Journal of the European Meteorological Society 3 (2025) 100015

Contents lists available at ScienceDirect

Journal of the European Meteorological Society

journal homepage: https://www.sciencedirect.com/journal/journal-of-the-european-meteorological-society

Implementing digital twin technology of the earth system in Destination Earth

Nils Wedi [a,*], Irina Sandu [a], Peter Bauer [b,1], Mario Acosta [c], Rune Carbuhn Andersen [d], Ulf Andrae [e], Ludovic Auger [f], Gianpaolo Balsamo [b], Vasileios Baousis [b], Victoria Bennett [a], Andrew Bennett [b], Carlo Buontempo [a], Pierre-Antoine Bretonnière [c], René Capell [e], Miguel Castrillo [c], Matthew Chantry [b], Matthieu Chevallier [b], Ricardo Correa [b], Paolo Davini [g], Leif Denby [d], Francisco Doblas-Reyes [c], Peter Dueben [a], Claude Fischer [f], Claudia Frauen [h], Inger-Lise Frogner [i], Barbara Früh [j], Estíbaliz Gascón [a], Elisabeth Gérard [f], Oliver Gorwits [b], Thomas Geenen [k], Kat Grayson [c], Nadia Guenova-Rubio [f], Ioan Hadade [a], Jost von Hardenberg [l], Utz-Uwe Haus [m], James Hawkes [b], Marcus Hirtl [n], Joern Hoffmann [a], Kristian Horvath [o], Heikki Järvinen [p], Thomas Jung [q], Alexander Kann [n], Daniel Klocke [r], Nikolay Koldunov [q], Jenni Kontkanen [s], Outi Sievi-Korte [s], Jørn Kristiansen [i], Emma Kuwertz [b], Jarmo Mäkelä [s], Ilja Maljutenko [t], Pekka Manninen [s], Ursula S. McKnight [e], Sebastian Milinski [a], Andreas Mueller [a], Antony McNally [b], Umberto Modigliani [a], Devaraju Narayanappa [s], Kristian Pagh Nielsen [d], Thomas Nipen [i], Henrik Nortamo [s], Vincent-Henri Peuch [a], Suraj Polade [u], Tiago Quintino [b], Irene Schicker [n], Balthasar Reuter [a], Simon Smart [b], Mike Sleigh [b], Martin Suttie [b], Piet Termonia [v], Stephan Thober [w], Roger Randriamampianina [i], Natalie Theeuwes [x], Daniel Thiemert [a], Benoît Vannière [a], Stéphane Vannitsem [v], Christoph Wittmann [n], Xiaohua Yang [d], Marc Pontaud [f], Bjorn Stevens [r], Florian Pappenberger [b]

[a] *European Centre for Medium Range Weather Forecasts (ECMWF), Bonn, Germany*
[b] *European Centre for Medium Range Weather Forecasts (ECMWF), Reading, UK*
[c] *Barcelona Supercomputing Center (BSC), Barcelona, Spain*
[d] *Danish Meteorological Institute, Copenhagen, Denmark*
[e] *Swedish Meteorological and Hydrological Institute, Norrköping, Sweden*
[f] *Météo-France, Toulouse, France*
[g] *Istituto di Scienze del Atmosfera e del Clima, Torino, Italy*
[h] *Deutsches Klimarechenzentrum (DKRZ), Hamburg, Germany*
[i] *Norwegian Meteorological Institute, Oslo, Norway*
[j] *Deutscher Wetterdienst, Offenbach, Germany*
[k] *European Centre for Medium Range Weather Forecasts (ECMWF), Bologna, Italy*
[l] *Politecnico di Torino, Torino, Italy*
[m] *Hewlett Packard Labs, Zuerich, Switzerland*
[n] *GeoSphere Austria, Vienna, Austria*
[o] *Croatian Meteorological and Hydrological Service, Zagreb, Croatia*
[p] *University of Helsinki, Finland*
[q] *Alfred Wegener Institute, Bremerhaven, Germany*
[r] *Max–Planck-Institut für Meteorologie, Hamburg, Germany*
[s] *CSC - IT Centre for Science, Espoo, Finland*
[t] *Tallinn University of Technology, Tallin, Estonia*
[u] *Finnish Meteorological Institute, Helsinki, Finland*
[v] *Royal Meteorological Institute, Brussels, Belgium*
[w] *Helmholtz-Zentrum für Umweltforschung, Leipzig, Germany*

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[*] Corresponding author.
E-mail address: nils.wedi@ecmwf.int (N. Wedi).

[1] retired.

https://doi.org/10.1016/j.jemets.2025.100015
Received 23 December 2024; Received in revised form 25 March 2025; Accepted 1 June 2025

x Royal Netherlands Meteorological Institute, De Bilt, Netherlands

ARTICLE INFO

Dataset link: platform.destine.eu

Keywords:
Numerical weather prediction
High performance computing
Climate Change Adaptation
Earth system modelling
Digital Twins
Destination Earth

ABSTRACT

The Destination Earth (DestinE) initiative of the European Commission applies digital twin technology to the Earth system, enabling bespoke, high-resolution simulations of extreme weather events and climate scenarios. At its core, DestinE features Digital Twins and a Digital Twin Engine — a software framework that connects computing, Earth system models, data, and applications. DestinE's Digital Twins combine observations, physics-based high-resolution simulations and emerging Artificial Intelligence (AI) methods, and leverage Europe's most powerful supercomputers, through a strategic partnership with the European High Performance Computing Joint Undertaking (EuroHPC JU). DestinE enables tailored Earth system simulations to dynamically explore future weather and climate scenarios and to address "what-if" questions. It also establishes an operational framework for multi-decadal, multi-model climate projections, linking them to applications that transform vast climate data into actionable insights for climate sensitive sectors. By offering detailed, customized information on weather and climate extremes, DestinE enhances existing capabilities and supports both immediate and longer-term climate adaptation strategies.

3 Key points of the paper:

- Defines the Destination Earth digital twin concept
- Demonstrates the implementation of the world's first two digital twin prototypes for two distinct purposes, anticipating weather-induced extremes and supporting climate change adaptation and mitigation
- Discusses the challenges of the first 2 years of Earth system digital twin technology capacity building, highlighting the future potential for supporting public institutions in their effort to respond and adapt to climate change and extreme events.

1. Introduction

Destination Earth (DestinE, https://destination-earth.eu/) is a European Commission (EC) initiative to develop a digital replica – or digital twin – of the Earth, improving Europe's ability to respond and adapt to climate change and extreme events.

DestinE is implemented through a partnership between the European Centre for Medium-Range Weather Forecasts (ECMWF), the European Space Agency (ESA), and the European Agency for Meteorological Satellites (EUMETSAT), led by EC's Directorate-General for Communications Networks, Content and Technology (DG CNECT). Launched in 2022, DestinE has rapidly expanded into a major European effort, involving over 110 institutions from 26 countries. These include national meteorological and hydrological centres, climate institutes, universities and private-sector organizations, including small and medium-sized enterprises.

At the core of DestinE are two Earth system Digital Twins, implemented by ECMWF together with many partners across Europe: one focused on Weather-Induced Extremes (Extremes DT) and the other on Climate Change Adaptation (Climate DT). These Digital Twins combine Earth system observations, physics-based high-resolution simulations and emerging Artificial Intelligence (AI) methods. They are powered by the Digital Twin Engine, a software infrastructure that enables dynamic simulations and interactive access to digital twin data.

