

1 **The Destination Earth digital twin for climate change adaptation**

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

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

73 **1 Introduction**

74 Providing reliable climate information is essential for enabling effective climate change adaptation (Orlove, 2022). The latest
75 report from the Intergovernmental Panel on Climate Change (IPCC) Working Group I (IPCC, 2021) highlights major gaps in
76 our ability to simulate regional and local climate change and to deliver climate information that supports decision-making
77 (Collins et al., 2024; Shaw et al., 2024). It also emphasises the challenge of ensuring that the information is salient¹, equitable,
78 and credible for diverse audiences (Doblas-Reyes et al., 2021).

79 With globally averaged annual-mean temperatures, for the first time, exceeding 1.5 °C global warming level threshold^{2,3} set in
80 the Paris Agreement (Betts et al., 2023) and with the profound relevance of climate change impacts on both the economy and
81 society (Kotz et al., 2022), future climate information at scales where impacts are already observed is needed. This requires to
82 move from plausibility assessments of changes in local and regional climate (e.g., Collins et al., 2024) to comprehensive
83 climate adaptation plans and targeted measures at both large (e.g., EUCRA, 2024) and small scales (e.g., Schubert et al., 2024).
84 The urgency for new approaches to deliver climate information is further motivated by evolving policy frameworks like the
85 European Green Deal⁴.

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

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

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

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

- 99 • **Timeliness and innovation:** Climate projections are currently updated in multi-year cycles through coordinated
100 community exercises aligned with IPCC assessment reports (e.g., Eyring et al., 2016; Jones et al., 2024). While these
101 efforts feed in highly policy-relevant reports⁵, they are not generally structured to provide continuous, on-demand
102 climate information (Stevens, 2024). Moreover, a closer dialogue with policy needs and integration of innovations in
103 digital solutions and artificial intelligence (AI) technologies (Bauer et al., 2023) are required to make climate
104 information more accessible, interpretable, and ultimately actionable (Jones et al., 2024), complementing established
105 initiatives such as the Coupled Model Intercomparison Project (CMIP⁶) and the Coordinated Regional Climate
106 Downscaling Experiment (CORDEX⁷).
- 107 • **Co-production:** Climate-related decisions increasingly rely on evidence from multiple disciplines, yet decision-
108 makers may require climate information with features that cannot be anticipated by physical climate scientists. The
109 absence of regular channels for climate-sensitive sectors to influence the design of climate information hinders some
110 effective adaptation efforts. For instance, participatory processes that involve selected decision makers (Baulenas et
111 al., 2023) in the transformation of climate data into climate information can uncover user needs requiring
112 modifications in how climate data is generated and delivered. The fact that this dialogue does not systematically
113 happen can be explained by the relationships established between the research and service communities (Rodrigues
114 and Shepherd, 2022). The need for systematic co-production mechanisms (Bojovic et al., 2021) and the limited ability
115 of the physical climate science community to react to a variety of decision-making requirements (Jones et al., 2024)
116 can weaken the effective provision of future climate information (Kruk et al., 2017; Fiedler et al., 2021).

117 Current practice, represented by the CMIP and CORDEX international modelling exercises, has demonstrated to be both useful
118 and relevant. However, some of the aspects above have not yet been fully addressed (Jakob et al., 2023; Stevens, 2024). While
119 efforts are underway to improve timeliness and co-production in the forthcoming CMIP phase (Dunne et al., 2025; Naik et al.,
120 2025), important challenges remain to respond to non-research and operational decision-making needs.

121 In this paper we present a complementary approach to existing practices for the generation and delivery of future climate
122 projection data. This approach aims to address the challenges identified above and bridge the gap between the provision of
123 timely, decision-relevant climate information (Hewitt and Stone, 2021). It established an operational⁸ 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.

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

129 A promising way to design and implement the interactions between data producers and data consumers is to co-develop the
130 required systems using the digital twin concept (Wright and Davidson, 2020). Digital twins are replicas of physical assets,
131 processes, and systems using a highly interconnected workflow, enabling interaction, exploration of “what-if” questions, and,
132 where relevant, links to physical reality. This paper describes the characteristics and novelties of a digital twin for climate
133 change adaptation (Climate DT henceforth) implemented in the framework of the Destination Earth⁹ initiative of the European
134 Union (DestinE henceforth; Sandu, 2024; Hoffmann et al., 2023; Wedi et al., 2025). The paper summarises the Climate DT
135 characteristics and describes how it aims to support the salience, credibility, and equity principles of climate information for
136 adaptation.

137 **2 The Climate DT concept**

138 A digital twin of the climate system targeting adaptation is expected to make use of observations, integrate several climate
139 models to consider uncertainty sources, include applications for climate-sensitive sectors directly connected to the climate
140 models, and provide adequate interfaces to configure the simulations, their output, and the timely interaction with data
141 consumers. The climate models embedded in the digital twin could be either process- or AI-based, with the requirement of
142 being explainable. For the digital twin to be usable and useful, its components, including the climate models and decision-
143 oriented applications, should be co-designed and offer full traceability in terms of both documentation and operation. The
144 resulting output must be of sufficient quality (Dee et al., 2024) to support well-informed decisions while the results should be
145 available fast enough for the decisions to be made within acceptable time scales (Wright and Davidson, 2020). To build trust
146 in the digital twin, documentation, verification (traceability of both operation and testing protocols), and validation
147 (comparison with reality whenever possible) procedures must be included. Validation needs to be treated as a statistical
148 process, which in climate is traditionally addressed using multi-model and multi-member ensembles of solutions (Bauer et al.,
149 2021b; Jones et al., 2024) for several emission scenarios to address uncertainty. Additionally, a climate digital twin should
150 make use, in a structured, interactive, and iterative manner, of the instruments developed by social sciences for climate
151 adaptation (Tao and Qi, 2019).

