The Destination Earth digital twin for climate change adaptation

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Abstract. The Climate Change Adaptation Digital Twin (Climate DT), developed as part of the European Commission's Destination Earth (DestinE) initiative, sets up an operational system for producing multi-decadal, multi-model global climate projections and translating climate data into climate impact information to support adaptation efforts. This system delivers data with local granularity at spatial resolutions of 5–10 km and hourly outputs, leading to globally consistent information at scales that matter for decision-making. It also enables the testing of what-if scenarios such as high-resolution storylines, which are physically consistent global simulations of extreme events under different climate conditions and provide contextual insights to support concrete adaptation decisions. They support the generation of more equitable (understood as accessible and relevant across regions) climate information. The Climate DT is built on cutting-edge infrastructure, expert collaboration, and digital innovation. It is designed to support on-demand responses to policy questions, with quantified uncertainty. It will foster interactivity by allowing users to influence simulation design, model output portfolios, and application integration through co-design. AI-based tools, including emulators and chatbots, are being developed in parallel to enhance climate information access. Sector-specific applications are embedded in the system to synchronously translate climate data into tailored climate-impact indicators, with examples provided for energy, water, and forest management. The applications have been co-designed with informed users. A unified, cross-platform workflow defines the orchestration of all components, which is handled by a single workflow manager and relies on containerised components, facilitating automation, portability, maintainability, and traceability. Data management is unified through the use of standard grids (HEALPix), ensuring consistency and easing data usability under a strict governance policy. Streaming enables real-time data use by the data consumers and unlocks access to the unprecedented data wealth produced by the high-resolution simulations. Monitoring tools provide real-time quality

control of data and model outputs and enable continuous assessment of the realism of the climate simulations during Climate DT operation. The compute-intensive system is powered by world-class supercomputing capabilities through a strategic partnership with the European High Performance Computing Joint Undertaking (EuroHPC). Despite high computational demands, the Climate DT sets a new benchmark for delivering equitable, credible, and actionable climate information. It complements existing initiatives like CMIP, CORDEX, and national and European climate services, and aligns with global climate science goals to support climate adaptation.

1 Introduction

Providing reliable climate information is essential for enabling effective climate change adaptation (Orlove, 2022). The latest report from the Intergovernmental Panel on Climate Change (IPCC) Working Group I (IPCC, 2021) highlights major gaps in our ability to simulate regional and local climate change and to deliver climate information that supports decision-making (Collins et al., 2024; Shaw et al., 2024). It also emphasises the challenge of ensuring that the information is salient[1], equitable, and credible for diverse audiences (Doblas-Reyes et al., 2021).

With globally averaged annual-mean temperatures, for the first time, exceeding 1.5 ºC global warming level threshold[2,3] set in the Paris Agreement (Betts et al., 2023) and with the profound relevance of climate change impacts on both the economy and society (Kotz et al., 2022), future climate information at scales where impacts are already observed is needed. This requires to move from plausibility assessments of changes in local and regional climate (e.g., Collins et al., 2024) to comprehensive climate adaptation plans and targeted measures at both large (e.g., EUCRA, 2024) and small scales (e.g., Schubert et al., 2024). The urgency for new approaches to deliver climate information is further motivated by evolving policy frameworks like the European Green Deal[4].

For climate information sources to be salient, equitable, and credible, they need to consider a wide range of spatial scales, be timely and innovative, and be co-produced with decision-makers to adequately address societally-relevant questions (e.g., Pitman et al., 2022; Doblas-Reyes et al., 2024). These requirements have unveiled an important climate-change information gap for effective climate adaptation strategies to be designed and implemented successfully:

- Equitability: Climate information for adaptation must be provided at spatial scales where the impacts of climate change are observed and expected, and are needed globally to support decision making across a broad range of climate-sensitive sectors (Schubert et al., 2024). Ensuring equitable access to climate information (Hazeleger et al., 2024) therefore requires globally-consistent climate information sources with the highest possible resolution. Current global climate simulations typically do not provide information at spatial resolutions tailored to support adaptation

[1] Meaning the quality of being particularly noticeable or important.
[2] https://climate.metoffice.cloud/current_warming.html
[3] https://climate.copernicus.eu/june-2024-marks-12th-month-global-temperatures-15degc-above-pre-industrial-levels
[4] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

and mitigation decisions and are usually complemented with local and regional simulations (e.g., Soares et al., 2024). Ensembles of regional simulations often require investment and time to cover every region, resulting in infrequent updates and illustrating the structural imbalances and power relations that affect regions that do not have the resources to produce simulations for their own area. This limits the equitable access to decision-relevant climate information.

- Timeliness and innovation: Climate projections are currently updated in multi-year cycles through coordinated community exercises aligned with IPCC assessment reports (e.g., Eyring et al., 2016; Jones et al., 2024). While these efforts feed in highly policy-relevant reports[5], they are not generally structured to provide continuous, on-demand climate information (Stevens, 2024). Moreover, a closer dialogue with policy needs and integration of innovations in digital solutions and artificial intelligence (AI) technologies (Bauer et al., 2023) are required to make climate information more accessible, interpretable, and ultimately actionable (Jones et al., 2024), complementing established initiatives such as the Coupled Model Intercomparison Project (CMIP[6]) and the Coordinated Regional Climate Downscaling Experiment (CORDEX[7]).
- Co-production: Climate-related decisions increasingly rely on evidence from multiple disciplines, yet decision-makers may require climate information with features that cannot be anticipated by physical climate scientists. The absence of regular channels for climate-sensitive sectors to influence the design of climate information hinders some effective adaptation efforts. For instance, participatory processes that involve selected decision makers (Baulenas et al., 2023) in the transformation of climate data into climate information can uncover user needs requiring modifications in how climate data is generated and delivered. The fact that this dialogue does not systematically happen can be explained by the relationships established between the research and service communities (Rodrigues and Shepherd, 2022). The need for systematic co-production mechanisms (Bojovic et al., 2021) and the limited ability of the physical climate science community to react to a variety of decision-making requirements (Jones et al., 2024) can weaken the effective provision of future climate information (Kruk et al., 2017; Fiedler et al., 2021).

Current practice, represented by the CMIP and CORDEX international modelling exercises, has demonstrated to be both useful and relevant. However, some of the aspects above have not yet been fully addressed (Jakob et al., 2023; Stevens, 2024). While efforts are underway to improve timeliness and co-production in the forthcoming CMIP phase (Dunne et al., 2025; Naik et al., 2025), important challenges remain to respond to non-research and operational decision-making needs..

In this paper we present a complementary approach to existing practices for the generation and delivery of future climate projection data. This approach aims to address the challenges identified above and bridge the gap between the provision of timely, decision-relevant climate information (Hewitt and Stone, 2021). It established an operational[8] framework for producing

[5] https://10insightsclimate.science/
[6] https://wcrp-cmip.org/
[7] https://cordex.org/
[8] Operational practice is understood as the set of processes delivering timely and application-ready data, following quick updating cycles, continuous quality monitoring, using a DevOps methodology, and generating machine learning ready datasets.

multi-decadal climate projections and associated impact-sector information, while enabling the exploration of what-if scenarios relevant to climate adaptation across different application domains. This is achieved within a framework that fosters interactions between data producers and "data consumers" through an inclusive pathway that fosters mutual recognition. A data consumer is any "application" using the climate model data, be it for scientific evaluation and understanding, climate impact and risk assessment, or for policy-making purposes.

A promising way to design and implement the interactions between data producers and data consumers is to co-develop the required systems using the digital twin concept (Wright and Davidson, 2020). Digital twins are replicas of physical assets, processes, and systems using a highly interconnected workflow, enabling interaction, exploration of "what-if" questions, and, where relevant, links to physical reality. This paper describes the characteristics and novelties of a digital twin for climate change adaptation (Climate DT henceforth) implemented in the framework of the Destination Earth[9] initiative of the European Union (DestinE henceforth; Sandu, 2024; Hoffmann et al., 2023; Wedi et al., 2025). The paper summarises the Climate DT characteristics and describes how it aims to support the salience, credibility, and equity principles of climate information for adaptation.

2 The Climate DT concept

A digital twin of the climate system targeting adaptation is expected to make use of observations, integrate several climate models to consider uncertainty sources, include applications for climate-sensitive sectors directly connected to the climate models, and provide adequate interfaces to configure the simulations, their output, and the timely interaction with data consumers. The climate models embedded in the digital twin could be either process- or AI-based, with the requirement of being explainable. For the digital twin to be usable and useful, its components, including the climate models and decision-oriented applications, should be co-designed and offer full traceability in terms of both documentation and operation. The resulting output must be of sufficient quality (Dee et al., 2024) to support well-informed decisions while the results should be available fast enough for the decisions to be made within acceptable time scales (Wright and Davidson, 2020). To build trust in the digital twin, documentation, verification (traceability of both operation and testing protocols), and validation (comparison with reality whenever possible) procedures must be included. Validation needs to be treated as a statistical process, which in climate is traditionally addressed using multi-model and multi-member ensembles of solutions (Bauer et al., 2021b; Jones et al., 2024) for a number of emission scenarios to address uncertainty. Additionally, a climate digital twin should make use, in a structured, interactive, and iterative manner, of the instruments developed by social sciences for climate adaptation (Tao and Qi, 2019).

This is the concept that inspires the Climate DT (Figure 1). DestinE is a European Union funded initiative launched in 2022, with the aim to build digital replicas of the Earth system by 2030. The initiative is being jointly implemented, under the lead

[9] https://destination-earth.eu/

of the European Commission Directorate General CNECT, by three entrusted entities: the European Centre for Medium-Range Weather Forecasts (ECMWF), the European Space Agency (ESA), and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) together with over 100 partner organisations in Europe. The Climate DT has been developed since September 2022 by a partnership led by the CSC-IT Center for Science bringing together climate, weather and supercomputing centres, as well as academic institutions from six European countries[10]. This is done in close collaboration with ECMWF, who is responsible for the implementation of the digital twins. The necessary computational resources are provided through a special access call by the European High-Performance Computing Joint Undertaking (EuroHPC JU[11]).