DestinE's Digital Twins aim at supporting authorities, at national or European level, to better prepare, respond and adapt to the challenges posed by extreme events and climate change. They complement existing capabilities, by providing a flexible cutting-edge Earth-system modelling infrastructure that:

(i) enables advanced "what-if" simulations to assess how extreme events may unfold and how climate system might evolve under different plausible scenarios.

(ii) produces globally consistent Earth system and impact sector data, both regularly and on-demand, at kilometre-scale – where many extreme weather and climate-related impacts are observed – with high-temporal frequency.

This world's first large-scale effort to develop Earth system digital twin[2] technology is enabled by a strategic partnership with the European High-Performance Computing Joint Undertaking (EuroHPC JU), which provides access to world-class supercomputers. These include Europe's first pre-exascale systems, LUMI (Finland), Leonardo (Italy), and MareNostrum 5 (Spain), as well as tier-1 facilities such as Meluxina (Luxembourg).

In its first two years, DestinE has developed its Digital Twins and linked their vast data flows into the wider DestinE system. It has demonstrated the ability to run cutting-edge Earth system simulations on leading EuroHPC supercomputers and deliver high-resolution climate and near real-time extreme event information. This has established a blueprint for an ecosystem of specialized knowledge and collaboration that fosters innovation. This approach is consistent with and has informed similar initiatives, including the European Commission's emerging Artificial Intelligence (AI) factories.

The second phase of DestinE (2024–2026) focuses on ensuring reliable, high-quality data production with continuous updates. It also focuses on building trust in the provided information, which constitutes a key aspect of fit-for-purpose climate data (Dee et al., 2024) and is essential for the effective use of advanced weather and climate information by public institutions to support climate adaptation and response to extreme events. DestinE is also expanding its capabilities by integrating Artificial Intelligence (AI) and Machine Learning (ML). These emerging technologies have the potential to significantly accelerate and enhance Earth system predictions, although they require high-quality input data and transparent methodologies to maintain trust (Pappenberger et al., 2024; Eyring et al., 2024).

2. Building on a rich past

DestinE builds on decades of European investment in science, technology and supercomputing to advance weather and climate prediction. The digital twins build on advances in numerical weather prediction (Bauer et al., 2015) and climate modelling (e.g. Haarsma et al., 2016), combining physics-based high-resolution Earth system simulations with observational data and computer science techniques. They leverage advances in supercomputing, marked by the emergence of (pre-)exascale high-performance computing (HPC) systems. They also exploits breakthroughs in digital technologies, and more particularly the emergence of end-to-end workflows that incorporate HPC, cloud storage, AI/ML, to link Earth-system models to impact-sector applications in an advanced digital framework.

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[2] Specific terms such as 'digital twins' are explained in more detail in the Glossary at https://destine.ecmwf.int/glossary/.

Accurate weather forecasts are increasingly important for limiting the devastating consequences of extreme events such as floods, hurricanes or wind-storms. The United Nations (UN)' initiative 'Early Warnings for All',[3] launched in 2022, and endorsed by 193 member states[4] of the World Meteorological Organization (WMO), underscores the urgency of improving prediction capabilities for flash-floods, drought/dry spells, riverine floods, tropical cyclones, thunderstorms/squall lines, and heat waves in a changing climate. DestinE contributes to this global effort through its Digital Twins, which enhance the ability to predict extreme events and assess how they may unfold in a changing climate.

Advances in Earth system modelling – in particular in the coupling between the atmosphere, land, ocean, sea-ice and waves– have also improved the ability to predict environmental changes from global to regional scales over longer timescales, from subseasonal to centuries ahead. This has brought the fields of weather and climate science closer together (Randall and Emanuel, 2024). However, further improvements are needed to better capture complex feedback processes, such as the interactions between the carbon and hydrological cycles with human activities (e.g. Agustí-Panareda et al., 2019; Schaeffer et al., 2024). DestinE offers an opportunity to further advance Earth system modelling capabilities at the fine scales at which these complex feedbacks take place. It also offers capabilities to exploit and fuse climate information with the wealth of existing knowledge on human and socio-economic impacts to drive adaptation policy.

These advances in Earth system prediction systems are enabled by recent breakthroughs in supercomputing technology (Schulthess et al., 2019; Bauer et al., 2021a), combined with Europe's substantial investments in world-leading HPC infrastructure and in adapting weather and climate models and their underpinning software engine to these emerging supercomputing architectures. DestinE builds on these efforts, further advancing Earth system modelling capabilities (Bauer et al., 2021b; Wedi et al., 2022; Hoffmann et al., 2023), and thereby aligning with WMO scientific advisory panel'[5] recommendations.

DestinE also builds on the European Commission funded Copernicus Services,[6] which provide atmospheric composition, marine, land and climate monitoring, and support emergency management. For example, the Copernicus Climate Change Service (Buontempo et al., 2022) provides state-of-the-art re-analyses (Hersbach and co authors, 2020), that integrate past and real-time Earth observations with numerical prediction techniques to create a consistent historical reconstruction of the Earth system state, allowing to monitor the past and recent evolution of the climate. DestinE complements these existing capabilities through its Climate DT,[7] which provides multi-decadal climate projections, both in a regular, sustained, mode and on demand, at unprecedented global spatial (∼5 km) and temporal (hourly) resolutions.

Finally, DestinE builds on decades of progress in climate science and its contributions to intergovernmental policy on climate change (Jones et al., 2024; IPCC, 2021, 2023)[8]. It uses forcing scenarios defined in the Coupled Model Intercomparison Project (CMIP[9]) and exploits the CMIP global climate simulations to assess uncertainties in the Climate DT multi-decadal simulations. The Coordinated Regional Climate Downscaling Experiment (CORDEX[10]) is a framework of the World Climate Research Programme (WCRP) aiming to produce regional climate projections for all major inhabited areas of the world. This contributes to advancing the science of downscaling and deriving climate information at the regional level. However, outstanding challenges remain in translating emerging hazards to risks and to climate action (Collins et al., 2024).

By delivering globally consistent high-resolution climate projections, DestinE aims to support public institutions to develop effective adaptation and mitigation policies from local, to regional and global scales. It thereby aims to support efforts to respond and adapt to climate change, targeting specific policy relevance (cf. Boehmer-Christiansen, 1994) and more directly regulatory, technological or behavioural change at the regional level.

DestinE also aims to address limitations in existing approaches (Stevens et al., 2019; Stevens, 2024a; Stevens et al., 2024b; Jones et al., 2024; Hohenegger et al., 2020; Hohenegger and co authors, 2023; Jakob et al., 2023), by creating for the first time a framework that allows to produce climate projections, both regularly and on-demand to address 'what-if' questions, such as : 'How would a recent extreme event would unfold in a world that is 2 degrees warmer?' This allows to make climate change more tangible and create storylines (Shepherd et al., 2018; Sánchez-Benítez et al., 2022), while delivering globally consistent information on weather extremes in a changing climate. The increased frequency of DestinE simulations introduces new requirements, including faster generation of climate forcings, improved accessibility and validation of these essential datasets. At the same time, DestinE can serve as a testbed for evaluating novel scenario forcing datasets, advancing climate modelling techniques.

3. What defines earth system digital twin technology

A key goal of DestinE's Earth system Digital Twin technology is to support the digital transformation of society, enabling countries, meteorological services, businesses and individuals to better understand and respond to climate change (Wedi et al., 2022; Hoffmann et al., 2023). By collaborating with national services and leveraging investments in European supercomputing, DestinE enhances institutional and technological readiness, ensuring a shared understanding of the necessary domain-specific tasks.