152 This is the concept that inspires the Climate DT (Figure 1). DestinE is a European Union funded initiative launched in 2022,
153 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/>

154 of the European Commission Directorate General CNECT, by three entrusted entities: the European Centre for Medium-Range
155 Weather Forecasts (ECMWF), the European Space Agency (ESA), and the European Organisation for the Exploitation of
156 Meteorological Satellites (EUMETSAT) together with over 100 partner organisations in Europe. The Climate DT has been
157 developed since September 2022 by a partnership led by the CSC-IT Center for Science bringing together climate, weather
158 and supercomputing centres, as well as academic institutions from six European countries¹⁰. This is done in close collaboration
159 with ECMWF, who is responsible for the implementation of the digital twins. The necessary computational resources are
160 provided through a special access call by the European High-Performance Computing Joint Undertaking (EuroHPC JU¹¹).
161 The Climate DT delivers an operational framework for the regular and on-demand production of multi-decadal global climate
162 simulations and their translation into impact-sector information at high spatial resolution. It is designed to support climate
163 adaptation by enabling the exploration of “what-if” scenarios relevant to decision-making across a range of climate-sensitive
164 sectors. The Climate DT builds on decades of experience from numerical weather prediction and Earth system modelling,
165 extending established operational practices to the climate adaptation timescale. It consists of a number of components
166 integrated into an end-to-end workflow and uses a co-design approach to deliver climate and impact-sector information. This
167 end-to-end workflow includes three global kilometre-scale (km-scale henceforth) climate models (ICON, Hohenegger et al.,
168 2022; IFS-NEMO and IFS-FESOM, Rackow et al., 2025) that explicitly represent essential physical processes that critically
169 influence the evolution of the climate system. The climate models and impact-sector applications are embedded in an
170 infrastructure built following practices recommended by both the climate services and digital technology communities to
171 ensure the delivery of operational (understood as timely and routine production) climate information. The backbone of the
172 infrastructure is the unified end-to-end workflow that offers full traceability and permits a consistent data handling procedure
173 based on common variables, grids, and formats, while continuously responding to evolving user requirements. The data
174 handling must cope with unprecedented data volumes associated with the high spatial resolution. This challenge is addressed
175 through the introduction of a data streaming strategy for the data consumers embedded in the workflow. Both the unified
176 workflow and data handling practices, which work seamlessly across multiple high-performance computing (HPC)
177 environments, are fundamental Climate DT innovations.

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

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

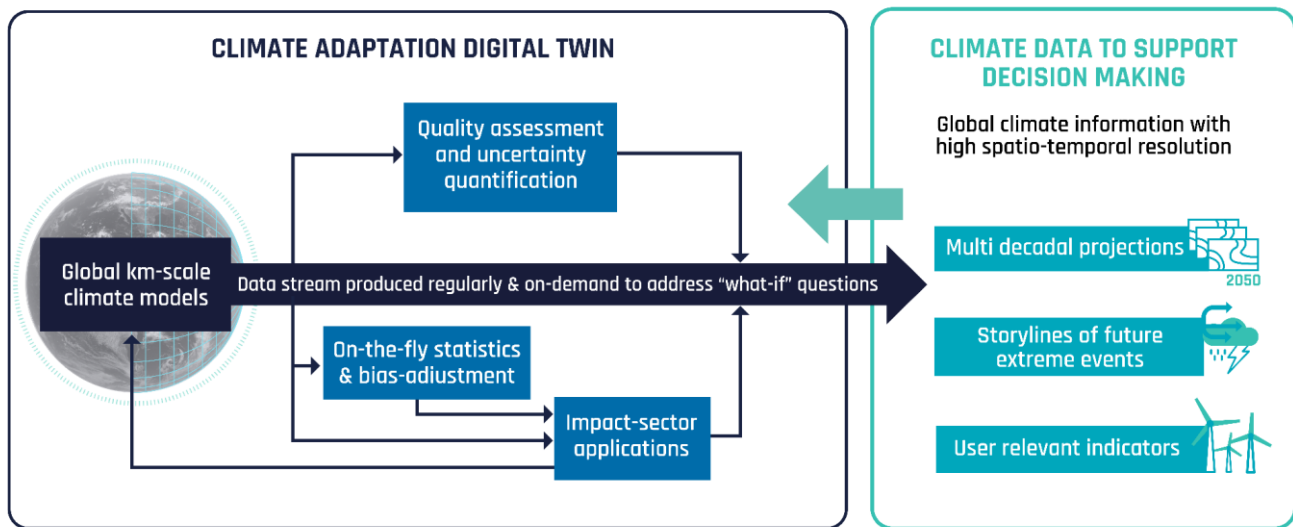
¹⁰ The Climate DT team includes personnel from Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI), Barcelona Supercomputing Center (BSC), Max Planck Institute for Meteorology (MPI-M), Institute of Atmospheric Sciences and Climate (CNR-ISAC), German Climate Computing Centre (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

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

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

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



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

202 **3 End-to-end work and data flow**

203 Digital twins require a multi-layered flexible and interoperable software infrastructure that allows data consumers to easily
 204 access the data and interact with the system. The infrastructure should be designed to handle models that aim for the highest

205 possible throughput and applications that consume data online, either in situ or remotely. For this approach to work, the Climate
206 DT uses a unified workflow approach that integrates the three climate models and all data consumers, with the execution
207 coordinated by a single workflow manager. The same software solution is employed on the various EuroHPC platforms used
208 by the Climate DT. This is an improvement over the current practice of engineering different solutions for each climate model
209 and platform. Data consumers use Singularity¹² containers to reduce portability challenges.