The Climate DT delivers an operational framework for the regular and on-demand production of multi-decadal global climate simulations and their translation into impact-sector information at high spatial resolution. It is designed to support climate adaptation by enabling the exploration of "what-if" scenarios relevant to decision-making across a range of climate-sensitive sectors. The Climate DT builds on decades of experience from numerical weather prediction and Earth system modelling, extending established operational practices to the climate adaptation timescale. It consists of a number of components integrated into an end-to-end workflow and uses a co-design approach to deliver climate and impact-sector information. This end-to-end workflow includes three global kilometre-scale (km-scale henceforth) climate models (ICON, Hohenegger et al., 2022; IFS-NEMO and IFS-FESOM, Rackow et al., 2025) that explicitly represent essential physical processes that critically influence the evolution of the climate system.The climate models and impact-sector applications are embedded in an infrastructure built following practices recommended by both the climate services and digital technology communities to ensure the delivery of operational (understood as timely and routine production) climate information. The backbone of the infrastructure is the unified end-to-end workflow that offers full traceability and permits a consistent data handling procedure based on common variables, grids, and formats, while continuously responding to evolving user requirements. The data handling must cope with unprecedented data volumes associated with the high spatial resolution. This challenge is addressed through the introduction of a data streaming strategy for the data consumers embedded in the workflow. Both the unified workflow and data handling practices, which work seamlessly across multiple high-performance computing (HPC) environments, are fundamental Climate DT innovations.

A protocol has been developed for the Climate DT operationalisation that considers different workflow definitions and actions for the production cycle:

- development, where new capabilities of the Climate DT components are implemented,
- experimental, where the end-to-end workflow and dataflow are tested and fixes implemented,
- and operational, where a scheduled and robust production is ensured,

[10] The Climate DT team includes personnel from Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI), Barcelona Supercomputing Center (BSC), Max Planck Institute for Meteorology (MPI-M), Institute of Atmospheric Sciences and Climate (CNR-ISAC), German Climate Computing Centre (DKRZ), National Meteorological Service of Germany (DWD), Finnish Meteorological Institute (FMI), Hewlett Packard Enterprise (HPE), Polytechnic University of Turin (POLITO), Helmholtz Centre for Environmental Research (UFZ), and University of Helsinki (UH)

[11] https://eurohpc-ju.europa.eu/index_en

These different workflow "suites" are inspired by common practice in operational weather and ocean prediction (e.g., Alvarez Fanjul et al., 2024).

Important characteristics of the Climate DT infrastructure is its flexibility and resilience (Wedi et al., 2022). This solution enables performing bespoke simulations to address targeted "what-if" questions. The Climate DT simulations, and the resulting impact indicators, are monitored in real time by dedicated operators and regularly evaluated. The results are published in an internal dashboard. These are essential requirements for a system that aspires to offer the possibility to determine its added value for users as soon as the data is produced, with the aim of better informing decision-making (Hallegate, 2009).

Given the computational cost associated with the high spatial resolution of the simulations, the efficient use of HPC resources is another defining aspect for the Climate DT. The climate simulations performed leverage strategic access to the most powerful European supercomputers with dedicated cloud storage and delivery systems. Additional capabilities using AI are under development to ease the exploitation of the climate information generated, enhancing the Climate DT equitability and timeliness. It is important to note that the Climate DT concept and infrastructure do not restrict themselves to the use of km-scale simulations nor of pre-exascale HPC platforms.

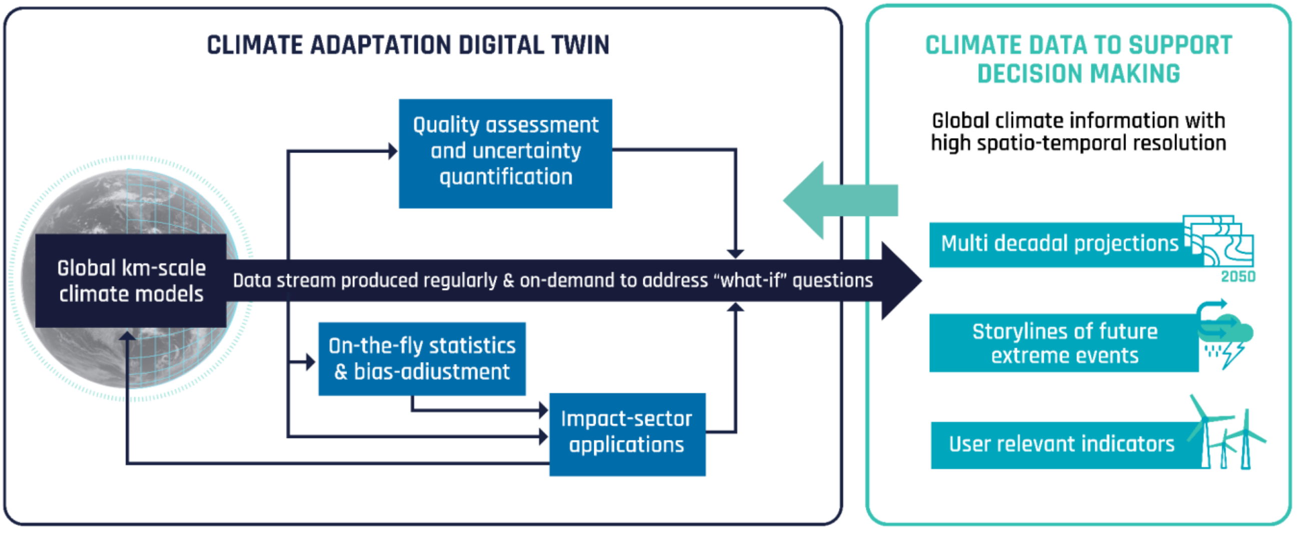

Figure 1: Conceptual diagram illustrating the main Climate DT components. The Climate DT uses data streams from the global high-resolution climate models to feed a range of data consumers embedded in the workflow. The data consumers include climate-sensitive applications and a comprehensive monitoring and quality assessment procedure. User feedbacks are regularly incorporated in the Climate DT design (hence the thick arrows pointing in both directions) so that the global information with local granularity adequately supports climate adaptation decision-making.

3 End-to-end work and data flow

Digital twins require a multi-layered flexible and interoperable software infrastructure that allows data consumers to easily access the data and interact with the system. The infrastructure should be designed to handle models that aim for the highest possible throughput and applications that consume data online, either in situ or remotely. For this approach to work, the Climate DT uses a unified workflow approach that integrates the three climate models and all data consumers, with the execution coordinated by a single workflow manager. The same software solution is employed on the various EuroHPC platforms used by the Climate DT. This is an improvement over the current practice of engineering different solutions for each climate model and platform. Data consumers use Singularity[12] containers to reduce portability challenges.

As a result, the Climate DT workflow (Figure 2) comprises the full production chain, from setting up and running global climate simulations to serving seamlessly their output to a range of data consumers, including tasks to monitor and quality control, both scientifically and in terms of data integrity, and to transfer and remove data. It also incorporates the elements required to configure the Climate DT suites, both for development and operations, supporting different levels of configurability. New data consumers can be included in the workflow and profit from the one-pass algorithms (OPA) and bias-adjustment (BA) methods to perform time aggregations and bias adjustment, respectively. ;Alternatively, they can run as standalone workflows using the same workflow software, benefiting from the streaming mechanism if required. In this case, they can read the data either directly from the HPC disk or from the long-term repository (the data bridges) after data has been transferred. This may happen concurrently during the climate simulation execution in both cases. This approach gives data consumers additional flexibility for integrating their applications into the system while enabling operators to handle different operational scenarios effectively.

The unified approach represents a fundamental shift from the traditional paradigm in climate modelling, where fixed and static flows of components, experimental setups, model outputs, and a variety of software solutions are managed independently by layers of experts, often isolated from each other and from climate-vulnerable communities. This new way of developing climate modelling workflows and performing climate simulations significantly improves workflow maintainability and portability, reduces the cost of maintaining a specific environment on different HPC platforms, and facilitates the introduction of user-relevant Climate DT modifications. This choice, together with regular end-to-end testing of the unified workflow, ensures that updates to any workflow component, model, or data processing step are consistently applied across the whole system and that the system is resilient.

The development and deployment of this end-to-end workflow on the LUMI and MareNostrum5 (MN5) pre-exascale supercomputers (both part of the EuroHPC network) was one of the main priorities during the first phase of Climate DT development (2022-2024). In the second phase (2024-2026) the main focus has shifted to its transitioning towards an operational status and the demonstration of a routine delivery of climate information.

The Climate DT workflow requires an orchestrator that executes tasks in a traceable manner (Bauer et al., 2021b) and makes use of a unified interface where developers and operators can configure the whole digital twin production. The interface configures in a set up file the workflow definition, from the experiment creation to the features required by the data consumers. Domain-oriented workflow managers (e.g., Uruchi et al., 2021; Leo et al., 2024) have proven very useful in the past for similar

[12] https://sylabs.io/docs/

duties and are used on a regular basis in operational numerical weather prediction and climate simulations. The backend of the Climate DT workflow uses the workflow manager Autosubmit (Manubens-Gil et al., 2016) as part of the Digital Twin Engine (DTE)[13]. Autosubmit is a lightweight workflow manager designed to meet climate research needs. It integrates the capabilities of both manager and orchestrator in a self-contained application. Autosubmit stands out for its portability and resilience across different scenarios, from research to operations, and across diverse computing environments, from traditional HPC infrastructure to virtual research environments on cloud resources, such as the European Digital Twin Ocean Virtual Ocean Model Lab[14]. It offers full traceability (Leo et al., 2024) to capture and manage prospective and retrospective provenance, in addition to a notification system that informs users of production progress.

[13] https://stories.ecmwf.int/the-digital-twin-engine/
[14] https://edito-modellab.eu/news/what-is-the-virtual-ocean-model-lab