The implementation of Earth System Digital Twins – from launch and execution to data production, monitoring, quality control and translation of outputs into sector-specific information – is complex and requires specialized expertise from multiple disciplines. Following common practice in other disciplines, Earth system digital twins are realized by bringing together a broad range of expertise that develops and continuously evolves the digital twin, defines, prepares, detects, triggers simulations and responds to specific scientific or technological user needs as required. For example, an open question is estimating how past policy decisions will shape the future evolution of the climate. The effectiveness of all these elements, e.g. fast-tracking the simulation of specific "what-if" scenarios, with quality and uncertainty assessments, defines the success of digital twin technology.

These elements are essential to implementing complex Earth system digital twins, requiring advanced interdisciplinary expertise, HPC resources and big data infrastructure to ensure seamless data access and interoperability. Other simulations also apply digital twin concepts, focusing on specific Earth system processes or local impacts. These can be considered as extensions of the broader Earth system digital twin framework and may interact with it through data exchange, either weakly or strongly. While they typically do not require extensive HPC resources for their application, they may depend on HPC during their development, such as for AI/ML training.

The information system set up in DestinE is composed of several innovative elements: the first two digital twins and the Digital Twin Engine; the Data Lake; and the DestinE Service Platform (Fig. 1).

DestinE's digital twins simulate different aspects of the Earth system. The initial high-priority digital twins on weather-induced extremes and climate change adaptation currently use cutting-edge physics-based

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[3] https://www.un.org/en/climatechange/early-warnings-for-all.

[4] https://wmo.int/about-wmo/wmo-members

[5] https://community.wmo.int/en/activity-areas/scientific-advisory-panel

[6] https://www.copernicus.eu/

[7] https://destine.ecmwf.int/climate-change-adaptation-digital-twin-climate-dt/

[8] https://www.ipcc.ch/

[9] https://wcrp-cmip.org/

[10] https://cordex.org/

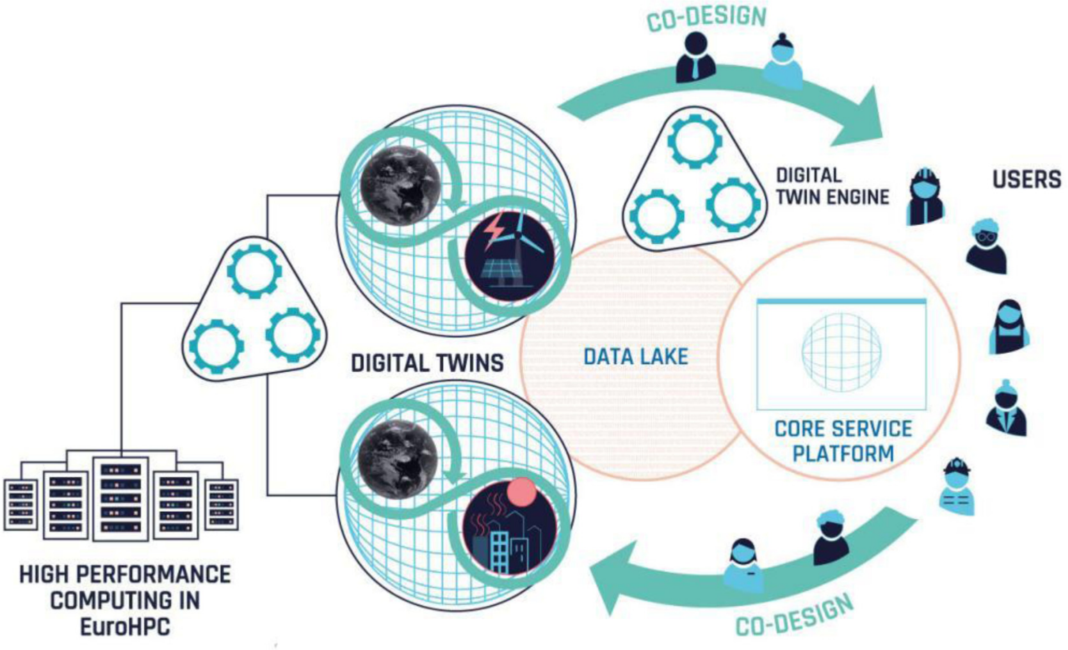

Fig. 1. Key elements of the DestinE system, funded by the EU and implemented by ECMWF (digital twins and Digital Twin Engine), EUMETSAT (Data Lake) and ESA (Core Service Platform).

models to simulate the Earth system behaviour ~5 km/10 km grid-spacing. The high-frequency coupling of the Earth system model components allows to capture diurnal cycles over land, ocean, and sea ice. The models also include representations of waves, lakes, and cities. The digital twin simulations are currently initialized using operational (re-)analyses produced by ECMWF and national meteorological services, by blending a wide range of Earth system observational data sets with numerical models through data assimilation techniques to derive the best possible reconstruction of the atmospheric, land, ocean and sea-ice states. The past and future evolution of greenhouse gases and aerosols in the Climate DT simulations is defined using forcings derived in the framework of CMIP. A comprehensive set of observational data sets is also used to assess the quality of the digital twin simulations over historical periods.

The Extremes DT consists of a global component developed by ECMWF and a higher-resolution, regional on-demand component led by Météo-France, in collaboration with 32 institutions from 26 countries, including many European national meteorological services (NMS).

The Climate DT is developed by a partnership led by the Finnish IT Centre for Science Ltd. (CSC), currently involving 12 leading climate institutions, supercomputing centres, national meteorological services, academia and industrial partners, in close collaboration with ECMWF.

Compendia of the digital twins that describe their current and evolving setups and an up-to-date list of the available simulations from Destination Earth are regularly maintained at Destination Earth Climate D.T. (2025), Destination Earth Extremes D.T. (2025). The first DestinE digital twin implementations are based on existing global models and regional models; namely ICON, IFS-NEMO and IFS-FESOM2, and Arome, Harmonie-Arome and Alaro, respectively; some of which are used for operational predictions from days to seasons ahead.

ICON (Zängl et al., 2015; Korn, 2017; Giorgetta et al., 2018) is the ICOsahedral Non-hydrostatic model developed by the German Meteorological Service (DWD), the Max Planck Institute for Meteorology (MPI-M), the German Climate Computing Centre (DKRZ), the Karlsruhe Institute of Technology (KIT), and the Center for Climate Systems Modeling (C2SM); IFS-NEMO is ECMWF's Integrated Forecasting System (IFS[11]) atmospheric/land model coupled to the latest release of the NEMO ocean model (Madec and Nemo team, 2016) implemented by BSC in collaboration with ECMWF; and IFS-FESOM2 is the IFS coupled to the Alfred Wegener Institute's Finite-VolumE Sea ice–Ocean Model (Koldunov et al., 2019; Rackow et al., 2025 and references therein). These three models are used for the Climate DT, and IFS-NEMO is used for the global Extremes DT. The Extremes DT regional component builds on the ACCORD[12] system and can be configured (e.g. for regions, event types) to zoom in on selected extreme events over Europe.

In DestinE, the global models are run at resolutions ranging between 4.4 and 10 km for the different components (atmosphere, land, ocean, wave and sea ice), building on pioneering collaborative efforts to adapt them to these resolutions in several Horizon Europe projects (nextGEMS,[13] EERIE[14]) and national projects (WarmWorld in Germany, Gloria in Spain). Additional regional models are run for extreme events occurring over Europe at 500–750 m resolution. The Extremes DT simulations focus on a timescale of a few days ahead, while the Climate DT focuses on multi-decadal simulations covering past and future periods (1990–2040).