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

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

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

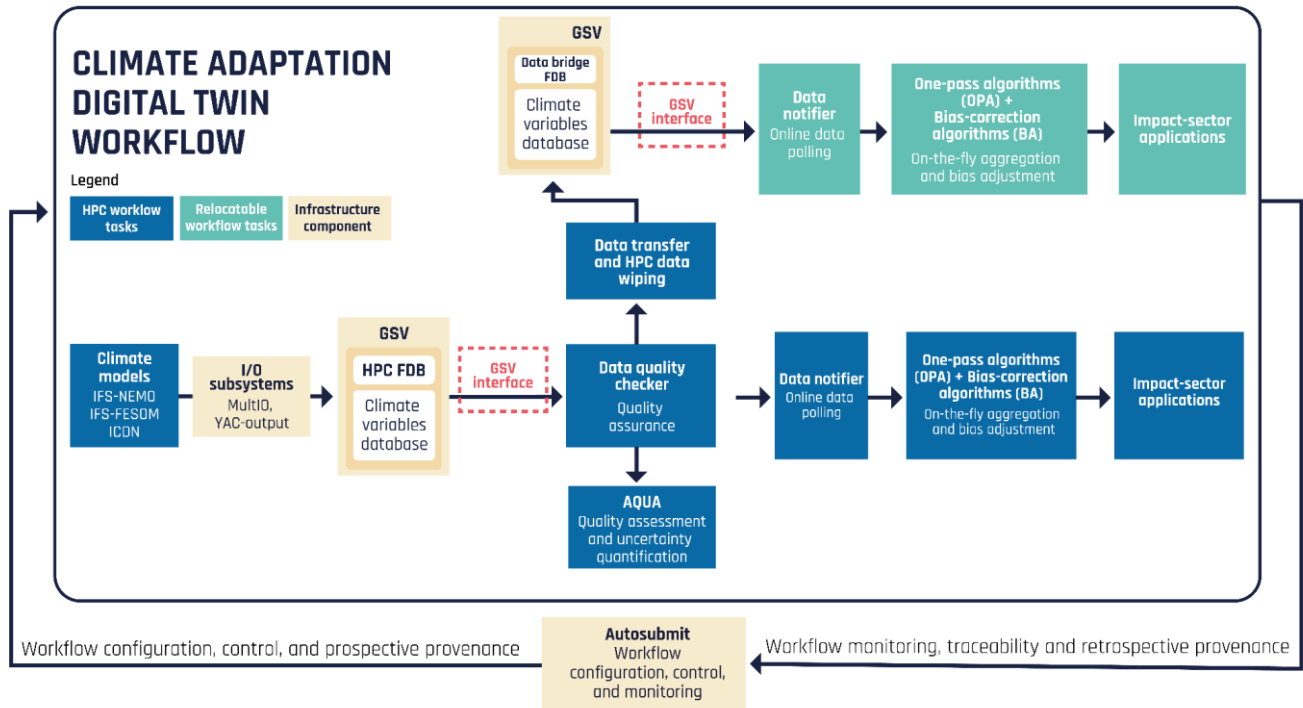
233 The Climate DT workflow requires an orchestrator that executes tasks in a traceable manner (Bauer et al., 2021b) and makes
234 use of a unified interface where developers and operators can configure the whole digital twin production. The interface
235 configures in a set up file the workflow definition, from the experiment creation to the features required by the data consumers.
236 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/>

237 duties and are used on a regular basis in operational numerical weather prediction and climate simulations. The backend of
238 the Climate DT workflow uses the workflow manager Autosubmit (Manubens-Gil et al., 2016) as part of the Digital Twin
239 Engine (DTE)¹³. Autosubmit is a lightweight workflow manager designed to meet climate research needs. It integrates the
240 capabilities of both manager and orchestrator in a self-contained application. Autosubmit stands out for its portability and
241 resilience across different scenarios, from research to operations, and across diverse computing environments, from traditional
242 HPC infrastructure to virtual research environments on cloud resources, such as the European Digital Twin Ocean Virtual
243 Ocean Model Lab¹⁴. It offers full traceability (Leo et al., 2024) to capture and manage prospective and retrospective
244 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>



MultIO - C++ libraries for data routing from distributed meteorological and Earth-system models.

FDB - Fields DataBase. Domain-specific object store for meteorological objects. Used to store and share all the results of the simulations.

YAC-Output - A tool that receives data from the YAC coupler and assigns the correct metadata and writes in different output format, used to write from ICON in HEALPix to FDB.

GSV - Generic State Vector. Minimum set of information to describe the Earth system, transformed into homogenous spatial grid and meta-data.

GSV Interface - Software library to retrieve any of the climate model data.

Data Quality Checker - Validates the data portfolio by ensuring simulations produce necessary variables with correct metadata.

Data Notifier - Workflow task that checks and notifies for the presence of specific data fields in the FDB.

OPA - One pass algorithms. A unique request configured by a data consumer to compute a temporal statistic on the climate model data, required for their impact application. e.g. monthly p90 (the 90th percentile) of precipitation.

BA - Bias Adjustment. As part of the one-pass algorithms, users can request bias-adjusted data based on their reference data.

Autosubmit - Automated workflow manager that configures and runs the Climate DT simulations.

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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.

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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.

