resource management. As AI evolves, its integration into digital twins will push the boundaries of responsiveness, accuracy, and strategic foresight.

EU and UN Promote Digital Twins

At the European Union level, the European Commission is promoting digital twins through major initiatives like Destination Earth (DestinE) and the Digital Strategy, as well as domain-specific projects, such as digital twins of the ocean under the EU Ocean Mission. The Commission is funding the development of digital twins to better understand the impacts of climate change and extreme events, explore future scenarios, and enable rapid response measures. In addition, other components of the Earth system are also being developed as digital twins through various European initiatives under the EU Horizon science projects, including Water Twins, Biodiversity Twins, Ocean Twins (DTO), and Geo Twins. At the global level, the United Nations is also promoting the development of digital twins through the UN Ocean Decade and programs like DITTO, which focus on sustainable marine management and climate resilience. These efforts contribute directly to the United Nations Sustainable Development Goals (SDGs). In particular, they address goals related to climate action, life below water, and sustainable resource use.

Digital Twins in the Helmholtz Research Field Earth & Environment

The nine Topics in the research program "Changing Earth" of the Helmholtz Research Field Earth & Environment (see Fig. 2 and box below) provide the basis for an integrated overall strategy for Earth System DTs. The goal is to create a family of applied DT engines including a variety of data from models and observations. The long-term vision is to digitally represent the entire Earth system with high temporal and spatial resolution in a single DT framework.