In addition, DestinE explores interoperability with national digital twin initiatives also operating on EuroHPC platforms. An initial focus in the Glori4DE[15] project is on data handling and workflow management to leverage global and regional simulation data & observations, and on defining a blueprint for connecting with systems routinely operated by National Hydro-Meteorological Services (NHMS). The focus of Glori4DE is on the Mediterranean and Alpine regions, exploring the impact of different initial and boundary conditions for simulating extreme event impacts.

The Digital Twin Engine provides the software infrastructure to integrate Earth system digital twins within the DestinE system, enabling extreme-scale simulations, data handling, and ML training and inference. It provides a unified approach to orchestrate Earth system digital twins and allows users to interact with their data in novel ways, improving both communication and policy-relevant translation.

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[11] https://www.ecmwf.int/en/publications/ifs-documentation

[12] https://www.umr-cnrm.fr/accord/

[13] https://nextgems-h2020.eu/

[14] https://eerie-project.eu/

[15] https://leonardo-supercomputer.cineca.eu/glori4de/

For example, it enables the direct extraction of selected hypercubes of data – such as along a flight path, at a specific point, or over a country – facilitating the targeted use of the vast data volumes generated by the digital twins.

The Data Lake, implemented by EUMETSAT, incorporates different data locations and provides users with technically harmonized access to different datasets. Its three main pillars are: harmonization of diverse data access, facilitation of access to the digital twins' data outputs and other existing datasets, and big data and near-data processing. Digital Twin data is hosted on infrastructure (data bridges), part of the Data Lake, located near the selected EuroHPC and jointly operated by EUMETSAT and ECMWF, interconnecting the Digital Twin Engine services and the wider harmonized data access.

The Destination Earth Service Platform, implemented by ESA, is an entry point to the DestinE ecosystem, addressed to a diverse community of users, providing access to applications, tools and services supporting DestinE data exploitation.

Since the start of the initiative, substantial efforts have been devoted to building these elements, defining their interfaces, and ensuring seamless integration. This paper focuses primarily on the digital twin technology concept, while other system components are described elsewhere and are available via the provided links.

4. What has been achieved?

4.1. Digital Twin Engine

The Digital Twin Engine (DTE) encompasses the workflows that run the digital twins and the software services that deliver, allow access to and handle the digital twin data, as well as notifications regarding its availability, in a decentralized, distributed computing/data environment. A major achievement since the beginning of DestinE consisted in designing, deploying and prototyping the Digital Twin Engine elements, for routinely performing km- and sub-km-scale global and regional weather and climate simulations on the EuroHPC systems and handling their vast data sets. Procedures have been devised for research-to-operations transition to the diverse and externally managed EuroHPC supercomputers. The DTE functions derive from the wider concept of the ECMWF Software Engine (ESEE) and its deployments are instances thereof.

Fig. 2 shows the actual implementation of these elements in the DestinE production cycle, which includes flexible and dynamic data processing pipelines that write output to a semantically addressable object storage (Smart et al., 2019). The innovative methods used for managing the "deluge of data" – up to 1 Petabyte per day – have been described in more detail in Geenen et al. (2024), Leuridan et al. (2023, 2024), Sarmany et al. (2024), Wedi et al. (2020, 2022). These approaches are changing the view of data provision towards data as a stream. They provide for example tailored notifications regarding data production and access during production, allowing impact sector applications to run in parallel with the Earth system simulations. They also enable users to tailor digital twin outputs or make their own fine-grained collections of data (selected area or point), specific to their application, without the need to handle files or global fields.

A data management system adhering to international standards has been established to ensure interoperability and to enable continuous adaptation of the Digital Twins data to the evolving user needs and decentralized information sources. Data governance follows international WMO standards and WMO Information System 2.0 (WIS2[16]) access patterns, and includes a monitoring framework that contains a series of checks ensuring quality control. The object storage – which contains model output that is consistent across different components, such as atmosphere and ocean – facilitates fast semantic data access, hierarchical and sub-selected access (using HealPix, native octahedral Gaussian grid and more traditional latitude–longitude representations) of the global data. The digital twin data representation follows FAIR (findable, accessible, interoperable, and reusable data) principles and is aligned with the data representation of the future next generation Copernicus reanalysis ERA6 to be produced in 2026. Data transformations are built into the system to align the climate research community and the 193 WMO member states represented through the well established WMO Integrated Processing and Prediction System (WIPPS[17]) distribution system. This enables synergies between weather and climate modelling, at both regional and global scales, while also supporting regional modelling worldwide and enhancing equity.

An example of an innovative approach to managing Big Data within the Digital Twin Engine is the Polytope service. Polytope[18] supports novel advanced feature extraction from hypercubes of digital twin data, reducing the access time to sub-selected data (e.g., extracting data in a point, over a country or region), and ensuring interoperability with an increasing number of python-based data access ecosystems (Leuridan et al., 2023, 2024; Pangeo[19]). For example, the Polytope service is used within the DestinE system by the harmonized data access (HDA[20]) and other DestinE platform services.

Another innovation of the Digital Twin Engine is the streaming of Earth system data to sector-specific applications embedded within the digital twins workflow, enabling dynamic data tailoring to user needs. The latter still needs to mature as it necessitates a shift of responsibility regarding the data collection and accumulation to the sector-specific applications.

All these developments represent investments in translation layers and the two-way communication anticipated for digital twins (Fiedler et al., 2021). Initial developments in visualizing digital twin data aim to enhance decision support by improving communication and understanding of complex Earth system interactions. This could potentially influence public opinion and drive behavioural change, e.g. the visual representation of the future day-to-day dependency of a given region on wind and solar energy as a function of weather-induced dependencies, supply and demand (as the latter can be influenced by changing human patterns in daily routines). The focus is on accessibility, education, and exploring innovative AR/VR techniques for visualizing both fundamental and applied knowledge. The initial implementation illustrated the actual flow and needs for European energy redistribution due to weather-related uncertainties in the supply of renewable energy in both near-real time and future scenarios.

Another key focus of the Digital Twin Engine is optimizing the complex digital twin simulations for efficient execution on diverse pre-exascale EuroHPC platforms with varying CPU and GPU hardware. The models employ a large-scale domain decomposition approach (MPI) for parallelization, combined with support for OpenMP threading to further parallelize computational regions within an MPI task on CPUs, and GPU offloading using OpenACC and some CUDA/HIP kernels as well as optimized GPU libraries such as cuFFT and cuBLAS. OpenMP offload support as an optional alternative to OpenACC directives for improved flexibility is also under development. Beyond the specific implementation details listed before, the Destination Earth initiative has helped to accelerate the reorganization of workflows and supported the adaptation of Digital Twin model codes to the EuroHPC CPU–GPU architectures, benefitting the ICON, FESOM, NEMO, IFS and the ACCORD consortium models. Despite specific challenges encountered when adapting these complex, coupled Earth system models to the EuroHPC platforms, performing multi-decadal climate simulations at

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[16] https://community.wmo.int/en/activity-areas/wis/wis2-implementation