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

258 **4 Seamless and homogeneous data access**

259 To ease the use of climate data by all data consumers, the output of the different climate models is homogenised by introducing
260 a “generic state vector” (GSV). In the GSV, the output of all climate models is unified in terms of parameters¹⁵ and units
261 (similarly to what CMIP does), as well as in spatial and temporal resolution, following a strict data governance that regularly
262 accommodates new user requirements. The GSV facilitates consistency across models and enables a step change in the
263 interoperability and usability of climate model output. This solution allows data consumers to seamlessly access the output
264 from any of the Climate DT models as the simulations progress.

265 Climate model data is individually encoded in a message format. This choice was made to align with the World Meteorological
266 Organisation (WMO) member states’ national authorities represented through the WMO Integrated Processing and Prediction
267 System (WIPPS¹⁶) distribution system. The GRIB format has been chosen as it conveniently aligns with these standards and
268 is proven to mitigate the risks of data loss and recovery since each data message is self-contained with its metadata. The data
269 under this format is written in the HPC storage using the Field DataBase (FDB¹⁷) technology, to provide standardised access.
270 The metadata governance solution follows WMO standards¹⁸. However, it is recognised that other formats combined with
271 suitable conventions (e.g., CF convention¹⁹) are used in the climate community, often with a shift away from a focus on long-
272 term storage to a focus on scalable cloud-based access of vast volumes of both area-specific and global data. For this reason,
273 the data management includes the possibility to load xarray data structures, the use of compressed representations, and the
274 inclusion of zarr as a storage format to support its increased acceptance among the community. This is recognised in DestinE
275 so far with interoperable interfaces being developed to access and process native GRIB fields. Additionally, compliance with
276 existing metadata conventions that map both GRIB definitions and established CF conventions is ongoing work.
277 Notwithstanding this, the models underpinning the Climate DT may choose additional output streams in native zarr stores,
278 which some recent European research projects such as nextGEMS²⁰ and EERIE²¹ have shown to provide performant data
279 access for users across a wide range of applications.

280 Computational grids used internally by the Climate DT model components are different from one another and from the
281 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/>

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

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

296 The list of climate variables produced by the Climate DT simulations is defined in the data portfolio²². The data portfolio is
297 flexible between production cycles to serve any new requirements from the data consumers. The output is offered with a daily
298 frequency for the (two- and three-dimensional) ocean and sea ice variables, and hourly for the (two- and three-dimensional in
299 pressure levels) atmosphere and land. Higher frequency output, requested by some applications, is not yet possible. The data
300 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
301 gone through a quality-assurance process. The HEALPix resolution closest to the Climate DT climate model components is
302 H1024 nested²³ (where 1024 corresponds to the *Nside* parameter described in the documentation²⁴) for simulations of 5 km
303 nominal horizontal resolution and H512 for those of 10 km resolution. As an example, each climate model produces around
304 100 GB of output per simulated day at H1024 resolution. With the target throughput of one simulated year per day (SYPD) at
305 5 km, each of the Climate DT models thus generates more than 35 TB per wallelock day in routine production mode. These
306 production estimates could be at times higher when climate models perform more than one simulation simultaneously, should
307 a large enough HPC share be available. The Climate DT is inspired by the global weather forecasting experience where similar
308 data volumes are regularly dealt with.

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

309 To handle these large data volumes that are continuously produced, both in terms of storage and efficient consumption, the
310 Climate DT employs the streaming concept. In the Climate DT streaming is offered to the data consumers embedded in the
311 workflow. It involves making data available to the data consumers as soon as a set of automatic checks²⁵ to detect missing
312 fields, flawed metadata, and other potential errors such as unrealistic physical values, have been passed. If any of the critical
313 checks fail, the workflow manager stops the production and warns the operators, who follow agreed procedures to continue
314 after diagnosing and solving the problem. During data production the workflow regularly notifies the data consumers about
315 the availability of new data. The Climate DT continuity is controlled by the data notifier task, which is called by the consumer
316 to trigger its task. In this way, the streaming to the data consumers in the workflow is decided by the consumer.

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

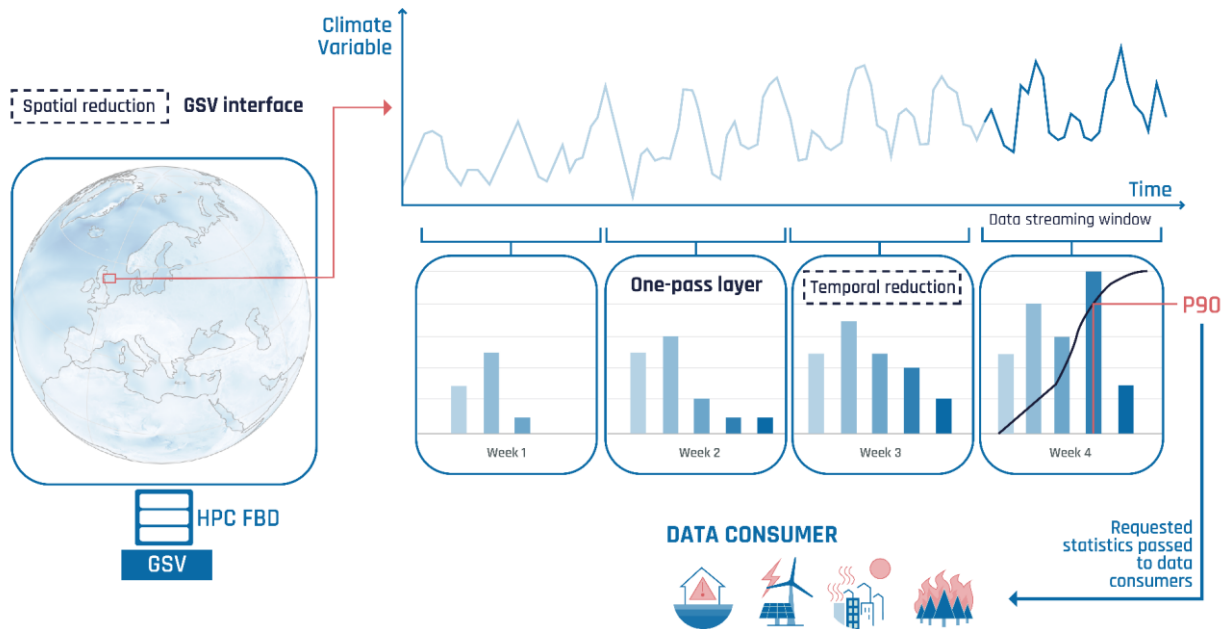
320 As the Climate DT produces regularly multi-decadal simulations from several models, accumulating high-frequency, high-
321 resolution data soon becomes prohibitive for any HPC storage system. This has been solved by addressing both data storage
322 and access with a tiering system. Data (so far all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