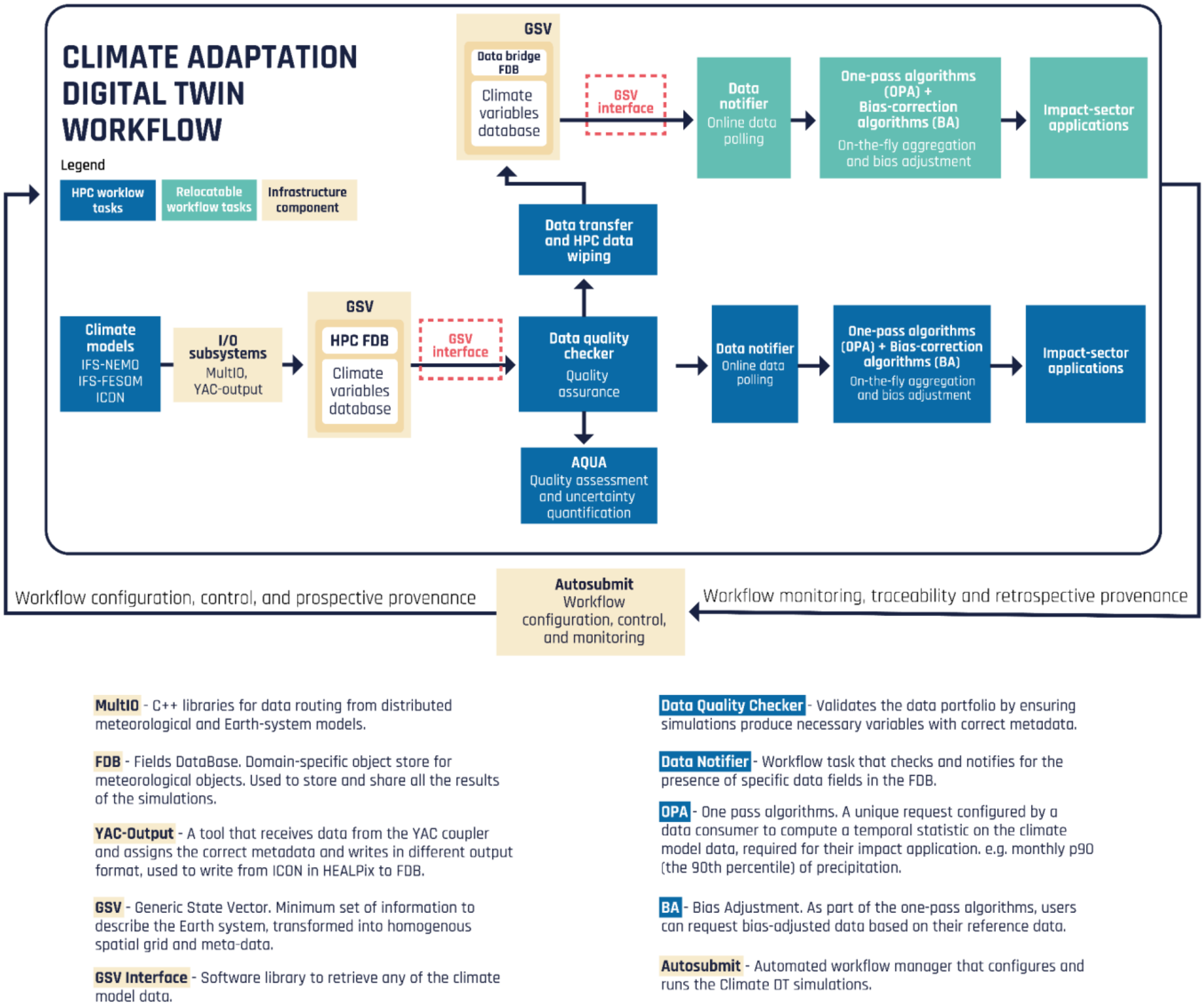

Figure 2: Climate DT workflow and dataflow. The end-to-end workflow tasks (blue colour) are executed on a HPC, supported by the digital twin engine software infrastructure (yellow colour). The data bridge allows the relocatable tasks (which run using containers) to be executed also out of the main workflow suite (green colour) for additional flexibility and data reuse. The Autosubmit workflow manager is used to configure, control, and orchestrate the end-to-end workflow, as well as tasks that are not part of the critical production path. The workflow manager allows the execution of all tasks to be monitored and traced.

The Climate DT infrastructure is developed with a generalised use of continuous integration and delivery, agile software development methodologies, documentation of best practices, performance analysis, and portability. Continuous integration provides measurable indicators about reproducibility, replicability, and efficiency, and supports code quality. Autosubmit handles an automatic testing framework to validate changes in any Climate DT component, which is an essential aspect for the continuity of operational production.

The unified workflow facilitates a homogeneous and fast data treatment with traceability of its availability through the data notifier tasks, which are used along the production chain. The details are presented in the next section.

4 Seamless and homogeneous data access

To ease the use of climate data by all data consumers, the output of the different climate models is homogenised by introducing a "generic state vector" (GSV). In the GSV, the output of all climate models is unified in terms of parameters[15] and units (similarly to what CMIP does), as well as in spatial and temporal resolution, following a strict data governance that regularly accommodates new user requirements. The GSV facilitates consistency across models and enables a step change in the interoperability and usability of climate model output. This solution allows data consumers to seamlessly access the output from any of the Climate DT models as the simulations progress.

Climate model data is individually encoded in a message format. This choice was made to align with the World Meteorological Organisation (WMO) member states' national authorities represented through the WMO Integrated Processing and Prediction System (WIPPS[16]) distribution system. The GRIB format has been chosen as it conveniently aligns with these standards and is proven to mitigate the risks of data loss and recovery since each data message is self-contained with its metadata. The data under this format is written in the HPC storage using the Field DataBase (FDB[17]) technology, to provide standardised access. The metadata governance solution follows WMO standards[18]. However, it is recognised that other formats combined with suitable conventions (e.g., CF convention[19]) are used in the climate community, often with a shift away from a focus on long-term storage to a focus on scalable cloud-based access of vast volumes of both area-specific and global data. For this reason the data management includes the possibility to load xarray data structures, the use of compressed representations, and the inclusion of zarr as a storage format to support its increased acceptance among the community. This is recognised in DestinE so far with interoperable interfaces being developed to access and process native GRIB fields. Additionally, compliance with existing metadata conventions that map both GRIB definitions and established CF conventions is ongoing work. Notwithstanding this, the models underpinning the Climate DT may choose additional output streams in native zarr stores, which some recent European research projects such as nextGEMS[20] and EERIE[21] have shown to provide performant data access for users across a wide range of applications.

Computational grids used internally by the Climate DT model components are different from one another and from the common output grid used in the GSV. The common grid of choice for the GSV is the Hierarchical Equal Area isoLatitude

[15] Ocean vertical levels are specific to each of the three global ocean models included in the Climate DT, while atmospheric data are output using a common set of pressure levels.
[16] https://community.wmo.int/en/wipps-web-portal
[17] https://github.com/ecmwf/fdb
[18] http://codes.wmo.int/grib2
[19] https://cfconventions.org/
[20] https://nextgems-h2020.eu/
[21] https://eerie-project.eu/

Pixelation (HEALPix; Górski et al. 2005). While this deviates from common practice in weather and climate, where historically data sharing in common grids has used a regular latitude-longitude grid, managing unprecedented output volumes at high temporal frequency and fine spatial resolution required rethinking the approach. The advantages of the HEALPix grid are its equal-area uniformity, reducing over-resolution near the poles and hence minimizing the storage requirement for any given resolution. HEALPix also simplifies hierarchical access patterns, AI training and data-driven workflows. It is also well suited to the aforementioned data access capabilities (e.g., zarr with specific chunking) minimising data movement, and facilitating subsetting and nesting efforts when local information from global fields is requested. The integration into end-to-end workflows and data delivery services benefits from quick data transformations (e.g., interpolating to coarser grids) to suit consumer needs.

Climate models use their input/output (I/O) software to interpolate and write the output fields in the HEALPix grid. For IFS, FESOM and NEMO the efficiency of the process is ensured by the use of the parallelised I/O software MultIO (Sarmany et al., 2024). ICON handles the parallel output using external processes coupled with YAC, as in Hanke et al. (2016) with version 2.6.1. An experimental alternative to further improve efficiency of model output is currently being explored with the use of the Maestro middleware (Haine et al., 2021).

The list of climate variables produced by the Climate DT simulations is defined in the data portfolio[22]. The data portfolio is flexible between production cycles to serve any new requirements from the data consumers. The output is offered with a daily frequency for the (two- and three-dimensional) ocean and sea ice variables, and hourly for the (two- and three-dimensional in pressure levels) atmosphere and land. Higher frequency output, requested by some applications, is not yet possible. The data is available in the HPC file systems to be used by the data consumers included in the workflow as soon as it is produced and gone through a quality-assurance process. The HEALPix resolution closest to the Climate DT climate model components is H1024 nested[23] (where 1024 corresponds to the *Nside* parameter described in the documentation[24]) for simulations of 5 km nominal horizontal resolution and H512 for those of 10 km resolution. As an example, each climate model produces around 100 GB of output per simulated day at H1024 resolution. With the target throughput of one simulated year per day (SYPD) at 5 km, each of the Climate DT models thus generates more than 35 TB per wallclock day in routine production mode. These production estimates could be at times higher when climate models perform more than one simulation simultaneously, should a large enough HPC share be available. The Climate DT is inspired by the global weather forecasting experience where similar data volumes are regularly dealt with.

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[22] https://destine-data-lake-docs.data.destination-earth.eu/en/latest/dedl-discovery-and-data-access/DestinE-Data-Portfolio/DestinE-Data-Portfolio.html

[23] Descriptions of the specific HEALPix grids can be found in https://easy.gems.dkrz.de/Processing/healpix/index.html#healpix-spatial-resolution, where the grid resolution is expressed by the parameter Nside, which defines the number of divisions along the side of a base-resolution pixel that is needed to reach a desired high-resolution partition; see also https://healpix.sourceforge.io/html/intro_Geometric_Algebraic_Propert.htm#SECTION420.

[24] https://healpix.sourceforge.io/html/intro_Geometric_Algebraic_Propert.htm#SECTION420

To handle these large data volumes that are continuously produced, both in terms of storage and efficient consumption, the Climate DT employs the streaming concept. In the Climate DT streaming is offered to the data consumers embedded in the workflow. It involves making data available to the data consumers as soon as a set of automatic checks[25] to detect missing fields, flawed metadata, and other potential errors such as unrealistic physical values, have been passed. If any of the critical checks fail, the workflow manager stops the production and warns the operators, who follow agreed procedures to continue after diagnosing and solving the problem. During data production the workflow regularly notifies the data consumers about the availability of new data. The Climate DT continuity is controlled by the data notifier task, which is called by the consumer to trigger its task. In this way, the streaming to the data consumers in the workflow is decided by the consumer.

To the best of our knowledge, this is the first time that such a detailed simulated multi-model climate state is offered to data consumers as the climate simulation progresses offering both a homogeneous data model (whose definition consumers can contribute to) and automated quality control.

As the Climate DT produces regularly multi-decadal simulations from several models, accumulating high-frequency, high-resolution data soon becomes prohibitive for any HPC storage system. This has been solved by addressing both data storage and access with a tiering system. Data (so far all of data produced in phases 1 and 2 of DestinE) is transferred soon after it is produced to a managed storage cloud system. These “data bridges”, of which there is one attached to each HPC used, are implemented by EUMETSAT, as part of the DestinE “data lake”, and managed jointly together with ECMWF (Fig. 2). The residence time of the data in the HPC, which is the time data consumers with HPC access have to exploit the full GSV, is known as the streaming window. The streaming window has been so far of up to one year, but as the simulation production ramps up it is expected to be reduced to several weeks, striking a balance between the limited data storage in the HPC and the access patterns by data consumers in both the HPC and the cloud. The streaming approach offers a unique opportunity, without precedents in climate adaptation, for data consumers to efficiently exploit the full model state at native resolution while it still resides in the HPC. Once the data has been transferred to the data bridges, it is gradually erased from the HPC filesystem to make space for new climate simulation output. The transfer to the data bridge is another task managed by the Climate DT workflow.