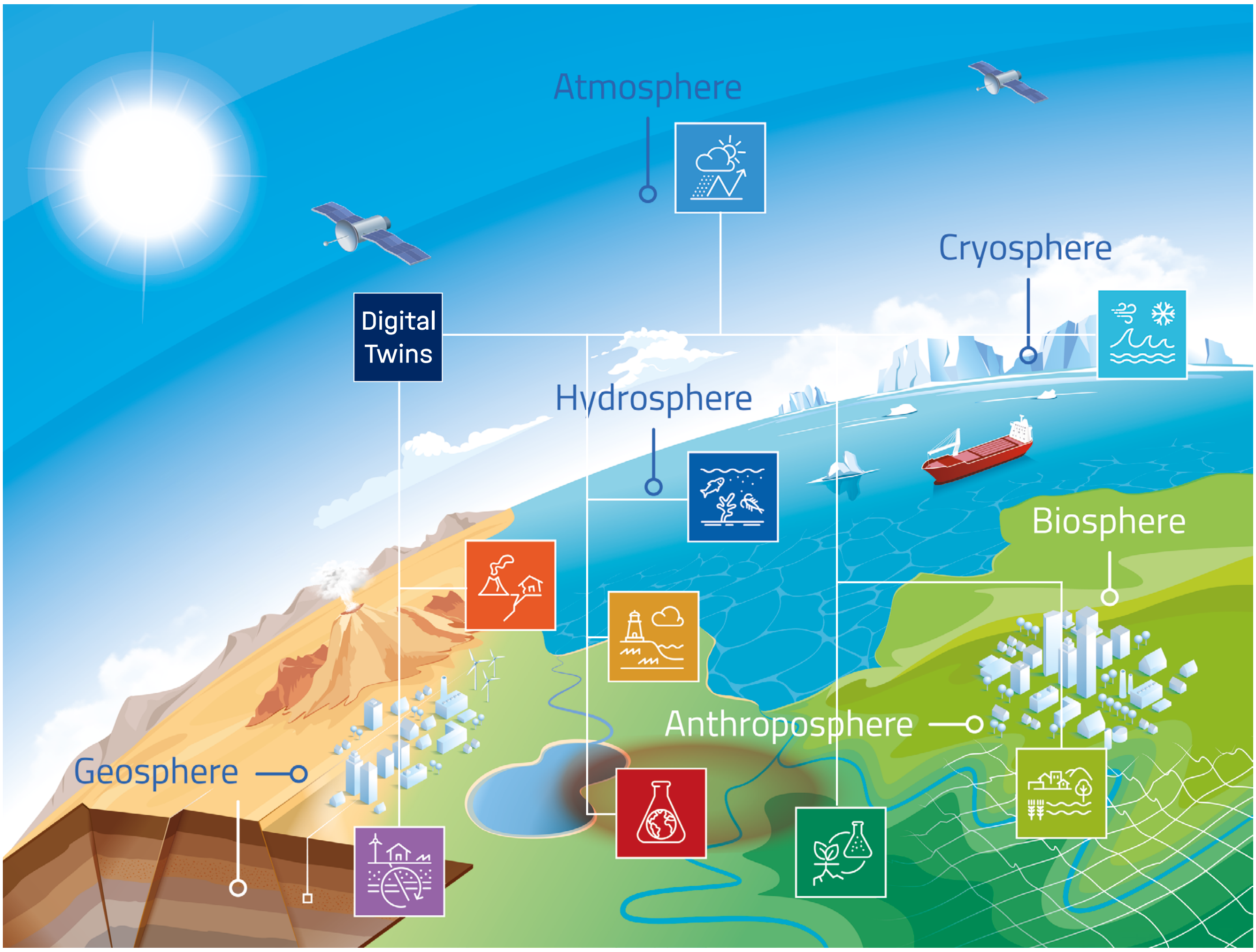

Fig. 2: The research program of the Helmholtz Research Field Earth & Environment with its nine Topics (icons) reflects the complexity of the Earth system with its six subsystems and their interconnectedness. (Graphics: Helmholtz Research Field Earth & Environment) © UFZ/dieaktivisten.

The nine Topics in the research program "Changing Earth" of the Helmholtz Research Field Earth & Environment

- The atmosphere in global change
- Oceans and cryosphere in climate change
- Restless Earth
- Coastal transition zones under natural and human pressure
- Landscapes of the future
- Marine and polar life
- Sustainable bioeconomy
- Georesources
- One healthy planet

The following examples outline the range of possible applications of DTs in the Helmholtz Research Field Earth & Environment. These examples do not cover all activities within the Helmholtz Research Field Earth & Environment and their respective Helmholtz Centers. Rather, they only represent a selection.

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Digital Twin of the Climate System

A digital climate twin is intended to help decision-makers to explore, analyze, and gauge possible development paths, and plan their response to climate change-related impacts and events in their decision-making area. Anthropogenically induced climate change ultimately has impacts down to local scales, so climate adaptation measures start here. However, current global climate models do not have the temporal and spatial resolution needed to assess local/regional impacts of the climate crisis and downscaling had to be employed in the past. It is therefore difficult for regional planners and decision-makers to obtain climate information at the fine resolution they need. In the context of the Destination Earth (DestinE) Initiative, the DT Climate Adaptation will create a climate information system based on Earth system models, featuring innovative tools and methods designed to improve the assessment of climate impacts at local and regional scales.

The climate digital twin (Climate DT) represents a breakthrough in climate modeling and forecasting, offering high-resolution and interactive tools to help us understand and respond to climate change. Below are the most significant advancements:

Global Km-Scale Modeling: The Climate DT introduces models that operate at kilometer-scale resolution (approx. 2.5 – 9 km), allowing for highly detailed simulations of the Earth's climate. This approach reduces biases found in traditional climate models and offers more accurate climate projections at both, global and local levels. Advanced visualization techniques make these simulations almost indistinguishable from real-world observations, providing a clearer view of future climate scenarios.

Operational Climate Projections: Climate DT is designed for the continuous production of climate data, ensuring that up-to-date information is always available. It employs automated workflows that deliver reliable climate projections and include quality control measures to ensure the integrity of the data. The DT also quantifies uncertainties, offering decision-makers actionable insights.

Interactivity: A key feature of Climate DT is its interactive nature. Climate DT will develop capacity to explore ‚what-if' scenarios, helping decision-makers to assess policy impacts and other interventions. The DT also includes „twins within twins," allowing for detailed analysis of specific areas like urban environments in different climates.

From Models to Impacts: Climate DT integrates climate models with impact assessments, enabling users to see the direct consequences of climate change on various sectors, such as hydrology, agriculture or infrastructure. This integration ensures that users can assess not just climate trends but also the real-world implications of those trends.

Storylines: Climate DT provides "storyline" capabilities that will allow users, in near real-time, to determine how recent extreme weather events might unfold under different future climate conditions. By comparing the unfolding of these extreme in different climates, these storylines help to make climate change more relatable and easier to understand, which is vital for planning effective adaptation strategies.

Data Innovations: Climate DT introduces new ways to handle climate data, ensuring consistency across models and datasets. It uses advanced algorithms to process large amounts of data quickly and prepares analyses for easy access, including through the use of large language models (LLM). This allows users to interact with the data more intuitively.