333 The approach used by the Climate DT connects the HPC platforms (which have user access restrictions) to infrastructures with
334 cloud-like data access and services. This spares data consumers not embedded in the production workflow the complexities of
335 the HPC data access and operational procedures, offering user-oriented access to federated, very large data sources through
336 DestinE’s data lake services implemented by EUMETSAT and the DestinE Service Platform (DESP) managed by ESA, always
337 applying DestinE’s data access policy (DestinE, 2025) and guidance. The description of these services, their objectives,
338 strategy, and guidance offered²⁶ 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/>

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



349
 350 **Figure 3: Schematic showing how the climate model output stored as the GSV in the FDB is retrieved via the GSV interface, including**
 351 **data interpolation if requested, and passed into the one-pass layer. The one-pass algorithms (OPAs) provide temporal reduction by**
 352 **computing a statistic requested by a data consumer from native data. The figure illustrates a case of percentiles from weekly**
 353 **histograms of a climate variable. The statistic is continuously updated, controlled by data notifiers tasks, as new data from the**
 354 **climate simulation becomes available, always within the streaming window allowed by the data management process.**

355 With its data streaming capability, providing the full access to the climate model state as the models perform their simulations
 356 and data processing enabled by the combination of GSV, data notifier and OPA capabilities, the Climate DT functions as a

357 virtual instance of the simulated climate. It can be considered a metaphor in the climate modelling realm of an observing
358 instrument, which samples reality with the highest frequency possible relevant to the process under study, while in parallel the
359 data is thinned from the high-frequency sample to make the data stream manageable. In this metaphor, if a data consumer
360 cannot make use of the data available in the streaming window (i.e., before the HPC storage is flushed to make space for more
361 model output), they will have to either 1) use model output from the data bridge as described previously, if the necessary
362 variables are available there, or 2) wait some time for a new climate simulation, either with a new model version or as a new
363 member of an ensemble.

364 **5 Production of the first set of global climate projections and storyline simulations with local granularity**