[17] https://community.wmo.int/en/wipps-web-portal

[18] https://platform.destine.eu/services/service/polytope/

[19] https://www.pangeo.io/

[20] https://platform.destine.eu/services/service/hda/

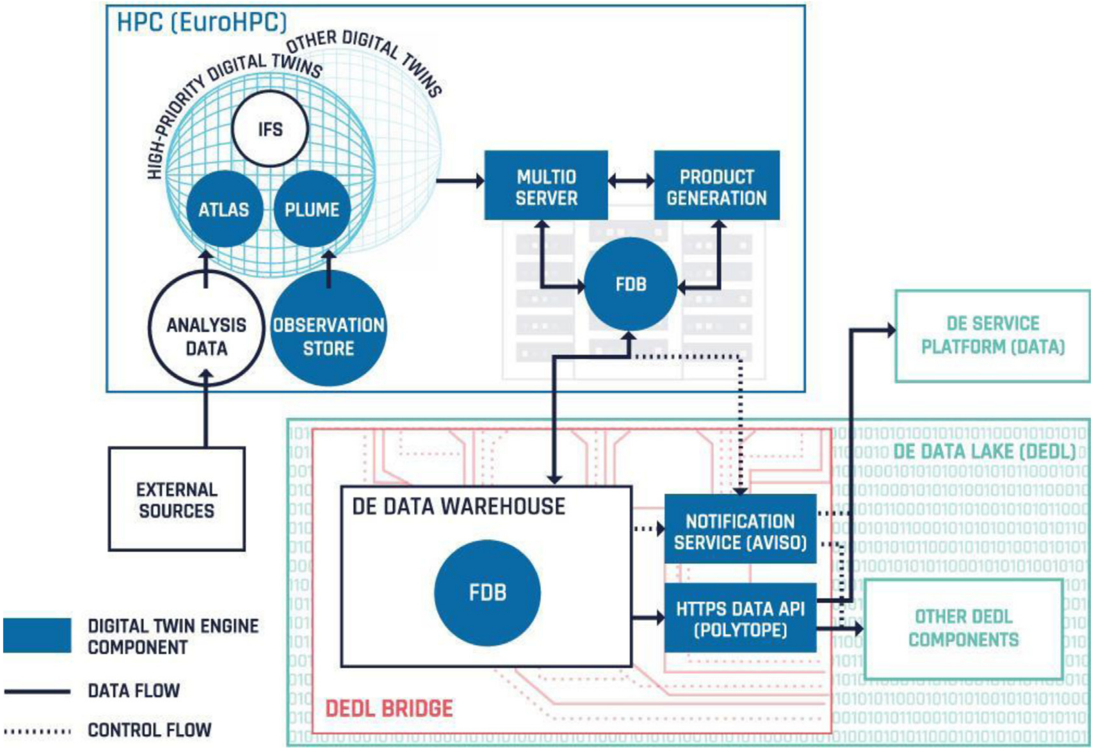

Fig. 2. Components of the Digital Twin Engine (DTE), spanning multiple infrastructure components of Destination Earth: the digital twins operating on the high-performance computing facility (HPC), the data warehouse embedded within data bridges of the Data Lake (DEDL), and DTE software clients being deployed within the DEDL and the service platform (DESP) services. Atlas is ECMWF's data structure library; Plume stands for model plugin architecture; MultiIO stands for multiplexing IO-server and on-the-fly post-processing; and the simulated fields database (FDB) is a key–value object storage with semantic data access (e.g. a request of temperature over Europe rather than a file). Data assimilation products and observations are provided from ECMWF and other sources, while the observation store indicates observational constraints and online verification of digital twins.

km-scales on the emerging pre-exascale facilities constituted an important breakthrough. For example, the ICON simulations leveraged LUMI's hybrid architecture, running ICON's atmosphere component entirely on the AMD GPUs. ML/AI training used the GPUs on the Leonardo Booster, while the IFS-NEMO and IFS-FESOM models at 5–10 km resolution exploited the available CPU clusters LUMI-C and MN5 GPP, respectively. This demonstrates how DestinE directly contributes to digitalization and optimizes the use of available infrastructures.

4.2. Digital Twins

A key milestone was the development of two digital twins – integrating multiple Earth system and impact models – and the deployment of their complex workflows – including production pipelines – on the EuroHPC supercomputers.

The Climate DT brings an additional capability compared to current climate modelling activities by: (i) being designed to operationally produce updated, quality-controlled climate information routinely (yearly or more frequently) to fast-track and complement CMIP activities; (ii) providing a framework for bespoke, on-demand climate simulations, tailored to user needs in terms of output variables and simulation design and (iii) providing globally consistent data at higher spatial (5–10 km) and temporal (hourly) resolution. More specific information on the Climate DT can be found in Doblas-Reyes, (2025).

A major achievement of the Climate DT was performing for the first time ever global multi-decadal climate projections at 5 km resolution with three models on EuroHPC. The multi-decadal Climate DT simulations cover the recent past (from 1990) and possible future evolutions of the climate up to 2040.[21] Another key innovation of the Climate DT is the routine production of storyline simulations using IFS-FESOM. This framework was used to generate a first set of global, kilometre-scale storylines of recent extreme weather events – from 2017 to today – illustrating climate change effects and informing adaptation strategies. The simulations reconstruct recent extreme events, such as heatwaves, floods, and droughts under various climate conditions (e.g. pre-industrial, present-day, a +2 °C and +3 °C world). This is achieved by nudging the atmospheric circulation in IFS-FESOM, for the different climate conditions (John et al., 2024; Athanase et al., 2024), to the ERA5 reanalysis data produced by ECWMF in the frame of the Copernicus Climate Change Service (Hersbach and co authors, 2020). Processes on smaller scales and thermodynamic processes are free to evolve, which allows for example to study how a recently experienced heat wave would change in a warmer world (Fig. 3). Storyline simulations will be updated regularly to include most recent months, and small ensemble of simulations will be performed for certain extreme events to provide uncertainty quantification. These simulations complement the ongoing operationalization of climate attribution in the Copernicus Climate Change Service and represent another key application area with similar requirements and methodologies (Perkins-Kirkpatrick et al., 2024).

Addressing climate change requires multiple methodologies (Balaji et al., 2022). DestinE complements existing knowledge, while contextualizing local and regional changes. While DestinE can potentially capture early warning signs of major changes in ocean and atmospheric circulations, the full cycle of the Atlantic Meridional Overturning Circulation (AMOC) spans ∼1000 years. As a result, simulating paleo-climate perspectives to predict "tipping points" is beyond DestinE scope. However, assessing these tipping points in what-if scenarios and exploring possible adaptation scenarios to such tipping points remains within scope.

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[21] https://destine.ecmwf.int/climate-change-adaptation-digital-twin-climate-dt/

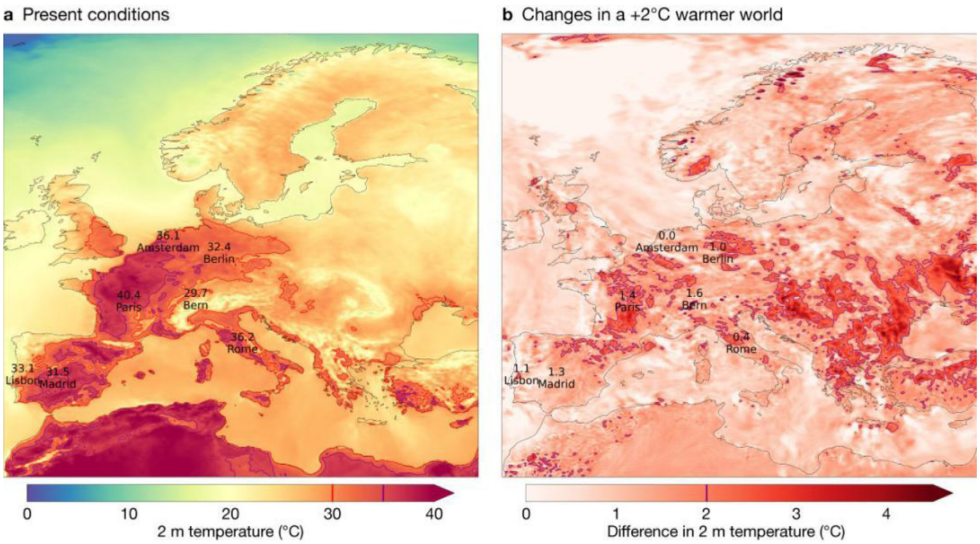

Fig. 3. The figure shows (a) the European heatwave of 25 July 2019 and (b) the additional warming in a +2 °C warmer world compared to present conditions. The results are based on kilometre-scale storyline simulations in which the large-scale atmospheric flow is nudged to ERA5, performed with IFS-FESOM (at 9 km in the atmosphere and approximately 5 km in the ocean) on LUMI.