AI Integration: Artificial intelligence (AI) plays a key role in Climate DT. Chatbots provide local climate services, making complex data more accessible to the public. AI will also be used to develop climate „emulators" that, once trained, will be computationally much less expensive than classical physics-based models. This will transform the ability to address „what-if" scenarios – for everyone.

High-Performance Computing (HPC): Climate DT relies on Europe's most powerful supercomputers to handle the massive amounts of data required for km-scale modeling. These advanced systems ensure that simulations are both fast and accurate, allowing for continuous updates and more reliable predictions.

The Alfred-Wegener-Institute (AWI) contributes its expertise in the areas of model development, in particular the next generation sea ice-ocean model (FESOM) employing unstructured mesh methods, as well as in the execution and analysis of the climate simulations (IFS-FESOM) and the development of storyline scenarios. Furthermore, AWI contributes to developing chatbots that will enable scalable climate services. The KIT contributes to the development of ICON and ICON-ART being part of the atmospheric digital twin in DT Climate as a well-tested weather and composition forecasting system that is run operationally at the German Weather Service (DWD). A particular emphasis at KIT is on seamless (composition) modeling, which enables ICON as a flexible DTE implementable in many different DT workflows addressing a range of applications. DT Climate is being developed into a constantly updated system for decision-makers. Initially, use cases are planned in five climate-relevant areas: energy, hydrology, hydrometeorology, forestry, and urban environment. There is an interface with the UFZ's DT Water. FZJ contributes its expertise in integrated modeling of terrestrial systems from groundwater to top-of-atmosphere. In particular, physics-based groundwater-surface water hydrology is being implemented in km-scale climate and Earth system models also from GFZ. In the realm of HPC, FZJ in cooperation with the Simulation and data Lab of JSC, achieves performance portability for the next generation supercomputers using novel software engineering concepts.

Digital Twin of the Ocean

The oceans play a dominant role in the Earth system. Covering over 70% of the Earth's surface, the oceans not only regulate global climate but also provide vital resources, including food, energy, and transportation, that support the livelihoods of billions of people worldwide. However, the oceans are increasingly threatened by human activities such as pollution, overfishing, and climate change, which are disrupting marine ecosystems and altering their capacity to function effectively. To address these urgent challenges and enhance our ability to manage and protect marine environments, Digital Twins of the Ocean (DTOs) are emerging as critical tools. They enable a wide range of users — ocean researchers, policymakers, educators, and the public — to interact with ocean data and information, simulate different WIS, and explore the ocean's response to changing conditions. By providing a platform for dynamic interaction, DTOs enhance understanding, inform decisions, and improve ocean literacy.

DITTO: An international program to advance digital twins of the ocean

The Digital Twins of the Ocean (DITTO) Program, part of the UN Decade of Ocean Science for Sustainable Development, is focused on creating a digital representation of the ocean, directly addressing Challenge 8 of the UN Ocean Decade. DITTO's vision is to use digital twins to support ocean science, governance, protection, and a sustainable ocean economy. Its mission is to develop and share a globally inclusive framework for digital twins, promoting best practices and empowering the ocean community to use these tools effectively.

Through international collaboration, DITTO aims to co-design digital twins with targeted end-users, raise awareness of their applications, and demonstrate their potential in decision-making processes across multiple sectors. Three Helmholtz institutes — Hereon, GEOMAR, and AWI — are key partners in this effort, with Hereon co-chairing the program.

Key Features of Digital Twins of the Ocean

DTOs rely on a combination of advanced technologies that allow them to dynamically replicate the ocean's state. These systems integrate various components, from data collection to user interaction, ensuring they provide accurate, actionable insights for ocean research and management. The following key components form the foundation of effective DTOs:

Sustained observations: Sustained ocean observation in key areas are critical to support the development and operation of digital twins.

Data lakes: Real-time and near-real-time data from in-situ sensors and satellites feed into data repositories, creating comprehensive data lakes. These lakes are frequently updated and accompanied by metadata for both user and machine-to-machine interaction, allowing the digital twin to reflect the evolving state of the ocean.

Artificial Intelligence (AI): AI enhances predictive modeling by analyzing vast amounts of ocean data, automating data fusion, and optimizing model performance. AI powers ‚what-if' scenarios and, along with emulators, accelerates simulations by replicating complex model outputs with reduced computational costs, providing users with quicker and more efficient decision-making tools.