The approach used by the Climate DT connects the HPC platforms (which have user access restrictions) to infrastructures with cloud-like data access and services. This spares data consumers not embedded in the production workflow the complexities of the HPC data access and operational procedures, offering user-oriented access to federated, very large data sources through DestinE’s data lake services implemented by EUMETSAT and the DestinE Service Platform (DESP) managed by ESA, always applying DestinE’s data access policy (DestinE, 2025) and guidance. The description of these services, their objectives, strategy, and guidance offered[26] is beyond the scope of this paper.

[25] https://pypi.org/project/gsv-interface/ and https://github.com/DestinE-Climate-DT/GSV-Interface

[26] https://platform.destine.eu/support-pages/data/

A challenge of the data streaming is that its implementation only allows instantaneous views of the data. To address this limitation a variety of OPAs (Grayson et al., 2025; Figure 3) have been developed to estimate statistics, such as time averages, variances, threshold exceedances, percentiles or histograms, and offer temporal buffering of the streamed variables. The OPAs can handle the output from any of the climate models seamlessly thanks to the homogeneity of the GSV and can be linked to the data notifiers. The OPAs can be called by the applications embedded in the workflow to access the data available either in the HPC or the data bridge, and deliver user-relevant processed variables and indicators. The functions have been optimised to deal with the high-resolution, high-frequency fields. They provide full traceability of the data processing. The OPAs are another Climate DT novelty to deliver data in different formats, including NetCDF on disk and Python's xarray in memory. When they are integrated as a task in the production workflow, they make use of a local buffer to restart the data consumer operations in case a climate model failure forces the climate simulation to restart from the last checkpoint file available.

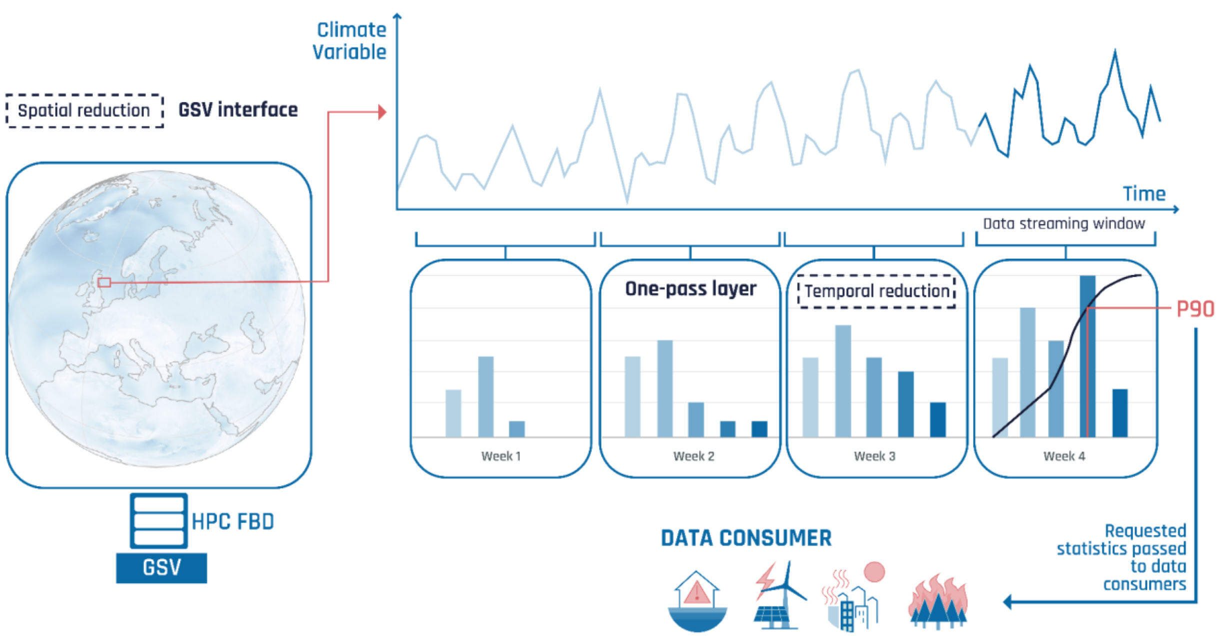

Figure 3: Schematic showing how the climate model output stored as the GSV in the FDB is retrieved via the GSV interface, including data interpolation if requested, and passed into the one-pass layer. The one-pass algorithms (OPAs) provide temporal reduction by computing a statistic requested by a data consumer from native data. The figure illustrates a case of percentiles from weekly histograms of a climate variable. The statistic is continuously updated, controlled by data notifiers tasks, as new data from the climate simulation becomes available, always within the streaming window allowed by the data management process.

With its data streaming capability, providing the full access to the climate model state as the models perform their simulations and data processing enabled by the combination of GSV, data notifier and OPA capabilities, the Climate DT functions as a virtual instance of the simulated climate. It can be considered a metaphor in the climate modelling realm of an observing instrument, which samples reality with the highest frequency possible relevant to the process under study, while in parallel the data is thinned from the high-frequency sample to make the data stream manageable. In this metaphor, if a data consumer cannot make use of the data available in the streaming window (i.e., before the HPC storage is flushed to make space for more model output), they will have to either 1) use model output from the data bridge as described previously, if the necessary variables are available there, or 2) wait some time for a new climate simulation, either with a new model version or as a new member of an ensemble.

5 Production of the first set of global climate projections and storyline simulations with local granularity

The Climate DT exploits and co-develops a new generation of global storm-resolving, eddy-rich models (Moreton et al., 2020; Beech et al., 2024; Segura et al., 2025), often referred to as km-scale models, and a set of HPC advances. A handful of these models have been built, among which those participating in the Climate DT (Bauer et al., 2021a; Rackow et al., 2022; Segura et al., 2022; Streffing et al., 2022; Rackow et al, 2025; Wedi et al., 2022: Taylor et al., 2023; Donahue et al., 2024). The three global climate models used, ICON, IFS-NEMO, and IFS-FESOM, have been adapted to perform km-scale simulations through a cooperative development approach supported by the European-funded research projects nextGEMS[27] and EERIE[28], as well as national initiatives such as WarmWorld[29] in Germany and Gloria[30] in Spain, involving climate, weather, and supercomputing centres, and academic partners throughout Europe. In the Climate DT, these models are used to perform climate simulations at nominal resolutions ranging from 5 and 10 km for the different components of the Earth system, exploiting the supercomputing facilities of the EuroHPC JU. The current throughput is approximately 0.5 simulated years per wall clock day (SYPD) at 5 km resolution, and 2–3 SYPD at 10 km, using around 200 and 100 computing nodes, respectively. Efforts are underway to improve the HPC adaptation of the models to enhance their energy efficiency, while aiming to reach a throughput of about 1 SYPD at 5 km through various optimizations such as reduced precision and efficient GPU porting.

[27] https://nextgems-h2020.eu/
[28] https://eerie-project.eu/
[29] https://www.warmworld.de/
[30] https://www.bsc.es/research-and-development/projects/gloria-global-digital-twin-regional-and-local-climate-adaptation

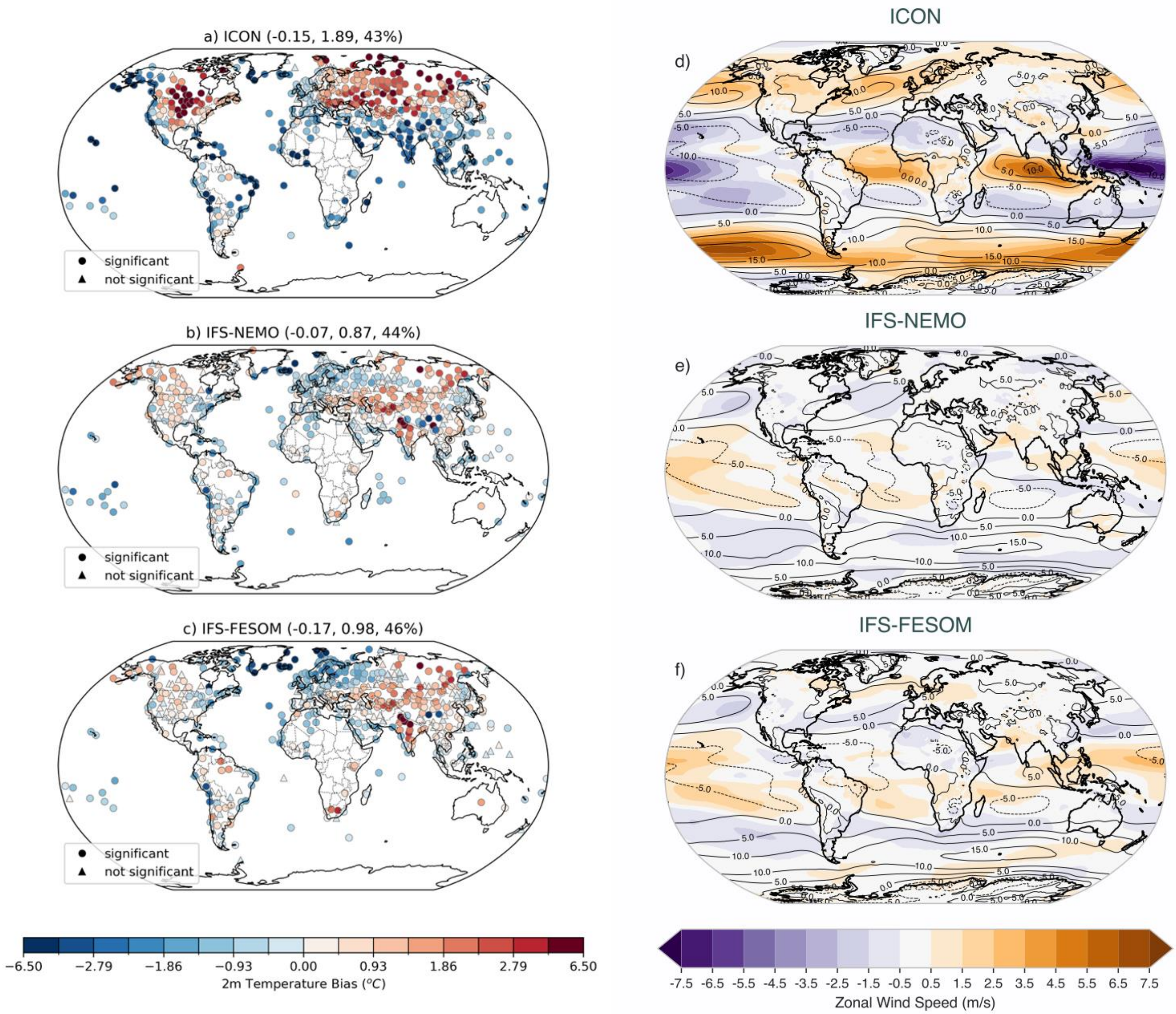

Figure 4: Example of AQUA-OBSALL diagnostics output. (Left column) Bias of annual mean 2-metre temperature (°C) at synoptic surface stations in (a) ICON, (b) IFS-NEMO and (c) IFS-FESOM. Stations where the simulated values differ at the 5% significance level from the observations are represented with closed circles and the rest of the stations with triangles. Values in the headings stand for average bias, average absolute bias, and the fraction of stations with positive bias, respectively. (Right column) 850 hPa zonal mean wind (contour, m/s) and bias against ERA5 (shading, m/s) in (d) ICON, (e) IFS-NEMO and (f) IFS-FESOM. For the three models, climate simulations considered are historical simulations (O25.1). For both simulations and references, the period considered is 1990-2014.