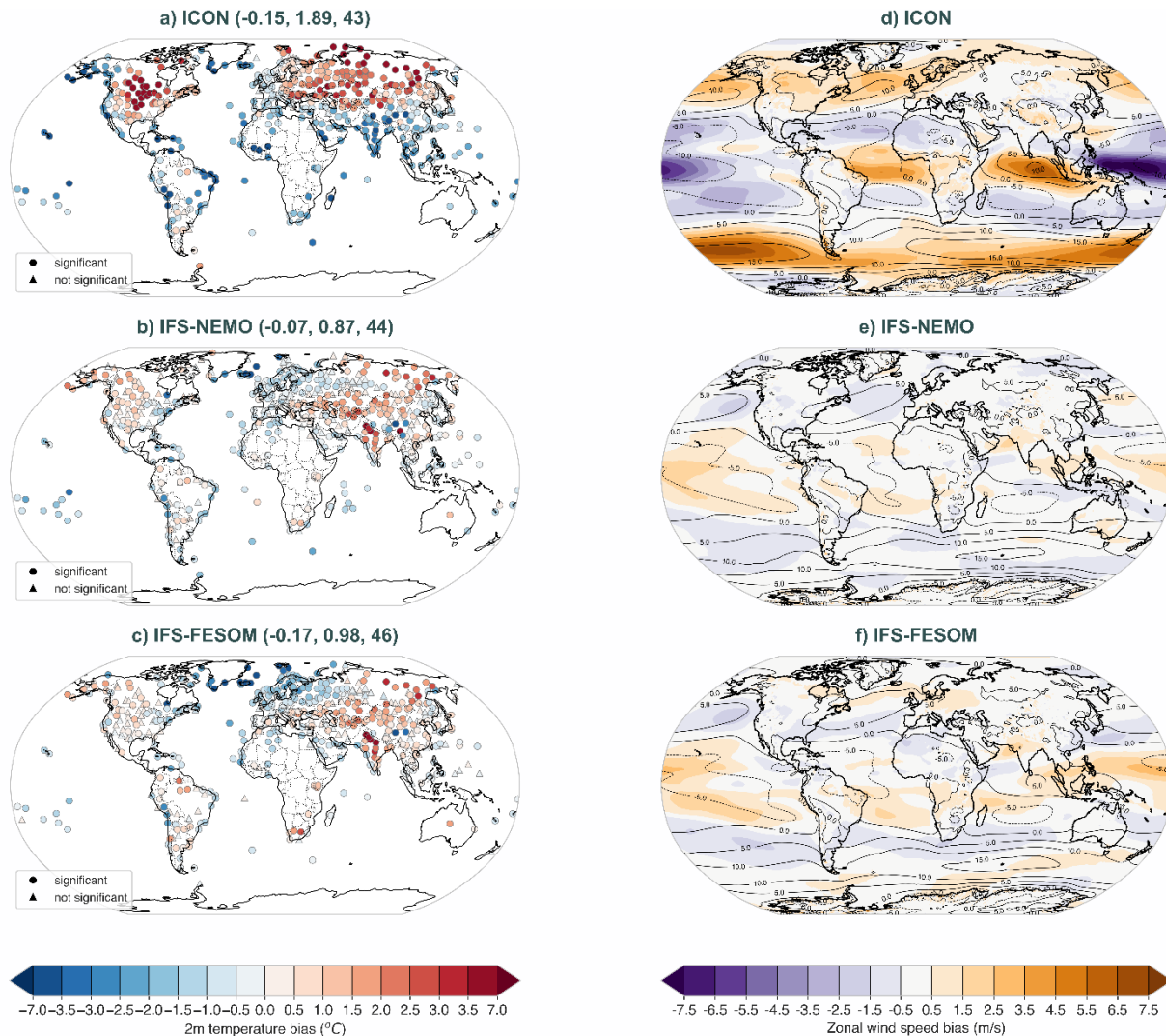
365 The Climate DT exploits and co-develops a new generation of global storm-resolving, eddy-rich models (Moreton et al., 2020;
366 Beech et al., 2024; Segura et al., 2025), often referred to as km-scale models, and a set of HPC advances. A handful of these
367 models have been built, among which those participating in the Climate DT (Bauer et al., 2021a; Rackow et al., 2022; Segura
368 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
369 global climate models used, ICON, IFS-NEMO, and IFS-FESOM, have been adapted to perform km-scale simulations through
370 a cooperative development approach supported by the European-funded research projects nextGEMS²⁷ and EERIE²⁸, as well
371 as national initiatives such as WarmWorld²⁹ in Germany and Gloria³⁰ in Spain, involving climate, weather, and supercomputing
372 centres, and academic partners throughout Europe. In the Climate DT, these models are used to perform climate simulations
373 at nominal resolutions ranging from 5 and 10 km for the different components of the Earth system, exploiting the
374 supercomputing facilities of the EuroHPC JU. The current throughput is approximately 0.5 simulated years per wall clock day
375 (SYPD) at 5 km resolution, and 2–3 SYPD at 10 km, using around 200 and 100 computing nodes, respectively. Efforts are
376 underway to improve the HPC adaptation of the models to enhance their energy efficiency, while aiming to reach a throughput
377 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/loria-global-digital-twin-regional-and-local-climate-adaptation>



378

379 **Figure 4: Example of AQUA-OBSALL diagnostics output. (Left column) Bias of annual mean 2-metre temperature (°C) at synoptic**
 380 **surface stations in (a) ICON, (b) IFS-NEMO and (c) IFS-FESOM. Stations where the simulated values differ at the 5% significance**
 381 **level from the observations are represented with closed circles and the rest of the stations with triangles. Values in the headings**
 382 **stand for average bias, average absolute bias, and the fraction of stations with positive bias, respectively. (Right column) 850 hPa**
 383 **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**
 384 **three models, climate simulations considered are historical simulations (O25.1). For both simulations and references, the period**
 385 **considered is 1990–2014.**

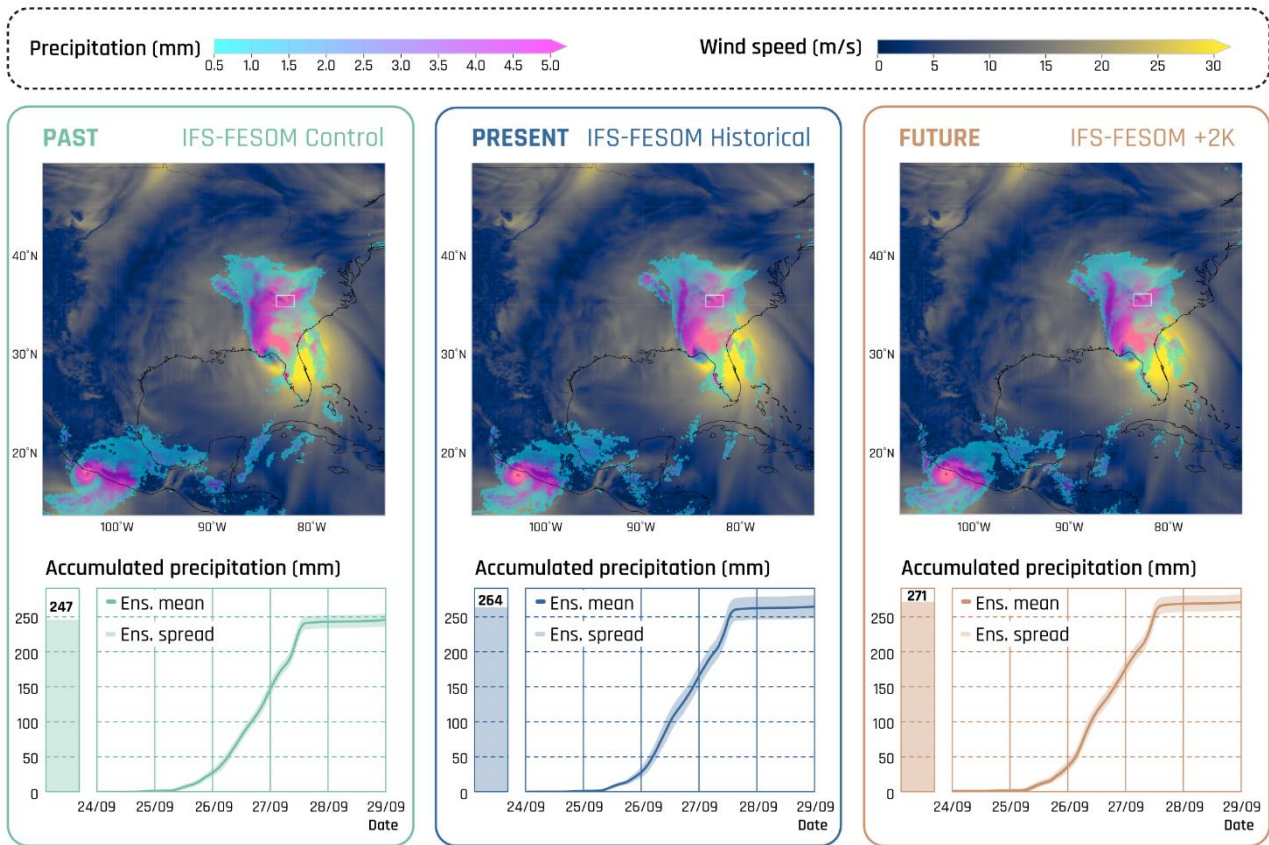
386 The Climate DT infrastructure is not limited to deterministic km-scale simulations but also allows the production of climate
 387 simulations following standard CMIP protocols, including ensembles. It can also be used to perform bespoke simulations to
 388 assess the impacts of different scenarios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