Integrative ocean modeling and processing capabilities: Advanced ocean models (hydrodynamic, global to coastal dynamics, ecosystem dynamics) are combined with AI-driven analysis to represent the physical, chemical, and biological components of the ocean as well as the socio-economical aspect. These models fuse observational and modeled data for comprehensive insights.

Computing infrastructure and visualization: From edge computing on sensor carriers to cloud-based systems and HPC, robust infrastructure supports user-driven WIS. This infrastructure also powers visualization tools, enabling users to view complex ocean data and simulation results in formats ranging from dashboards to immersive virtual and augmented reality environments.

User interaction layers: Intuitive interfaces, ranging from dashboards to immersive virtual and augmented reality visualizations, enable users to interact with the digital twin, run their own simulations, trigger alerts, and provide feedback to the twin.

Stakeholder involvement, education and capacity building: Ensuring the sustainable and equitable use of DTOs across all regions and communities requires strong users' involvement, education and capacity-building initiatives. These efforts aim to spread the necessary skills and knowledge globally.

DTO Components for Coastal Protection, the Blue Economy, and Biodiversity

Helmholtz's Digital Twin of the Ocean (DTO) efforts (Hereon, GEOMAR, AWI) focus on critical use cases like supporting biodiversity, enhancing coastal protection, and advancing the blue economy. These Helmholtz contributions play an important role in addressing ocean sustainability challenges on coastal, regional and global scales.

DTO for Coastal Protection

Helmholtz-Zentrum Hereon is leading efforts to advance DTO with a focus on Nature-Based Solutions (NBS) for coastal protection. These DTs simulate how natural ecosystems, such as seagrass meadows and mangrove forests, mitigate coastal erosion and storm surges. Co-developed in collaboration with local stakeholders, NBS provide sustainable alternatives to traditional coastal defenses like dykes and seawalls. The DITTO Program, EU Mission: Restore Our Ocean and Waters, and the European DTO infrastructure EDITO are key initiatives exploring the use of NBS in several European regions. MANCOGA project, endorsed by the UN Ocean Decade's Coast Predict program, focuses on DTO for using mangroves as an NBS along Ghana's southeastern coast. DTO for NBS has the potential to scale to other regions, aligning with global initiatives such as DITTO, the Green Deal's and UN Decade programs, enhancing coastal resilience and sustainable marine management.

DTO for Blue Economy

In the blue economy, Hereon, GEOMAR, and AWI leverage Digital Twins to model sustainable co-use of marine resources, with EU Mission Ocean projects like SeaDots, OLAMUR and EcoTwin at the forefront. These DTs explore scenarios where activities such as aquaculture are integrated with offshore wind farms (OWF), as well as DTOs specifically designed for OWF or fisheries management, providing insights into both environmental and economic impacts. WIS help stakeholders assess multi-use marine spaces, promoting sustainable development of marine industries. These WiS are integrated into infrastructures like the EDITO and Ocean Missions, supporting policymakers and marine operators in balancing economic growth with ecosystem health.

DTO for Biodiversity

The DTO-BioFlow project, with contributions from GEOMAR and Hereon, is unlocking inaccessible marine biodiversity data to drive sustainable integration into the EU Digital Twin Ocean. By creating a digital replica of marine biological processes, the project will transform new and existing data into actionable insights, aligning with the EU's Biodiversity Strategy and the mission „Restore Our Oceans and Waters by 2030." It enhances data interoperability and develops scalable monitoring technologies, ensuring that biodiversity data plays a key role in conservation and restoration efforts across marine ecosystems.

DTO Global Relevance of Stakeholders and Users

DTO engages a wide range of global stakeholders, including scientists, policymakers, industry leaders, and coastal communities. By providing advanced modeling tools and WIS, the DTO supports decision-making in areas such as ocean restauration, coastal resilience, sustainable energy production, biodiversity conservation, and resource co-use. Its relevance spans sectors like environmental management, marine industries, and governance, enabling informed, data-driven solutions to complex global challenges. Helmholtz DTOs align with international initiatives, including the European Green Deal, Horizon Europe, EU Mission: Restore our Ocean and Waters, and the UN Decade of Ocean Science for Sustainable Development, contributing to a more resilient and sustainable future for the world's oceans.