The Climate DT infrastructure is not limited to deterministic km-scale simulations but also allows the production of climate simulations following standard CMIP protocols, including ensembles. It can also be used to perform bespoke simulations to assess the impacts of different scenarios and policy decisions and to address "what-if" questions.

The simulations performed by the Climate DT have followed a streamlined version of the HighResMIP protocol (Haarsma et al., 2016; Roberts et al., 2025) on both the LUMI and MN5 EuroHPC pre-exascale supercomputers. The protocol consists of 1) 30-year long control simulations with constant 1990 forcing to evaluate model drift, 2) historical simulations starting in 1990 and ending in 2014, and 3) projections for the period 2015–2040 following the SSP3-7.0 scenario defined in the sixth phase of CMIP (CMIP6; Eyring et al., 2016). The projection simulations with IFS-NEMO were carried out at a horizontal resolution of 4.5 km for the atmosphere and land and 1/12º (around 8 km at the Equator) for the ocean and sea-ice, with IFS-FESOM using the same atmospheric and land resolution of 4.5 km and about 5 km over most of the globe for the ocean and sea ice, while the ICON simulations were performed at 5 km resolution for all Earth system components. In all simulations, the ocean/sea-ice models were spun up for five years using stand-alone ocean runs forced with the Copernicus Climate Change Service ERA5 reanalysis (Hersbach et al., 2020) for the corresponding initial date (1990 for the historical and control and 2020 for the projection) that were started from EN4.2 ocean estimates interpolated to the corresponding ocean grid (Good et al., 2013). The ocean spin up was followed by a two-year coupled ocean-atmosphere spin up with constant atmospheric forcing in the IFS-NEMO and IFS-FESOM cases.

Figure 4 shows an example of evaluation against synoptic surface observations (the bias of annual-mean 2-metre temperature) and against reanalysis (the bias of the mean zonal wind at 850 hPa) for the three Climate DT models using the historical simulations. The evaluation results are continuously fed to the model development team. In an operational context, additional simulations are performed on a regular basis as part of the production cycle, either with the same versions to increase the ensemble size or with new ones as part of a new operational cycle to take advantage of improvements in the Climate DT system. New operational cycles typically occur once a year.. The simulations performed after the initial set described above use homogeneous resolutions for the control, historical, and projection and include simulations at about 5 km horizontal resolution, with some additional simulations performed at 10 km.

In addition, the Climate DT produces high-resolution global storyline simulations that allow to "rewind and replay" recent extreme weather events, such as heat waves or floods, and explore how they would unfold under different climate conditions, from pre-industrial to warmer futures (John et al., 2025). These physically consistent "what-if" experiments link directly to observed events through spectral nudging, anchoring the simulations to the observations while exploring alternative climate trajectories (e.g., Athanase et al., 2024; Sánchez-Benítez et al., 2022).

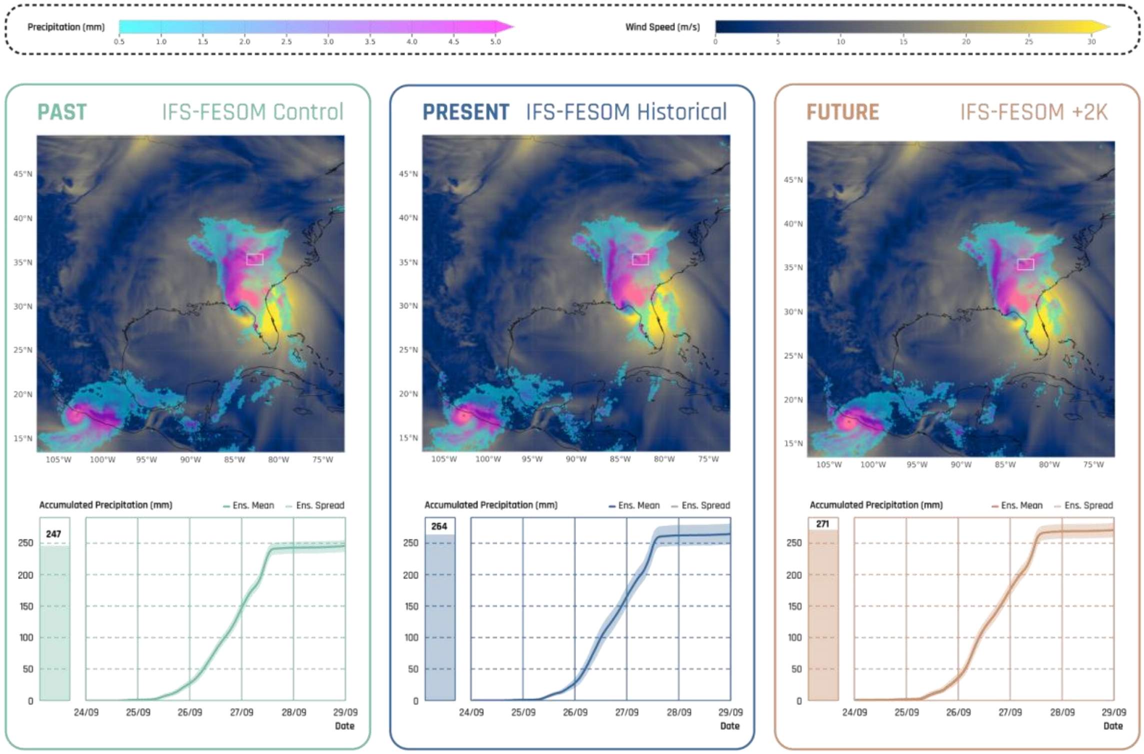

Figure 5: Snapshots of 850-hPa wind speed and precipitation associated with hurricane Helene just after landfall on the 27th of September 2024 at 04:00 UTC simulated using IFS-FESOM in which large-scale tropospheric winds nudged toward ERA5. The three panels represent different climate scenarios: PAST (IFS-FESOM Control, ~1950s climate), PRESENT (IFS-FESOM Historical, current climate), and FUTURE (IFS-FESOM +2K global warming level). The lower panels show accumulated precipitation (mm) in the region within the white box in each map from the 24th to the 29th of September, with totals increasing from 247 mm (PAST) to 264 mm (PRESENT) and 271 mm (FUTURE). Simulation details are described in John et al. (2025).

The storyline simulations are performed with IFS-FESOM (Sánchez-Benítez et al., 2022; John et al., 2025) at resolutions of about 10 km for the atmosphere and land and 5 km for the ocean and sea ice. They represent an important application of the Climate DT's capabilities because they provide concrete, location-specific insights into how climate change is reshaping extremes, making risks more tangible and adaptation planning more actionable. These simulations reconstruct the evolution of the climate system, including extreme events such as heatwaves, floods, storms, and drought, from 2017 to the present, with continuous updates close to real time, under three distinct climate conditions: a past climate resembling the 1950s, the present-day climate, and a future scenario with 2 °C warming above pre-industrial levels (assumed to be reached around the 2050s). To ensure realism, the large-scale atmospheric circulation of IFS-FESOM is nudged to ERA5 reanalysis data above the boundary layer, while other components evolve freely under the prescribed climate forcing. This approach allows the same physical event to be simulated across different climate states, offering insights into how thermodynamic changes modulate its intensity, duration, and impact. For example, Figure 5 shows how the simulations reproduce essential features of hurricane Helene, including mesoscale structures, and how climate change may have influenced its characteristics, supporting both event attribution and forward-looking scenario analysis. Because the simulations are global and consistently high-resolution, they enable the examination of multiple, concurrent extremes worldwide, providing locally relevant insights into compound climate risks.

The Climate DT simulations require the extreme computing power and data handling capacities provided by the EuroHPC JU machines. A substantial investment has been made in adapting the models to hybrid CPU-GPU architectures. Currently, a 20-year simulation at 5-km resolution typically requires around 0.6 million GPU-hours in the case of ICON or 23 million CPU core hours in the IFS-NEMO case on the LUMI HPC. With these figures, the computational resources available allow performing a small multi-model ensemble in each production cycle. Adaptation efforts have been accompanied by a systematic performance analysis of all the steps necessary to complete a climate simulation and bottlenecks are continuously addressed. In addition, automated performance information collection (Acosta et al., 2024) has been implemented in the workflow to monitor the progress of all models and detect anomalous behaviours. The analysis identified issues that limited performance and suggested code and runtime modifications. It inspired work leading to code refactoring, transfer of code sections to accelerators, pipeline restructuring, I/O choices, and runtime optimisation for the different computing platforms.

5.1 Real-time scientific quality assessment

The simulations produced with an operational system require a monitoring service that evaluates the scientific performance and allows detecting unexpected climate model behaviour. The scientific evaluation of the Climate DT simulations is carried out by two different tasks (Fig. 6).

The Application for QUality Assessment (AQUA; Nurisso et al., 2025) is an open-source Python package built upon a core engine using catalog access and designed to process high-resolution global data in an efficient and scalable way. AQUA has similar properties to other climate diagnostic packages (e.g., ESMValTool; Lauer et al., 2024) that also use a series of modular and independent diagnostics. It has been designed to analyse the simulations from all models and benefits from the data checks performed upstream in the workflow to detect corrupted data. It is another data consumer that can be used either embedded in the workflow (to monitor the simulation progress) or as a stand-alone tool for e.g. comparisons with either other simulations or observational references. The climate model output is compared by AQUA, as the climate simulations progress, with either reanalyses or benchmark simulations to evaluate and monitor basic aspects of their quality. This innovative capability helps to quickly identify potential problems by benchmarking the climate simulations against existing experiments and allows continuous monitoring of the simulation progress.