389 The simulations performed by the Climate DT have followed a streamlined version of the HighResMIP protocol (Haarsma et
 390 al., 2016; Roberts et al., 2025) on both the LUMI and MN5 EuroHPC pre-exascale supercomputers. The protocol consists of

391 1) 30-year long control simulations with constant 1990 forcing to evaluate model drift, 2) historical simulations starting in
392 1990 and ending in 2014, and 3) projections for the period 2015–2040 following the SSP3-7.0 scenario defined in the sixth
393 phase of CMIP (CMIP6; Eyring et al., 2016). The projection simulations with IFS-NEMO were carried out at a horizontal
394 resolution of 4.5 km for the atmosphere and land and 1/12° (around 8 km at the Equator) for the ocean and sea-ice, with IFS-
395 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
396 sea ice, while the ICON simulations were performed at 5 km resolution for all Earth system components. In all simulations,
397 the ocean/sea-ice models were spun up for five years using stand-alone ocean runs forced with the Copernicus Climate Change
398 Service ERA5 reanalysis (Hersbach et al., 2020) for the corresponding initial date (1990 for the historical and control and 2020
399 for the projection) that were started from EN4.2 ocean estimates interpolated to the corresponding ocean grid (Good et al.,
400 2013). The ocean spin up was followed by a two-year coupled ocean-atmosphere spin up with constant atmospheric forcing in
401 the IFS-NEMO and IFS-FESOM cases.

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

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



415

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

422 The storyline simulations are performed with IFS-FESOM (Sánchez-Benítez et al., 2022; John et al., 2025) at resolutions of
 423 about 10 km for the atmosphere and land and 5 km for the ocean and sea ice. They represent an important application of the
 424 Climate DT's capabilities because they provide concrete, location-specific insights into how climate change is reshaping
 425 extremes, making risks more tangible and adaptation planning more actionable. These simulations reconstruct the evolution
 426 of the climate system, including extreme events such as heatwaves, floods, storms, and drought, from 2017 to the present, with
 427 continuous updates close to real time, under three distinct climate conditions: a past climate resembling the 1950s, the present-
 428 day climate, and a future scenario with 2 °C warming above pre-industrial levels (assumed to be reached around the 2050s).
 429 To ensure realism, the large-scale atmospheric circulation of IFS-FESOM is nudged to ERA5 reanalysis data above the
 430 boundary layer, while other components evolve freely under the prescribed climate forcing. This approach allows the same
 431 physical event to be simulated across different climate states, offering insights into how thermodynamic changes modulate its

432 intensity, duration, and impact. For example, Figure 5 shows how the simulations reproduce essential features of hurricane
433 Helene, including mesoscale structures, and how climate change may have influenced its characteristics, supporting both event
434 attribution and forward-looking scenario analysis. Because the simulations are global and consistently high-resolution, they
435 enable the examination of multiple, concurrent extremes worldwide, providing locally relevant insights into compound climate
436 risks.