At Helmholtz-Zentrum Hereon, researchers are making significant contributions for advancing DTO technologies to address environmental challenges. As part of its leadership, Hereon serves as co-chair of the DITTO Program and contributes to key initiatives such as the European EDITO DT. Hereon also plays a crucial role in various EU (e.g. EU Mission: Restore our Ocean and Waters, Green Deal, COPERNICUS) and international (OceanPredict, UN Decade of Ocean, WMO) initiatives. The GCOAST model system integrates observations with cutting-edge hydrodynamic, wave, ecosystem and morphodynamical models, enhanced by artificial intelligence, to create comprehensive digital replicas of the ocean. GEOMAR plays an active role in furthering the development of DT for marine systems, focusing on biodiversity and ecosystem dynamics, making significant contributions to collaborative projects in support of global ocean sustainability. These efforts provide real-time insights for sustainable resource management, aligning with global initiatives like the UN Decade of Ocean Science for Sustainable Development. The AWI is involved in specific theme-based projects, as mentioned above.

Digital Twin for the Geosphere

The EU project DT-GEO (A Digital Twin for GEOphysical extremes) is an integral part of the Destination Earth Initiative. Here, the prototype for a DT for geophysical extremes is being developed through collaboration of 18 European institutions. The motivation is that large parts of Europe and the world are threatened by earthquakes, volcanic eruptions, and tsunamis. The aim is to analyze and predict the effects of these extreme events. Extreme geophysical events are the cause of more than 10 % of the damage caused by natural disasters of all kinds worldwide.

The Geo-DT prototype consists of interlinked digital twin components (DTC) that address different types of geohazards: natural and anthropogenically caused earthquakes, volcanoes, and tsunamis triggered by earthquakes and landslides.

DT for Tsunamis

Tsunamis are caused by earthquakes, volcanic eruptions, and landslides. Especially when tsunamis occur near the coast, a fast and effective response is required. In already existing tsunami early warning systems like GI-TEWS, the evaluation process is run partly automatically. The integration of real-time or near-real-time data in a DT, their assimilation, including the dynamic development of earthquake parameters, sea level and GNSS data streams into the running model allows successively more precise mapping of the situation, reduces uncertainties and has an effect on the decision module.
In the Geo-DT-Tsunami component, the GFZ is responsible for collecting and harmonizing the requirements and specifications developed for the tsunami twin. There is an interface to the Geo-DT component earthquake, from which data and information on earthquake rupture features and information on ground shaking are provided as input to the tsunami twin.

DT for Earthquakes

Earthquakes are difficult to predict. To mitigate their catastrophic consequences, it is necessary to know where they will occur, what magnitude they may develop, and what level of shaking they will produce. The European Seismic Hazard Map shows the hazard in Europe and quantifies the possible amplitudes of earthquake-induced ground shaking. From such a hazard assessment, the earthquake risk is derived, which describes the possible effects of earthquakes on people and buildings. Based on these models and maps, precautionary measures can be taken.
However, DT-GEO-Earthquake aims to go beyond such hazard and risk maps. Its goal is to better recognise, in near real time, what happens in the event of an earthquake and to draw conclusions, for example, about the region affected by an earthquake or the maximum size of aftershocks.
Several geothermal projects have triggered significant earthquakes, making the prediction of anthropogenic geophysical extremes (Anthropogenic Geophysical Extremes Forecasting, AGEF) particularly important for geothermal operations. The work being carried out under DTGEO/AGEF focuses on developing a functional Digital Twin for an existing reservoir and associated induced seismic events, with a specific focus on the seismic crisis in Strasbourg. Forecasting represents a subsequent phase, where the developed Digital Twin component will support decision-making strategies.

The GFZ is developing Europe-wide ground-shaking models for this twin component. These models predict the level and location of strong shaking produced by an earthquake. In addition, these models integrate knowledge from the latest European seismological databases and physics-based simulations. They consider regional characteristics of the geological conditions and the local properties of the subsurface below urban areas. As a result, the entire chain of effects – from tectonics and hazard to damage in the event of an earthquake – can now be calculated for all types of earthquakes conceivable today or in the future.

Digital Twin of Terrestrial Systems

Terrestrial systems are the immediate habitat of humans. They are shaped by a multitude of abiotic and biotic processes and interactions. Human interventions in natural systems have caused impairments that are now globally noticeable and have altered matter fluxes, posing a threat to vital ecosystem services. Biodiversity, landscape degradation, water quality – these are critical variables that are exacerbated by and feed back into climate change.