The assessment focuses on several state-of-the-art diagnostics and metrics targeting the mean state model biases over the historical period for selected regions (e.g., performance indices from Reichler and Kim, 2008) and variables or basic metrics (global mean air temperature, top-of-the-atmosphere energy balance, atmospheric teleconnections, metrics of ocean circulation, etc.) that are essential to understand the evolution of the climate system. This information contributes to the quality assurance of the climate simulations and builds trust into its use for any adaptation decision. AQUA also includes a reduced set of frontier diagnostics that exploit the native spatial resolution and high frequency of the data. They aim at providing statistics on physical processes that could not be systematically investigated in km-scale climate simulations due to the huge data management challenge they pose. These diagnostics include statistical properties of the tropical rainfall or tropical cyclone characteristics. The AQUA diagnostics are designed to deal with multi-model ensembles to provide a measure of uncertainty for both historical simulations and climate projections.

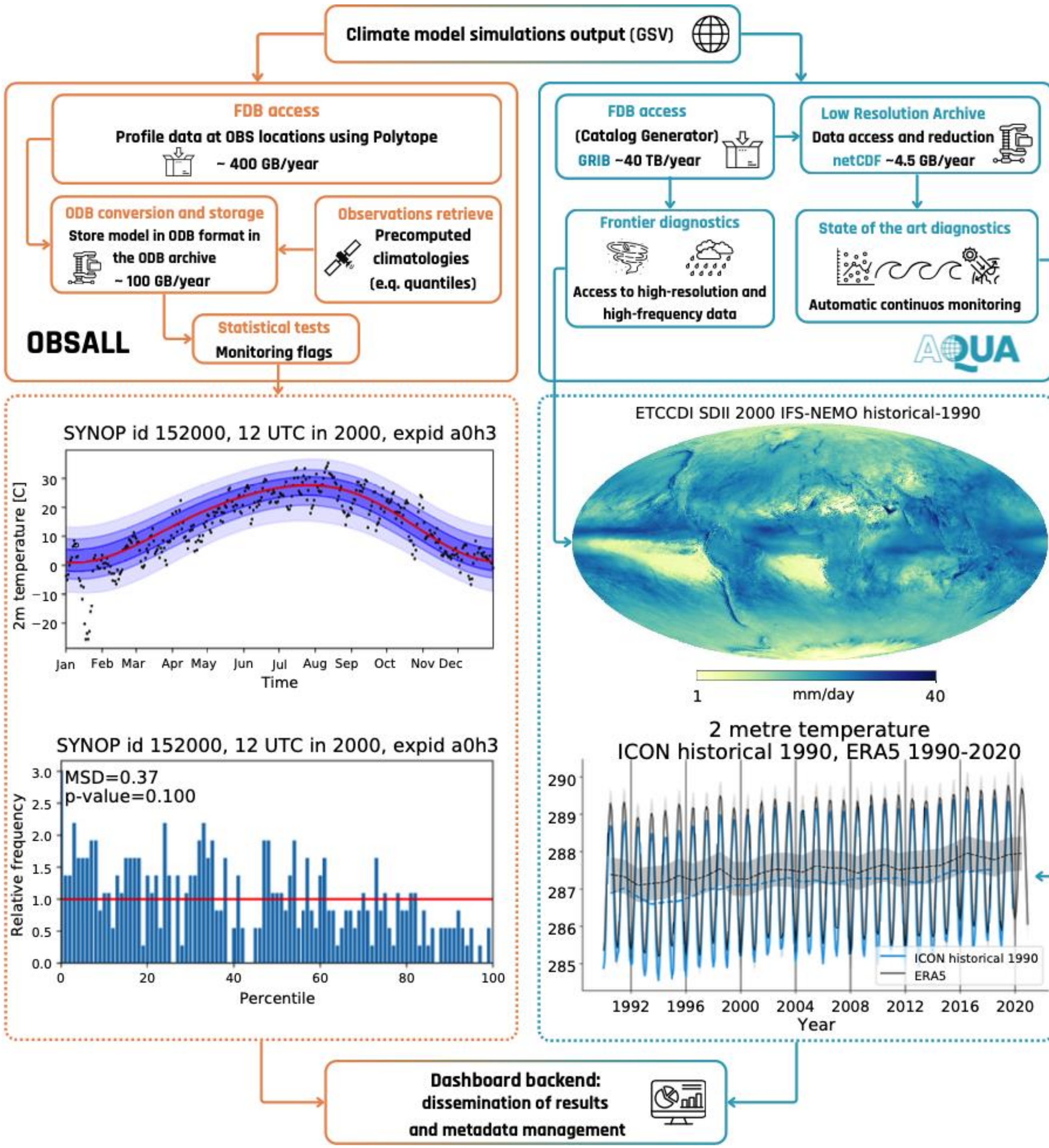

Figure 6: Scientific model evaluation strategy of the Climate DT. The AQUA processing (blue boxes) enables model evaluation through automatically-generated catalogue entries. High-resolution data supports high-granularity frontier diagnostics, such as the

precipitation-based simple daily intensity index (SDII) from the ETCCDI[31] collection, estimated for the year 2000 from an IFS-NEMO 10-km historical simulation (centre-right panel). Simultaneously, data is aggregated into a low-resolution archive (monthly averages on a one-degree regular grid) for continuous monitoring via a large set of state-of-the-art diagnostics: An example diagnostic shows global monthly and yearly averaged 2-metre temperature from an ICON 10-km historical simulation and ERA5 reanalysis (bottom-right panel). The OBSALL processing (orange boxes) involves time-critical GSV access, model profile retrieval, application of observation operators, and comparison with observed climatologies. Results for 12 UTC 2-metre air temperature from an IFS-NEMO 10-km historical simulation are shown: temperatures for the year 2000 at Arad, Romania, are shown against observed quantiles (centre-left panel) while the histogram illustrates the probability of differences over the whole year arising by chance, with a p-value set to 0.1 (bottom-left panel).

The Climate DT also includes a bespoke observation-based quality assessment system, named OBSALL. It generates an image of the full-resolution climate simulation in the observation space. The image is a trace of the simulation as if recorded by an observing system. In stand-alone mode, OBSALL allows the quality monitoring to focus on, e.g., the formation of surface temperature inversions in the polar night as viewed by the synoptic surface network. When embedded in the workflow, OBSALL makes a statistical assessment of whether the simulation stays within the envelope formed by the quantiles of the observed daily climatology and if not, it raises flags. Technically, OBSALL can be interpreted as an OPA that can access the full-resolution, high-frequency GSV data. It extracts model profiles at observation locations with the Polytope tool (Leuridan et al., 2023) and applies standard observation operators (ECMWF, 2015) to compute the model counterparts for observations. Both are archived into an instance of the Observation DataBase (ODB; ECMWF, 2010) using the ECMWF Python package pyodc (ECMWF, 2025). High-quality and stable observational platforms and networks are selected so that informative observation-based climate statistics can be precomputed and stored in the ODB and used in the quality assessment. The ODB input archive for Climate DT simulations contains observations from synoptic surface stations (Dunn et al., 2014), upper-air soundings (Madonna et al., 2022), and AMSU-A radiances (NOAA, 2025) as a remote sensing data demonstrator. The ODB archive and the observation projection in general are designed to be easily extendable. Results of both AQUA and OBSALL are regularly displayed on a Climate DT internal dashboard.

6 Prototype climate-change impact applications

A characteristic of the Climate DT is its ability to generate tailored and timely information for climate-sensitive sectors. The end-to-end production of user-relevant climate information is illustrated with a selected number of sectoral climate applications that have been embedded in the workflow as data consumers and can compute relevant indicators as the climate simulations are performed. At the same time, these applications play an important role in shaping the Climate DT operation. They provide continuous feedback about the digital twin development like the data portfolio, the experimental setup, the software to maximise the application throughput, the data strategy, the OPA capabilities, etc., all through a co-production process. Every embedded application has been co-produced with selected users, who participated in the process through regular interactions. The co-production allows to illustrate the relevance for the climate adaptation community. New pieces of climate information

[31] https://www.wcrp-climate.org/etccdi

can be generated by making use of the full climate model state described above, while more traditional asynchronous access to the resulting data included in the DestinE portfolio is still possible for those applications that are not embedded in the workflow by accessing data in the data bridge. These applications can also be included in the production workflow in later production cycles.

The climate-adaptation applications integrated in the Climate DT so far are:

- Wind-energy management and energy demand: This application illustrates the value of the Climate DT for informing the near- to mid-term investment and management strategies of the wind energy sector (Lacima-Nadolnik et al., 2026). Wind-energy generation is particularly sensitive to sudden variations in resource availability. This application provides global indicators, such as high- and low-wind event frequency (Rapella et al., 2023), capacity factors, and annual energy production estimates, among others, for a range of turbine types (Lledó et al., 2019), at global scale with high resolution from high-frequency wind data (Fig. 7). These indicators have been selected in collaboration with a company that provides estimates of the wind resource to energy producers. In addition, for specific areas with offshore installations, the application provides indicators relevant to the construction and maintenance that require high-frequency data, such as sea-ice occurrence, ice-related stress to structures, and expected navigability conditions..
- Freshwater availability and flood occurrence: This application, named HydroLand, provides global estimates of river runoff at the same spatial scale as the climate simulations. This is an improvement over current hydrology information systems for climate time scales. The HydroLand application is based on the mesoscale Hydrologic Model (mHM; Samaniego et al., 2010) and the multiscale Routing Model (mRM; Thober et al., 2019). mHM uses Climate DT data at the highest spatial and temporal resolution available and mRM provides a wide range of hydrological variables and indicators depicting global freshwater availability to support insights about the requirements for climate adaptation anywhere in areas of particular interest (Fig. 7). The application can also take advantage of the simultaneous bias-adjustment of the climate simulations. Cumulative distribution functions used for the statistical adjustment can be estimated on-the-fly using the method available in the OPA package (Grayson et al., 2025).
- Characteristics of hydrometeorological extreme events: The HydroMet application summarises user-selected statistics of hydrological extremes by identifying extreme rainfall events over Germany. This leads to information about the spatial and temporal extent, precipitation amounts, return time, and the frequency of extreme events. The application is based on KOSTRA-DWD-2020 (Junghänel et al., 2022), a solution for the evaluation of precipitation levels, duration, and the annual return interval, and on the Catalogue of Radar-based heavy Rainfall Events (CatRaRE; Lengfeld et al., 2021) software package that detects spatially and temporally independent heavy precipitation events leading to flash floods. High global spatial and temporal data frequency is required to estimate these indicators with the level of detail required by the range of users that collaborate with the developers.
- Fire weather and wildfire spread: This application focuses on wildfire management strategies. The high-resolution Fire Weather Index (FWI) identifies where meteorological drivers of fire weather conditions are conducive to the occurrence and persistence of fires (Abatzoglou et al., 2019). Additionally, the fire spread model Wildfire Safety

Evaluator (WISE) simulates critical fire parameters (e.g., burnt area and fire intensity) at high spatial resolution, utilizing input data co-developed with users, including land-use and ignition information (Touma et al., 2021). By leveraging the high-frequency, high-resolution Climate DT data along with user-defined local land-use scenarios, WISE is used to assess wildfire management options such as fuel and firebreaks management. This supports the user-driven planning and implementation of adaptation strategies to increasing fire risk (Hetzer et al., 2024).