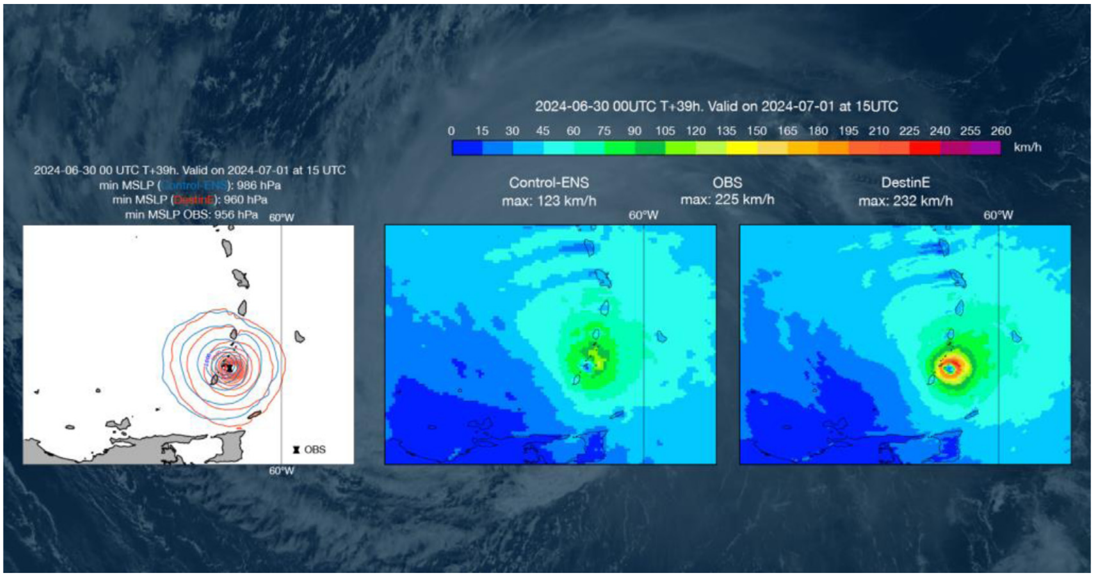

Fig. 4. Mean sea level pressure field of TC Beryl in the ECMWF Control-ENS (blue) and DestinE (red) in the left plot of the panel. The black hourglass indicates the location of the TC centre at the same valid time. The shaded plot on the right of the panel shows the 10 m wind speed in the ECMWF Control-ENS (left) and DestinE (right). The forecast is initialized on 30 June 2024 at 00 UTC, valid on 1 July 2024 at 15 UTC (forecast at T+39 h).

The Extremes DT[22] builds a capability to simulate extreme weather events and their impacts up to four days ahead, complementing existing capabilities, to support national authorities in their mandates to respond and adapt to the consequences of extreme events.

A key achievement consisted in producing regular global 4-days simulations at 4.4 km and regional 2-days simulations for extreme events emerging over Europe at 500 to 750 m. Another milestone consisted in conducting the first comprehensive assessment of near real-time global forecasts, initialized daily for nearly a year, at these km-scale resolutions, (Vanniere et al., 2024, Gascon Salvador et al., 2024). Initial assessments showed that the component of the Extremes DT did not consistently outperform ECMWF operational forecasts ‘out of the box’, in terms of large-scale skill scores. However, significant progress has been made in reducing forecast errors, particularly for the prediction of certain types of extreme events (Fig. 4). The global Extremes DT consistently improved forecasts of tropical cyclones and medicanes compared to routine ECMWF forecast products. Intense orographic precipitation was also improved, benefiting from the steeper slopes of the resolved orography and a larger orographic uplift, consistent with past experience from operational regional weather prediction systems . For the regional component, the representation of wind gusts and convective precipitation was often improved when simulating explicitly the sub-km scales, thus contributing to the improvement in assessment and skill on WMO’s Early Warnings For All (EW4All) priority events. Fig. 5 illustrates a simulation with the regional component of the Extremes DT, incorporating energy sector models, that predicted well the drop in energy production from a wind farm off the coast of Belgium during Storm Eunice in February 2022.

By using the same models, and resolutions, as the Extremes DT, the Climate DT simulates not only the evolution of the climate state, but

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[22] https://destine.ecmwf.int/weather-induced-extremes-digital-twin/

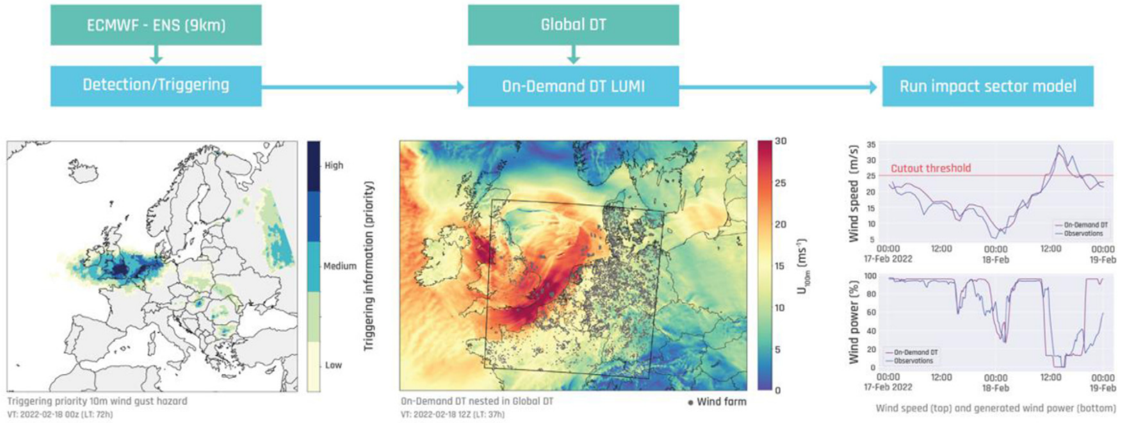

Fig. 5. End-to-end demonstration of the Extremes DT. A detection mechanism is used to detect various types of hazards based on ECMWF ensemble forecast (ENS). In the case of storm Eunice on 18 February 2022, the detection of a strong probability of 10 m wind gust hazard, led to the configuration and activation of a regional simulation at 750 m resolution, off the coast of Belgium, that used the global Extremes DT simulations as lateral boundary conditions. The high-frequency wind was used by a wind farm application that successfully predicted a drop in energy production due to the shutdown of wind farms two days in advance.

also the weather in a future climate, including some of its extreme manifestations. It can for example represent convectively driven extreme events, which existing global climate models often insufficiently capture due to resolution limitations and systematic structural biases (Frassoni et al., 2023). An enhanced representation of the land-atmosphere feedbacks and coupling frequency is another important novelty of the DestinE models. For example, the DestinE models continuously improve the land mapping data to reduce errors in land-atmosphere feedbacks (Rackow et al., 2025). Notably, new geographically diverse heterogeneous high-resolution mapping data can be fed into DestinE models, without averaging a-priori to coarse resolutions. There are increasing efforts on urban modelling (Nazarian et al., 2024) that specifically make the case for globally available km-scale data such as provided by DestinE. One of the DestinE use cases indeed explored digital twin data in forcing urban simulations, notwithstanding the outstanding challenges of representing weather phenomena at hectometric scales (Lean et al., 2024). Furthermore, the high time frequency coupling between the different earth system components translates into a realistic representation of the diurnal cycle over land, ocean and sea-ice.