Managing terrestrial areas, agriculture, forestry, and soil health requires a robust database. The provision and evaluation of such data primarily encounters the problem of an almost unmanageable heterogeneity, which is compounded by a wide range of temporal and spatial scales. Just to record the abiotic matter fluxes of carbon, phosphorus and nitrogen, a comprehensive and, above all, spatially far better resolution is required than is possible with the existing observatories. In addition, there is the diversity of life that makes our planet unique: biotic systems can vary greatly even at the meter scale, plant and animal species are directly dependent on each other, and biotic material cycles are closely interwoven with abiotic matter fluxes.

Model parametrization: the cleverlinking of the known and the unknown

Land areas like Europe with an area of 10.5 million km², cannot be covered extensively with terrestrial observatories. Terrestrial parameters such as soil porosity are not known over the entire area and must therefore be skillfully linked with existing area-wide information (from observatories, satellites, field measurements) and then brought to the required model scale. This link can be established by means of suitable statistical methods (e.g., non-linear regression) but in the future also increasingly with the help of AI. Parametrization interrestrial models is therefore not a description of sub-scale processes but rather the linking of known with unknown model parameters and the scaling of these parameters to the model scale. The goal here is to arrive at a uniform but seamless parameterization of the models at kilometer scales throughout Europe–an interface to the resolution of the climate models envisaged in DestinE. At this interface, the terrestrial DTs exchange information with DTClimate.

The Terrestrial-DT prototype consists of interlinked digital twin components (DTC) that address different parts of the terrestrial system: water, forests, grasslands, agriculture to name just a few.

Water-DT

The link between abiotic and biotic processes is the element of water. Water supply and distribution, precipitation up to extreme events, and changes in the terrestrial water cycle due to climate change are essential decision variables for terrestrial future planning. The National Water Strategy for Germany is a reaction to the change in water supply. Hydrological modeling provides the necessary data, analyzes the current state and helps with planning. In addition to the spatial grid size, such modeling also contains a great deal of temporal variability: extreme events in particular demonstrate the need to provide updated hydrology information in the input and output every hour. Forestry, on the other hand, needs reliable data over annual periods for its planning. And this is exactly the goal in Destination Earth: a water twin based on the hydrological model mHM of UFZ will communicate continuously with the weather/climate twin and can thus be used as an analysis and decision-making tool that adequately reflects the different landscape types. Here, there is close cooperation with AWI via DTClimate.

Ecosystems and Biodiversity

Terrestrial systems are the home of life, biogeochemical processes the interface between biotic and abiotic processes, and thus also between their modeling. Forest, grassland, and agricultural landscapes are inhabited by rather different life forms. Human intervention and climate change have decisively changed this system and led to the current biodiversity crisis.

The Bio-DT contributes to combating the biodiversity crisis by providing the necessary data for specific use cases in a highly precise and interactive manner; the UFZ is involved in this project.

Forests worldwide are under stress. In Germany, too, the drought of recent years has not only caused damage to forestry, but has also threatened the ecosystem. Space Twin is a Bio-DT that uses high-resolution forest models to investigate how droughts, fires and deforestation affect tropical and boreal forest ecosystems and how they interact with global climate change.

The UFZ is intensively involved in the development of several DT-components of the terrestrial system.
UFZ is leading e.g.the development of a Water-DT with DestinE that will closely communicate with the Climate DT. Additionally, UFZ ecosystem model components like the grassland model GRASSMIND and the forest model FORMIND but also components like BEEHAVE – a model to simulate the development of a honeybee colony and its nectar and pollen foraging behavior in different landscapes – play an important role in several EU digital twin initiatives and are further developed towards Bio-DTs. FZJ is involved in the development of the new land surface model ICON-Land providing improved physics-based hydrology, which will enable improved feedback modeling over continents at the km-scale resolution. Similar activities are ongoing with the German Weather Service (DWD) in the project GLORI, which aims for a <1km resolution DT over the alpine region. In the Collaborative Research Center 1502, DETECT, a DT of the terrestrial system is under development by integrating the Terrestrial Systems Modeling Platform, TSMP (www.terrsysmp.org) with the ocean model FESOM.