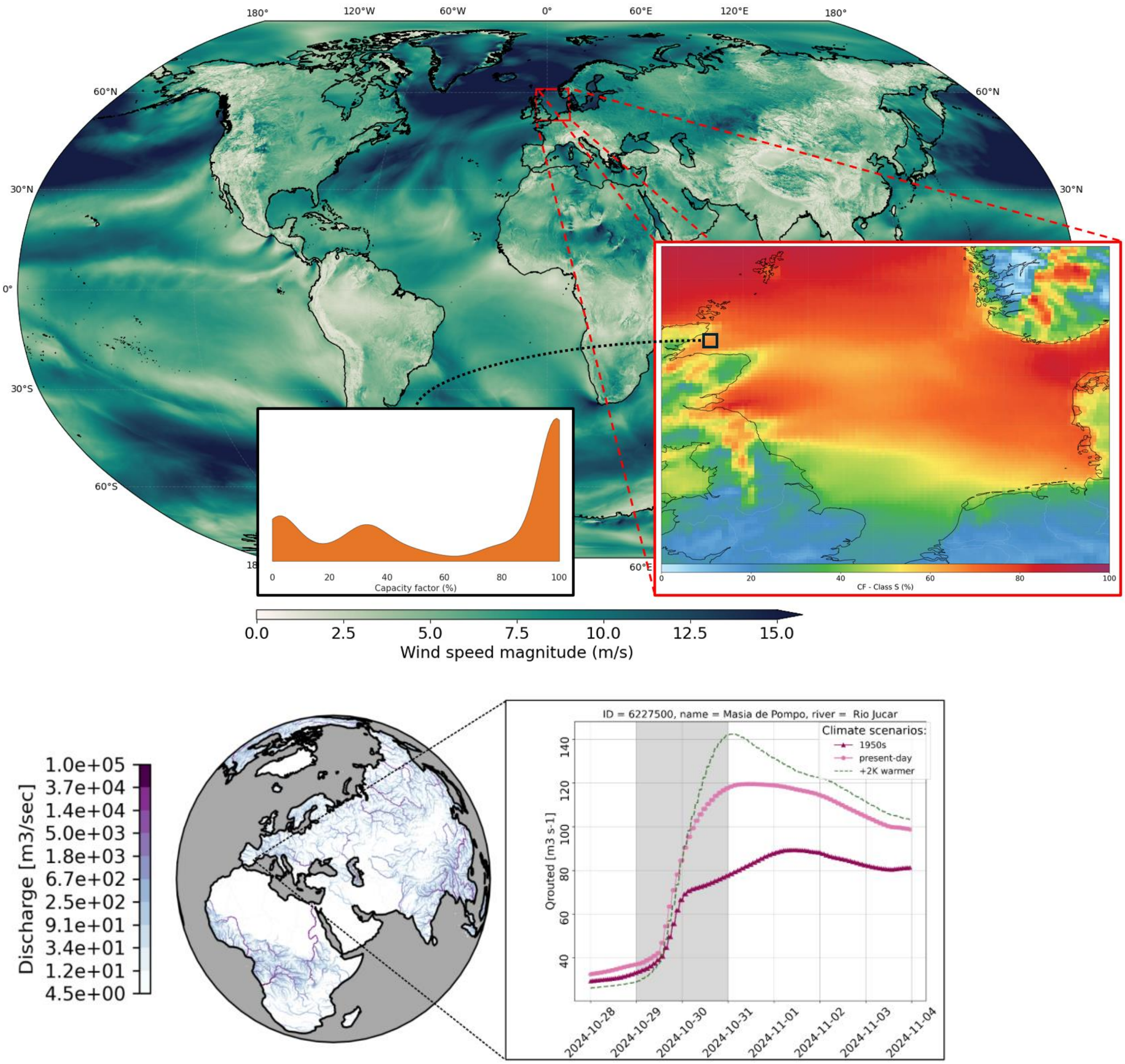

Figure 7: (Top panel) Global map with a snapshot of wind speed at 100 metres from the 10-km IFS-NEMO historical simulation. The regional zoom, highlighted with a red rectangle, shows the capacity factor averaged over a week for a class S Vestas V164 wind turbine over the North Sea computed from 1-hourly wind components (zonal and meridional 100-metre wind). The black square marks the location of the Moray East wind farm, off the coast of Scotland, which operates this specific type of turbine. The curve represents the distribution of the hourly capacity factor for Moray East during the week. (Bottom panel) The HydroLand application provides global estimates of terrestrial hydrological processes like river discharge over small areas (~80 km2), soil moisture deficits,

and extreme flooding events. The time series represent the river discharge values over the Jucar River in the Valencia region (Spain) during the period of the storm event at the end of October 2024 using climate data from the 1950s, present-day, and future climate (+2K global warming level) IFS-FESOM storyline simulations.

Commonalities among the applications have been identified to implement technical solutions that offer timely access to the climate data to all of them. The combination of GSV, through its unified access and formats, and OPA offer a flexible and responsive environment to address the emerging requirements, while reducing computational and data handling overheads. It also hides some of the complexity of the climate data from the application developers.

The experience gained with these applications underpins efforts to implement applications that address other user requirements. The continuous Climate DT production, generating new ensemble members in successive cycles, can leverage newly acquired knowledge about the digital twin performance from previous simulations that can be used to optimize any element of the production workflow. For instance, in each new production cycle the list of output variables can be modified to allow the creation of new user indicators or climate model diagnostics missing in previous simulations.

7 Consolidating the Climate DT

The Climate DT aims at producing operational, quality-assured simulations with frequent updates (at least yearly) and rapid access to the data generated. The frequent updates allow the integration of both the latest advances in science and technology and the new requirements from users to support decision-making. The previous sections describe the prototype Climate DT developed in the initial phases of DestinE (2022-2025). The focus has been put on consolidating, operationalising, and further evolving the Climate DT system, aiming to gradually enhance its capabilities and response to user requirements for efficient climate adaptation. This section briefly summarises some of the developments, some of limitations, and plans for the system improvement.

7.1 Operational framework

The Climate DT lays out the basis for the operationalisation of user-oriented, multi-decadal, multi-model global climate projections. This is an initiative complementary to the existing CMIP and CORDEX international efforts and to the activities of national climate services and the Copernicus Climate Change Service in the provision of future climate information sources. The regular production of climate simulations at this scale can only be maintained by ensuring that the computational performance of all elements is monitored, analysed, and optimised as the underlying HPC platforms evolve. Moreover, a protocol will be developed to decide how other climate models may be incorporated and benefit from the operational framework. The Climate DT simulations are not time-critical, compared to weather forecasts, but the operational context requires that they are regularly performed to address continuously emerging data consumer requirements. The production should be flexible enough to continue on alternative HPC systems whenever needed. This requires data consumers embedded in the workflow to use containers and integrate and schedule their own restarting mechanisms. The development team supports data consumers to develop these capabilities.

The plans to update the Climate DT include improved climate models (whenever significant developments are available and have been thoroughly tested), more adequate workflow management, additional data checks, faster and more user-driven data transfers to the data bridge, richer monitoring and evaluation, and a broader range of impact-sector indicators. Most of these developments are included in development suites. The experimental suite gathers all these developments and applies a thorough testing procedure with stringent acceptance criteria before they can be included (or not) in the operational suite. This ensures that transitions to operational configurations are robust. This makes the operational production increasingly stable, traceable, resilient, and fit-for-purpose (Dee et al., 2024) for both data consumers and users accessing products from the data bridges.

An efficient operationalisation requires computing resources to be readily available, not just for the operational suite but also for the development and experimental suites that a flexible, well-tested, regular production requires.

There are many other aspects under discussion relevant to the operationalisation of decision-oriented climate projections. A collaboration strategy with the CMIP and CORDEX communities, as well as with those developing emission scenarios, climate-impact models, and climate services is being developed to ensure that efforts remain aligned.

7.2 Increasingly flexible data management

The Climate DT data is a combination of a moderate volume set located in the data bridges for asynchronous climate applications and research, and an agile, rich, short-lived set in the HPCs for simulation evaluation, applications embedded in the workflow, and production of AI-ready datasets. The data needs to be accessed and consumed using the same tools. The data management strategy requires to balance storage constraints (both in the HPCs and the data bridge), the ability to recompute specific parts of the climate trajectories (using stored checkpoint files) with enhanced data output, and the commitment to serve global, high-resolution data to a wide range of users. This balance will benefit from input from as many stakeholders as possible. For instance, the selection of the data transferred to the data bridge, such as relevant vertical levels to retain, the possibility of reducing the numerical precision or resolution for some variables or the adequate data frequency for each variable, is currently discussed with data consumers with experience in the Climate DT production. This interaction will be widened to a broader range of DestinE users.

The data stored and made available in the data bridges are not necessarily homogeneous as there might be differences in the data portfolio across ensemble members and model versions. This happens because the archive is enriched over time with simulations that respond to emerging data consumer needs that lead to additions to and/or modifications of the data portfolio.

7.3 Penetration of artificial intelligence solutions

The integration of the current fast-evolving AI and machine learning breakthroughs is an important aspect for the future development of the Climate DT. The Climate DT has started to exploit these recent advances, acknowledging that they require good, traceable sources to build trust (Bracco et al., 2025; Eyring et al., 2024). Ongoing efforts in this regard focus on:

- enhancing the user experience through the development of chatbots that make the Climate DT data more accessible to decision-makers by including it into context-relevant reports (Koldunov and Jung, 2024; Kuznetsov et al., 2025) using fine-tuned large language models with the help of a climate-adaptation specific corpus;
- exploiting the wealth of the unprecedented high-resolution, high-frequency global data produced by the Climate DT models for AI model training to build emulators[32] of the physical climate models; the emulators will be used for uncertainty quantification of the simulated trajectories, for the fast reconstruction (Kadow et al., 2020) of the simulated trajectories as reruns for selected time slices (Rackow et al., 2024) that can provide high-frequency data on demand as described in the "AI on top" concept (Bauer et al., 2023), and for the exploration of the climate evolution for a range of emission scenarios not sampled by the physical models.

Results from these efforts will be reported separately in the near future.