DestinE will seek the most cost-effective approaches to constrain uncertainty. This will include AI-driven simulations (e.g. AI-based ensemble information generation is substantially cheaper than high-resolution physical model-based ensembles; AI-based simulations can also remove model bias), other multi-model data, or physics-based ensembles. AI supported observational constraints, which imply the application of different weights to individual model realizations based on an assessment of the simulation quality with respect to observational data, could also be used. These approaches may be combined with simulation data to further sample and constrain climate uncertainty, cf. O'Reilly et al. (2024). Another future step is to explore qualifiers of uncertainty for a given DestinE dataset and for a given target application.

From the outset, DestinE digital twins have targeted the support of decision-making in a variety of impact sectors by piloting several use cases (Hoffmann et al., 2023). These included air quality management, flood risk management, climate change adaptation (urban heat, flood risk, forestry), renewable energy management (on- and offshore wind energy, energy systems planning), water management and natural resource management and risks (https://destine.ecmwf.int). The aim was to ensure that from the early development phases technical and scientific developments are co-designed with selected impact sectors, accounting for their needs and creating user stories. This process allowed to establish a dialogue and capture requirements of selected sectors, but it is acknowledged that more effort is required to build robust interfaces to policy in future.

Each of these cases employed one or more impact sector models or indices – such as hydrologic models, energy system models, wildfire risk assessments – driven by DestinE digital twin data. For example, as part of an energy system use case, the German Aerospace Center (DLR) developed a representative energy system simulation workflow based on their REMix[23] model. The team demonstrated that the choice of climate datasets significantly affects resource adequacy assessments (Fig. 6), underscoring the need for the DestinE developments. This also highlights how DestinE can complement policy interfaces, such as those intended with the Copernicus Energy Hub.[24]

5. Computational cost

Balancing computing costs and resource efficiency on digital twin development has to balance the expected outcomes and the return on the investment for routinely conducting bespoke simulations. So far, ~90 years of high-resolution climate DT simulations were performed (e.g. covering 1990–2040, with historical and scenario forcings, using 3 different models), using only a small fraction of the total EuroHPC resources. The DestinE allocation constituted nominally 2.5% of each of the pre-exascale systems, i.e. LUMI, Leonardo, and MareNostrum 5. In phase 1 of DestinE these HPC systems were all newly installed with quite some variability in their availability and the bulk of the DestinE simulations were performed on LUMI. Although computing resources were granted without any guarantees on availability, DestinE worked closely with each site to perform and optimize the simulations. At LUMI, a two-month peak access period was also allocated to ensure the timely delivery of the first multi-decadal climate projections ahead of DestinE's official launch in June 2024.

DestinE registered over 300 scientists on EuroHPC machines. Table 1 states the total computing resources consumed by DestinE on EuroHPC in 2024 on LUMI, MareNostrum 5, Leonardo and on MeluXina.

A 30-year simulation performed on LUMI consumed on average, per model, 70 Million CPU core-h or 1.4 Million GPU h, respectively. This produced in fact a negative CO_2 balance, given that LUMI consumes 100% renewable energy and uses its surplus heat for providing heating to the nearby town.

While this is a significant computing resource, it remains a relatively small investment given the scale of the task. However, it demonstrates the potential for substantially reducing uncertainty in future climate

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[23] https://www.dlr.de/en/ve/research-and-transfer/research-infrastructure/modelling-tools/remix

[24] https://energy.hub.copernicus.eu/

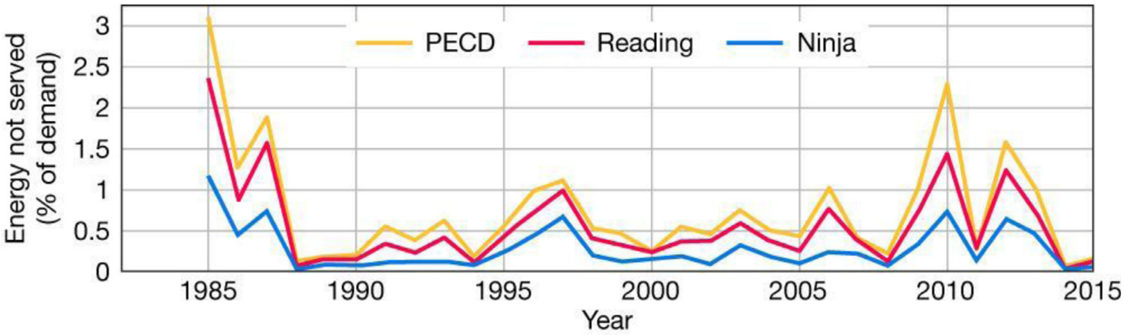

Fig. 6. Energy not served (the energy not supplied due to insufficient capacity resources to meet the demand) from 1985–2015 in per cent of the annual demand for Germany under the National Estimates 2030 scenario and given for three different meteorological datasets.

Table 1
Computing resources consumed by DestinE on EuroHPC in 2024.

	GPU h	CPU h
LUMI	3,624,193	48,005,975
MareNostrum 5	9,158	55,000,000
Leonardo	5,707,210	16,714,544
MeluXina	10,289	

projections if an entire system the size of LUMI were dedicated to this effort. Notably, several such installations, including the first exascale platform in Europe, Jupiter, are becoming available in Europe in 2025. In comparison, the past European contribution to CMIP6 is the equivalent of 1131 million CPU (useful) core-hours (Acosta et al., 2024), conducted entirely on 14 different national supercomputers.

6. Outlook & conclusion

In its first phase, DestinE established the digital twin and digital twin engine capabilities. It demonstrated them by performing the first digital twin simulations at scale on selected EuroHPC platforms and by making the data accessible within a production environment via the DestinE platform.[25] In its second phase, DestinE further evolves and operationalizes digital twin technology. It also significantly expands the AI capabilities, exploiting recent advances in AI/ML for both weather and climate timescales (e.g. Kochkov et al., 2024; Lang et al., 2024). Notably, DestinE will exploit the global high resolution digital twins datasets to train and refine the next generation of AI based models, advancing towards an European Earth system AI based model. AI based models are expected to enhance uncertainty quantification in digital twin simulations, at a fraction of the cost of traditional methods, leveraging HPC-compatible technologies. Moreover, AI models can recreate information at a fraction of the original computational cost, reducing data storage requirements. For example, providing the weights and the corresponding AI model instead of storing and making accessible all fields from a simulation constitutes a different load on the network when many users want to access relevant information in a geographically distributed environment. Moreover, AI opens potential pathways for augmenting and fusing the mix of weather, climate and non-weather related information. The key next steps consist in operationalizing the digital twins and building trust in the information provided, particularly for public institutions. This includes expanding knowledge on how to effectively use DestinE data, developing tailored interfaces for user communities and use cases that integrate DestinE data with other relevant information, and advancing expertise in AI model applications. DestinE has influenced parallel digital twin developments in other domains (e.g. biodiversity, oceans, geophysical extremes), and aims to enhance information exchange through interoperable interfaces for simulations and data beyond weather and climate.

To better define "what-if" scenarios, simulation protocols are further explored, with a focus on incorporating feedback and updates from stakeholders. Similarly, the triggering and detection frameworks for on-demand Extremes digital twin simulations are being refined to minimize the time-consuming production phases and streamline support for public institutions in identifying potential extremes and their impacts early on.