Digital Twin for Urban Development

Cities and municipalities are focal points of the sustainability crisis. The necessary transformation of energy supply, mobility, and housing confronts urban planners with complex questions that cannot be solved independently. At the urban planning level, flexible and user-friendly tools are needed that dynamically link climate and environmental sciences with urban requirements. For decision-makers, this also means considering what is required in terms of (natural) science in the regulatory cooperation between municipalities, the state, and the federal government when developing the necessary guidelines.

In the city as a living space, environmental parameters such as thermal comfort, wind comfort, and air quality are important parameters for well-being. The functionality of the city in terms of quality of life is determined by urban infrastructure parameters such as transport, energy and water supply. This complex structure is under increasing pressure from the climate crisis. Urban systems react sensitively to climate change, but urban planning thinks in terms of years, if not decades, especially in the case of major structural reconstruction measures.

Regional climate models on ever higher time/space resolution, such as those used in the international EURO-CORDEX initiative, can provide the necessary data to move from global to regional to urban space. While a climate model grid width of 12 kilometers still applies throughout Europe today, which can be refined regionally to 13 km and scaled to 15 m for individual representative days within cities, the resolution will further increase in future at the European level within EURO-CORDEX and globally with the Climate DT (see a)). In the future, urban planners will have methods and data at their disposal in a resolution that will allow them to run through scenarios of future climate on spatial and temporal scales of urban reality, to test suitable measures virtually, and to analyze their feedback on the overall city system.

Urban DTs reflect the reality of a city

The EU initiative DestinE explicitly provides for the development of DTs for urban areas. Within the EURO-CORDEX initiative, there will also be an ensemble of regional climate simulations considering urban structures on which Urban DTs can build. Ideally, twin components for the urban subsystems of housing, economy, and mobility can be developed here, which as a coupled system interweaves the respective planning variables of development, traffic, roads, planting, and water areas. The FONA project ProPolis is a step into this direction.

Data for real-time

The integration of such city models into climate models that resolve parts of the city down to a few meters requires the mutual scale adjustment of space and time (upscaling, downscaling) and a precise definition of the interfaces. Completely new information flows in from urban planning - if possible, in real-time - such as data from traffic control systems, energy and water supply. The resulting planning and control possibilities will allow for example a rapid response to extreme weather events. But they also make it possible to extract certain events, such as heat waves, from the larger-scale models and to recalculate them for the urban area for certain critical days in order to determine the effect down to the street scale. Playing out future climate scenarios allows the development and testing of adaptation measures that can, for example, prevent urban heat islands from heating up to health-threatening levels.

Future Urban DTs thus reflect the reality of a city. Their range of applications goes far beyond adaptation to climate change. In fact, they encompass all Helmholtz Research Fields on the urban scale.

The Climate Service Center Germany (GERICS), an institute of the Helmholtz-Zentrum Hereon, is a ProPolis project partner. The further development of the PALM model, a meteorology model for simulating the near-ground atmosphere, into a high-resolution urban climate model (PALM4U) is the goal of ProPolis. The aim is to create a practical, user-friendly urban climate model that is tailored to the needs of municipalities, urban planning, and practical users. Since it is also used in research, the practical application can be fed back into science.

Digital Twins for a Sustainable Bioeconomy

The bioeconomy aims to create sustainable material cycles based on renewable resources, playing a critical role in addressing climate change and environmental degradation. Helmholtz research focuses on plant-based food production for a growing global population and the replacement of fossil fuels with sustainable alternatives. These goals are deeply connected to the challenges posed by climate change and the need for circular economic systems. DTs are key tools in advancing the bioeconomy. By creating virtual models of biological systems, DTs help researchers simulate and optimize processes in real-time, improving the efficiency of resource use, and reducing environmental impacts. For instance, digital twins can represent plant growth and crop interactions with their environment, enabling better management of natural resources and optimizing agricultural production under changing climate conditions.

A transformative approach in achieving sustainability

DTs play a crucial role in providing insights that inform sustainable practices. The Jülich Biofoundry, for example, uses a fully automated system to produce genetically modified microorganisms for chemical production. By applying a digital twin approach, researchers can accelerate the development of biotechnological processes, significantly shortening timelines. By integrating AI and data analytics, these digital twins not only improve experimental outcomes but also help make real-time decisions with minimal human intervention, moving toward fully automated, data-driven product development. Similarly, digital twins are used in plant phenotyping, where automated systems analyze plant growth under different environmental conditions. This allows for the development of crops that are more resilient to climate change. The AGRASIM facility simulates agro-ecosystems in ecotrons under future climate scenarios, which are retrieved from story line simulations with the Climate DT, and uses digital twins to predict how changes in temperature and CO_2 levels will affect plant growth and soil health. This is a transformative approach to achieving sustainability in the bioeconomy, while accounting for its interactions with the Earth system.