7.4 Interactivity to address user needs

One area of increased focus is the interactivity of the Climate DT system. The operationalisation leads to significantly shortened production cycles compared to existing climate projection sources, enabling the possibility of enhancing the interactivity in the access to climate projection sources. As a result, some users will at some point be able to explore different scenarios and address their what-if climate-related questions with the Climate DT. The options could include requesting new projections or increased ensembles of storyline simulations. Impact-sector applications are considering what-if analyses specific to their domains in separate workflows supported by the Climate DT infrastructure. An example of this option consists in assessing how changes in land cover modify flood impacts using HydroLand. In addition, AI solutions introduce new possibilities for interactivity, such as fast, on-demand data generation through emulators supported by chatbot-based interfaces, allowing users to formulate requirements using natural language. Until now, stakeholder engagement has mainly taken place through discussions with key users to gather their feedback. Broadening this feedback requires an extensive development process that will involve the DestinE website and the DESP.

8 Summary and conclusions

The Climate DT is a pioneering effort to build an operational climate information system based on a digital infrastructure to support climate change adaptation. It provides globally consistent multi-decadal climate simulation data with very high temporal (hourly) and spatial resolution (between 5 and 10 km), and considers user needs in terms of the output variables, access patterns, data processing, and simulation design. It benefits from the convergence of hardware and software infrastructure, dedicated resources, digital innovation, and domain experts with the adequate knowledge, perspectives, and experience, in a transdisciplinary endeavour. The Climate DT supports tackling some of the existing challenges (Stevens et

[32] https://destine.ecmwf.int/news/spains-predictia-to-build-a-climate-emulator-for-destine/

al., 2024) in providing climate-vulnerable communities with timely, decision-oriented global climate information. It complements existing sources of climate information for adaptation focusing on the need for salience, equitability, and credibility. Besides, the Climate DT, while computationally more expensive than existing climate simulation approaches, is a trailblazer for the use of computational resources so far largely unused by the climate community, such as GPU-based platforms.

The features introduced by the Climate DT can be summarised as follows:

- Operational multi-decadal projections: The operational nature of the Climate DT enables the continuous production and delivery of climate simulations providing information for climate up to 2050. This capability relies on EuroHPC resources, operational end-to-end workflows, real-time monitoring, uncertainty quantification, professional software development, and continuous optimisation of all system components. The Climate DT simulation protocol ensures consistency with existing climate sources while opening opportunities for on-demand climate projections to address emerging policy-relevant questions. This helps closing a gap in the timeliness of actionable climate information.
- Global km-scale climate modelling: The Climate DT exploits global km-scale climate modelling capabilities through the integration of three km-scale climate models. By substantially increasing spatial resolution, these models can improve the representation of critical processes. Eddy-rich, storm-resolving simulations provide global downscaling with local granularity, supporting equitable access to climate information worldwide. These advances have been enabled by major code refactoring efforts (including code porting to use GPUs) and adaptation to modern HPC architectures.
- High-resolution climate storylines: The Climate DT includes high-resolution global storyline simulations in which the atmospheric circulation follows the reanalysis while thermodynamic conditions are compatible with a specific global warming level. Three simulations for 1950, present-day, and two-degree warming levels are performed in parallel. Produced continuously starting in 2017, these simulations deliver tangible and relatable estimates of the climate change impact on emerging extreme events, supporting contextualisation of personal experiences of climate change and enhancing the salience of the system..
- Unified workflow: The infrastructure is designed to handle climate models that aim for the highest possible computing throughput and impact-sector applications that consume climate model data, either in situ or remotely.. The unified approach to integrating different models, data consumers, and HPCs is a unique Climate DT feature. The modular end-to-end workflow, along with a generalised use of containers for the portability of embedded data consumers, significantly improves workflow maintainability and resilience, the extension to other climate models and data consumers, and the operational practice. External users do not have access to run the system because HPC platforms apply strict access rules and it has been designed to be run by dedicated operators, but are able to use the workflow and the system software in their own environments.
- Unified data handling: The Climate DT introduces a harmonised data framework, including the GSV concept and the use of the HEALPix grid for all climate outputs. This ensures homogeneity, consistency, and interoperability. A

common list of variables is delivered by all models at high frequency and near-native resolution under strict data governance that follows FAIR data principles (Wilkinson et al., 2016). Data are made available using either streaming, allowing data consumers embedded in the workflow to exploit quality-controlled full climate model output as the models run, or storage in the data bridges. In the former option data and workflow become closely linked together with full traceability. OPAs offer efficient data processing, supporting the translation of climate data into impact-sector information, and improve responsiveness to the data consumer requirements.

- AI integration: AI technologies are an emerging component of the Climate DT. Their use aims at improving interactivity and user experience, inspired by the Earth Virtualization Engines initiative (Stevens et al., 2024) ideas. AI-powered chatbots are being developed to ease the exploitation of Climate DT data. In addition, the DTE supports the creation of AI-ready datasets, enabling the development of data-driven climate emulators.
- Real-time monitoring and model evaluation: The Climate DT workflow integrates online model evaluation through the AQUA and OBSALL frameworks. AQUA provides real-time diagnostics of key climate aspects, including model biases, performance metrics, and variability indices. OBSALL delivers full-resolution comparisons in observation space using multiple observational networks. The results are summarised in a dashboard used by operators and climate model developers to assess the quality of the simulations as they are running.
- Action-oriented climate information: Climate-impact applications are embedded within the workflow to generate both global and regional indicators relevant for climate adaptation, such as renewable energy, water, and forest management. Co-designed with selected users, the applications exploit the high spatial and temporal resolution of Climate DT data and its streaming capabilities to support the system salience. Further work is required to advance uncertainty quantification beyond the current multi-model estimates.

The Climate DT ambitions respond to many of the objectives of the World Climate Research Programme and WMO's Scientific Advisory Panel[33] strategic vision. The Climate DT is an effort complementary to the sources offered by initiatives like CMIP and CORDEX, among others. These initiatives have different business models and governance, while they provide invaluable opportunities to exchange experiences and solutions with. The exchanges can follow the WMO concept of research to operations and operations to research transfers.

9 Acronyms and project names

Table 1. Acronyms employed in the Climate DT description.

Acronym	Description

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

AI	Artificial Intelligence
AMSU-A	NASA's Advanced Microwave Sounding Unit
AQUA	Application for QUality Assessment
BA	Bias Adjustment
CatRaRE	Catalogue of Radar-based heavy Rainfall Events
CF	Climate and Forecast conventions
Climate DT	Destination Earth’s Climate Change Adaptation Digital Twin
CPU	Central Processing Unit
DESP	Destination Earth’s Service Platform
DTE	Digital Twin Engine
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA5	Fifth generation of ECMWF’s atmospheric reanalysis of the global climate
EN4.2	Met Office’s subsurface temperature and salinity dataset for the global oceans v4.2
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
ESA	European Space Agency
ESMValTool	A community diagnostic and performance metrics tool for evaluation and analysis of Earth system models
ETCCDI	Expert Team on Climate Change Detection and Indices
FDB	Field DataBase object store
FESOM	Finite-Element/volumE Sea ice-Ocean Model
FWI	Fire Weather Index
GPU	Graphical Processing Unit
GSV	Generic State Vector
HEALPix	Hierarchical Equal Area isoLatitude Pixelation grid
HPC	High-Performance Computing
ICON	A flexible, scalable, high-performance modelling framework for weather, climate and environmental

	modelling and prediction developed by the ICON partnership
IFS	Integrated Forecasting System
I/O	Input/Output
IPCC	Intergovernmental Panel on Climate Change
LUMI	Large Unified Modern Infrastructure supercomputer
mHM	mesoscale Hydrologic Model
MN5	MareNostrum5 supercomputer
mRM	multiscale Routing Model
MultIO	I/O server and post-processing pipelines
NEMO	Nucleus for European Modelling of the Ocean
ODB	Observation DataBase
OPA	One-pass algorithms
OBSALL	Observation-based quality assessment system
SDII	Simple Daily Intensity Index
WIPPS	WMO’s Integrated Processing and Prediction System
WISE	Wildfire Safety Evaluator
WMO	World Meteorological Organisation
YAC	Coupling library for Earth system models

Project/initiative	Description
CMIP	Coupled Model Intercomparison Project
CORDEX	COordinated Regional Climate Downscaling Experiment
DestinE	European Union’s Destination Earth Initiative
EERIE	European Eddy-rich Earth System Models Horizon Europe project
EuroHPC/EuroHPC JU	European High Performance Computing Joint Undertaking

Gloria	Research project funded by the Spanish Ministry of Science
nextGEMS	Next Generation Earth Modelling Systems Horizon Europe project
WarmWorld	Research project funded by the German Federal Ministry of Research Technology and Space

Code and data availability

The Climate DT dataset is accessible via https://doi.org/10.21957/d3f982672e. There is a unique semantic data access for the data that allows users to clearly delineate the contributing models, experiment, dates, and variables, among other parameters. The availability policy of datasets in the data lake is defined in https://destine-data-lake-docs.data.destination-earth.eu/en/latest/dedl-discovery-and-data-access/DestinE-Data-Policy-for-DestinE-Digital-Twin-Outputs/DestinE-Data-Policy-for-DestinE-Digital-Twin-Outputs.html.

The ICON source code is available under https://gitlab.dkrz.de/icon/icon-model with doi:10.35089/wdcc/iconrelease2025.04, including all modifications used for this study. It can be used without any restrictions. The version of FESOM2.5 used in the Climate DT simulations is available at https://doi.org/10.5281/zenodo.10225420. The FESOM2.5 model is also available from GitHub https://github.com/FESOM/fesom2. The IFS source code is available subject to a licence agreement with ECMWF. ECMWF member-state weather services and approved partners have granted access. The IFS code without modules for data assimilation is also available. IFS used version cycle 48r1, available under an openIFS licence (http://www.ecmwf.int/en/research/projects/openifs, OpenIFS licence, 2024) for educational and academic purposes, with corresponding modifications available at https://doi.org/10.5281/zenodo.10223577. The NEMO4.0 source code version used in the Climate-DT is available at https://doi.org/10.5281/zenodo.5566313. The interfaces to NEMO can be obtained from ECMWF on request under the licence described above. Autosubmit is available at https://github.com/BSC-ES/autosubmit and the version used in the manuscript is available at https://doi.org/10.5281/zenodo.1559052. The Climate DT workflow is available in https://github.com/DestinE-Climate-DT/Workflow, and the version used is archived available at https://doi.org/10.5281/zenodo.15607598. The AQUA code is available at https://doi.org/10.5281/zenodo.14906075. The OBSALL and OPA versions used are available at https://doi.org/10.5281/zenodo.15628903 and https://doi.org/10.5281/zenodo.14591827, respectively. The code for the mHM model version used in the HydroLand application is available at https://doi.org/10.5281/zenodo.8279545, while the code for the energy application is at https://doi.org/10.5281/zenodo.15609171. The code developed for the wildfire FWI application is available from https://doi.org/10.5281/zenodo.15610494.

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Competing interests

The contact author has declared that none of the authors has any competing interests.

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