The use of fast-tracked climate projections, machine learning and digital twin concepts has gained substantial traction beyond Europe (e.g. Mariotti et al., 2024). The strategic shift towards fast-tracked, sustained production of climate projections is also gaining traction within the climate services community. This is driven in part by national weather services adapting their offerings to a changing climate and an evolving digital landscape (WMO, 2021). Additionally, the use of storylines, discussions on the trade-offs between increasing model complexity, ensemble size and spatial resolution, and a structured dialogue between Earth system modellers and impact sector applications have already reduced the gap between science and policy relevance. DestinE strengthens European capabilities in these areas, by establishing tailored simulation and data distribution pathways, enhancing interoperability and data exchange.

DestinE's long-term efforts to explore novel modelling and programming paradigms – executed on some of the world's most performant computing platforms – aim to provide immediate, accessible and understandable information beyond the traditional domains. This is a key step towards accelerating progress in "fit-for-purpose" climate modelling for the benefit of society. However, efforts will increasingly focus on tailoring DestinE information to specific impact assessments, such as water availability and quality, food and energy supply, and supporting national authorities in exploiting the DestinE capabilities in their roles to protect lives and assets from extreme events and climate change.

CRediT authorship contribution statement

Nils Wedi: Writing – review & editing, Writing – original draft, Supervision, Software, Funding acquisition, Data curation, Conceptualization. **Irina Sandu:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization. **Peter Bauer:** Writing – review & editing, Funding acquisition, Conceptualization. **Mario Acosta:** Supervision, Software, Data curation. **Rune Carbuhn Andersen:** Supervision, Resources. **Ulf Andrae:** Supervision, Software, Investigation, Data curation. **Ludovic Auger:** Supervision, Software. **Gianpaolo Balsamo:** Supervision, Software, Resources, Conceptualization. **Vasileios Baousis:** Writing – review & editing, Software, Methodology. **Victoria Bennett:** Writing – review & editing, Supervision, Resources. **Andrew**

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[25] https://platform.destine.eu/

Bennett: Supervision, Software. **Carlo Buontempo:** Writing – review & editing, Conceptualization. **Pierre-Antoine Bretonnière:** Validation, Software, Investigation, Data curation. **René Capell:** Validation, Software, Methodology. **Miguel Castrillo:** Supervision, Software, Investigation, Conceptualization. **Matthew Chantry:** Supervision, Software, Methodology, Investigation. **Matthieu Chevallier:** Visualization, Validation, Supervision. **Ricardo Correa:** Software, Conceptualization. **Paolo Davini:** Visualization, Validation, Software. **Leif Denby:** Software. **Francisco Doblas-Reyes:** Supervision, Resources, Conceptualization. **Peter Dueben:** Writing – review & editing, Supervision, Resources, Conceptualization. **Claude Fischer:** Resources, Project administration, Funding acquisition. **Claudia Frauen:** Software, Project administration, Data curation. **Inger-Lise Frogner:** Supervision, Methodology. **Barbara Früh:** Validation, Investigation. **Estíbaliz Gascón:** Visualization, Validation, Investigation. **Elisabeth Gérard:** Project administration. **Oliver Gorwits:** Supervision, Software. **Thomas Geenen:** Supervision, Resources, Conceptualization. **Kat Grayson:** Visualization, Validation, Methodology. **Nadia Guenova-Rubio:** Project administration. **Ioan Hadade:** Validation, Supervision, Software, Resources. **Jost von Hardenberg:** Visualization, Validation, Software, Methodology. **Utz-Uwe Haus:** Software. **James Hawkes:** Supervision, Software, Data curation. **Marcus Hirtl:** Validation, Methodology, Investigation. **Joern Hoffmann:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Kristian Horvath:** Validation, Software, Investigation. **Heikki Järvinen:** Supervision, Methodology, Conceptualization. **Thomas Jung:** Validation, Supervision, Methodology, Investigation, Conceptualization. **Alexander Kann:** Visualization, Validation, Software. **Daniel Klocke:** Validation, Supervision, Software, Data curation. **Nikolay Koldunov:** Visualization, Validation, Supervision, Software, Methodology, Investigation. **Jenni Kontkanen:** Supervision, Project administration, Investigation. **Outi Sievi-Korte:** Project administration. **Jørn Kristiansen:** Supervision, Resources, Funding acquisition. **Emma Kuwertz:** Validation, Software, Investigation, Data curation. **Jarmo Mäkelä:** Software, Investigation. **Ilja Maljutenko:** Visualization, Validation. **Pekka Manninen:** Supervision, Resources, Project administration. **Ursula S. McKnight:** Validation, Software, Methodology. **Sebastian Milinski:** Validation, Supervision, Software, Investigation, Data curation, Conceptualization. **Andreas Mueller:** Visualization, Software. **Antony McNally:** Validation, Supervision, Software, Methodology. **Umberto Modigliani:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Devaraju Narayanappa:** Validation, Supervision, Investigation. **Kristian Pagh Nielsen:** Validation, Supervision, Project administration, Investigation. **Thomas Nipen:** Visualization, Validation, Software. **Henrik Nortamo:** Supervision, Software, Resources. **Vincent-Henri Peuch:** Funding acquisition, Conceptualization. **Suraj Polade:** Validation, Investigation. **Tiago Quintino:** Visualization, Validation, Supervision, Software, Methodology, Data curation, Conceptualization. **Irene Schicker:** Validation, Software, Investigation. **Balthasar Reuter:** Supervision, Software, Investigation. **Simon Smart:** Supervision, Software, Investigation. **Mike Sleigh:** Validation, Supervision. **Martin Suttie:** Validation, Supervision, Resources, Investigation. **Piet Termonia:** Supervision, Software, Methodology, Investigation. **Stephan Thober:** Visualization, Validation. **Roger Randriamampianina:** Supervision, Project administration, Methodology, Investigation. **Natalie Theeuwes:** Visualization, Validation, Supervision, Methodology, Investigation. **Daniel Thiemert:** Project administration. **Benoît Vannière:** Writing – review & editing, Visualization, Validation, Supervision, Software, Methodology, Investigation. **Stéphane Vannitsem:** Visualization, Validation, Software. **Christoph Wittmann:** Validation, Supervision, Methodology. **Xiaohua Yang:** Validation, Supervision, Software, Investigation. **Marc Pontaud:** Supervision, Resources, Funding acquisition, Conceptualization. **Bjorn Stevens:** Supervision, Software, Methodology, Conceptualization. **Florian Pappenberger:** Supervision, Resources, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank their colleagues at ECMWF and the collaborators in the different participating institutes listed at https://destine.ecmwf.int/provider/ for their unwavering ambition and commitment to create new pathways and valuable contributions in DestinE. Destination Earth is implemented under the leadership of the European Commission DG CNECT, in partnership with the European Space Agency and the European Organisation for the Exploitation of Meteorological Satellites, and the authors acknowledge their continued support and important contributions to the implementation of Destination Earth's digital twin technology. We also acknowledge the EuroHPC Joint Undertaking for awarding this project access to the EuroHPC supercomputer LUMI, Leonardo, MeluXina, and MareNostrum 5 through a EuroHPC JU Special Access call. Finally, we would like to thank the editor and the reviewers for their helpful comments that improved the presentation.

The work presented in this paper has been produced in the context of the European Union's Destination Earth initiative and relates to tasks entrusted by the European Union to the European Centre for Medium-Range Weather Forecasts implementing part of this Initiative with funding by the European Union. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Data availability

The data is openly available upon successful application for upgraded access on the DestinE platform platform.destine.eu.

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