At Forschungszentrum Jülich researchers are working on further refining these digital twin technologies. With support from interdisciplinary teams and cutting-edge data science techniques, the use of digital twins will continue to expand, driving innovation in sustainable bioeconomy practices. Advanced facilities like the Jülich Biofoundry, automated greenhouses, and the AGRASIM soil-plant system are pioneering the DT approach in bioeconomy. These facilities are equipped with cutting-edge digital infrastructures that generate vast amounts of data and that are linked to DTs of the Earth System.

Outlook: Future Tasks for Digital Twins

Rapid human development and activities touch all compartments of our planet Earth with in parts dramatic effects. Digital twins have an enormous potential to support informed decision-making to address environmental problems and explore optimized pathways towards safe and sustainable interactions with our planet. International environmental agreements such as the UN 2030 Agenda with is 17 SDGs, the European Green Deal and the findings of UN panels (IPCC, WOA, IPBES, Ozone Assessment) call for knowledge-based development. This requires major efforts in global data collection, analysis, modeling and information sharing. This information can underpin decentralized, international knowledge platforms that enable multi-stakeholder collaborations and partnerships, sharing best practices and provisions of policy advice.

Digital twins are particularly suited to support decisions based on simulations of future „what-if" scenarios. Some AI-based digital twins can learn from and respond to system developments and reactions in the real world, other are driven by assumed scenarios based on expert judgement. They enable stakeholders and the general public to assess complex systems and derive actionable insight for themselves also by connecting the global patchwork of heterogeneous data infrastructures. Digital twins can capture the complex interactions of both natural and social phenomena. However, much remains to be done before digital twins become a wide-spread reality.

Academia and research, in collaboration with governments, the private sector and civil society should improve systematic observation of the environment, improve models, advance modeling techniques and increase data accessibility and interoperability. Here, we stress the enormous potential of digital twins and recall their early stage in their overall development. Science and innovation can accelerate their development, accuracy and usability and promote their use in appropriate applications.

Abbreviations and acronyms

AI	Artificial Intelligence
AGEF	Anthropogenic Geophysical Extremes Forecasting
AWI	Alfred Wegener Institute Helmholtz Center for Polar and Marine Research
CARE	Principle for data sharing: Collective benefit, Authority to control, Responsibility, Ethics
CMIP	Coupled Model Intercomparison Project
BioDT	Biodiversity Digital Twin prototype
DestinE	EU-Initiative Destination Earth
DITTO	Digital Twin of the Ocean
DT	Digital Twin
DTC	Digital Twin Component
DTE	Digital Twin Earth
DT-GEO	Digital Twin for GEOphysical extreme
DTO	Digital Twin Ocean
E&E	Helmholtz Research Field Earth & Environment
EMODnet	European Marine Observation and Data Network
EuroHPC	European High-Performance Computing Joint Undertaking
FAIR	Data standard: Findable, Accessible, Interoperable, Reusable
FESOM	Finite-Element/volumE Sea ice-Ocean Model
FZJ	Forschungszentrum Jülich GmbH
GEOMAR	GEOMAR Helmholtz Centre for Ocean Research Kiel
GERICS	Climate Service Center Germany
GFZ	Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences
GITEWS	German-Indonesian Tsunami Early Warning System
GMM	Ground Motion Model
GOOS	Global Ocean Observing System
GUI	Graphical User Interface
HAICU	Helmholtz Artificial Intelligence Cooperation Unit
Hereon	Helmholtz-Zentrum Hereon
HPC	High Performance Computing
ICON	Icosahedral Non-hydrostatic Model
IFS	Integrated Forecast System
IODE	International Oceanographic Data and Information Exchange
JUPITER	Joint Undertaking Pioneer for Innovative and Transformative Exascale Research
KIT	Karlsruhe Institute of Technology – KIT
LUMI	Large Unified Modern Infrastructure
NFDI4Earth	Nationale Forschungsdaten-Infrastruktur für Erdsystemwissenschaften
ODIS	Ocean Data and Information System
PALM	PALM model system for atmospheric and oceanic boundary-layer flows
UFZ	Helmholtz-Centre for Environmental Research

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