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

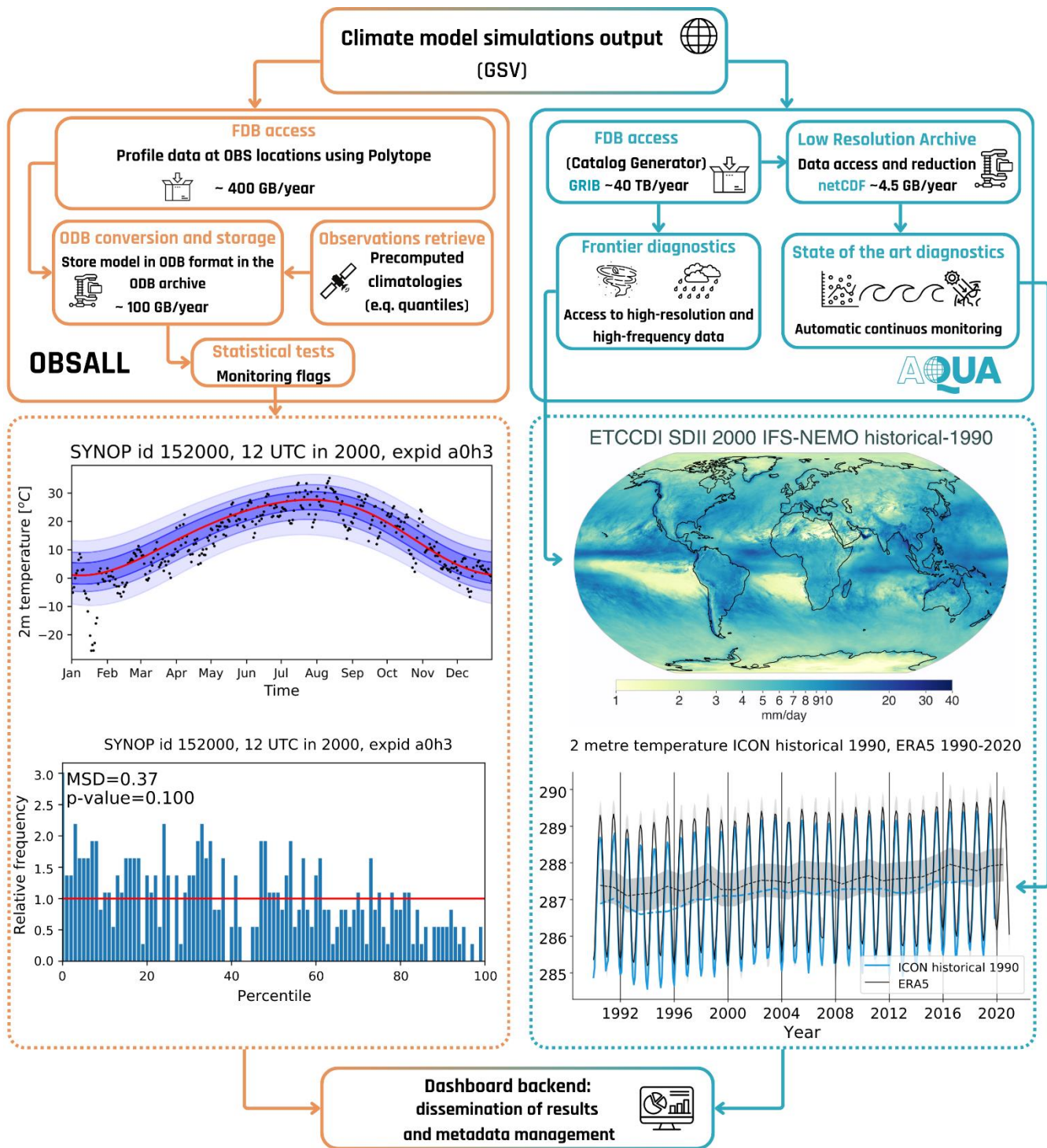
447 **5.1 Real-time scientific quality assessment**

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

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

461 The assessment focuses on several state-of-the-art diagnostics and metrics targeting the mean state model biases over the
462 historical period for selected regions (e.g., performance indices from Reichler and Kim, 2008) and variables or basic metrics
463 (global mean air temperature, top-of-the-atmosphere energy balance, atmospheric teleconnections, metrics of ocean
464 circulation, etc.) that are essential to understand the evolution of the climate system. This information contributes to the quality

465 assurance of the climate simulations and builds trust into its use for any adaptation decision. AQUA also includes a reduced
466 set of frontier diagnostics that exploit the native spatial resolution and high frequency of the data. They aim at providing
467 statistics on physical processes that could not be systematically investigated in km-scale climate simulations due to the huge
468 data management challenge they pose. These diagnostics include statistical properties of the tropical rainfall or tropical cyclone
469 characteristics. The AQUA diagnostics are designed to deal with multi-model ensembles to provide a measure of uncertainty
470 for both historical simulations and climate projections.



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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

474 precipitation-based simple daily intensity index (SDII) from the ETCCDI³¹ collection, estimated for the year 2000 from an IFS-
475 NEMO 10-km historical simulation (centre-right panel). Simultaneously, data is aggregated into a low-resolution archive (monthly
476 averages on a one-degree regular grid) for continuous monitoring via a large set of state-of-the-art diagnostics. An example
477 diagnostic shows global monthly and yearly averaged 2-metre temperature from an ICON 10-km historical simulation and ERA5
478 reanalysis (bottom-right panel). The OBSALL processing (orange boxes) involves time-critical GSV access, model profile retrieval,
479 application of observation operators, and comparison with observed climatologies. Results for 12 UTC 2-metre air temperature
480 from an IFS-NEMO 10-km historical simulation are shown: temperatures for the year 2000 at Arad, Romania, are shown against
481 observed quantiles (centre-left panel) while the histogram illustrates the probability of differences over the whole year arising by
482 chance, with a p-value set to 0.1 (bottom-left panel).

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

498 **6 Prototype climate-change impact applications**

499 A characteristic of the Climate DT is its ability to generate tailored and timely information for climate-sensitive sectors. The
500 end-to-end production of user-relevant climate information is illustrated with a selected number of sectoral climate applications
501 that have been embedded in the workflow as data consumers and can compute relevant indicators as the climate simulations
502 are performed. At the same time, these applications play an important role in shaping the Climate DT operation. They provide
503 continuous feedback about the digital twin development like the data portfolio, the experimental setup, the software to
504 maximise the application throughput, the data strategy, the OPA capabilities, etc., all through a co-production process. Every
505 embedded application has been co-produced with selected users, who participated in the process through regular interactions.
506 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>

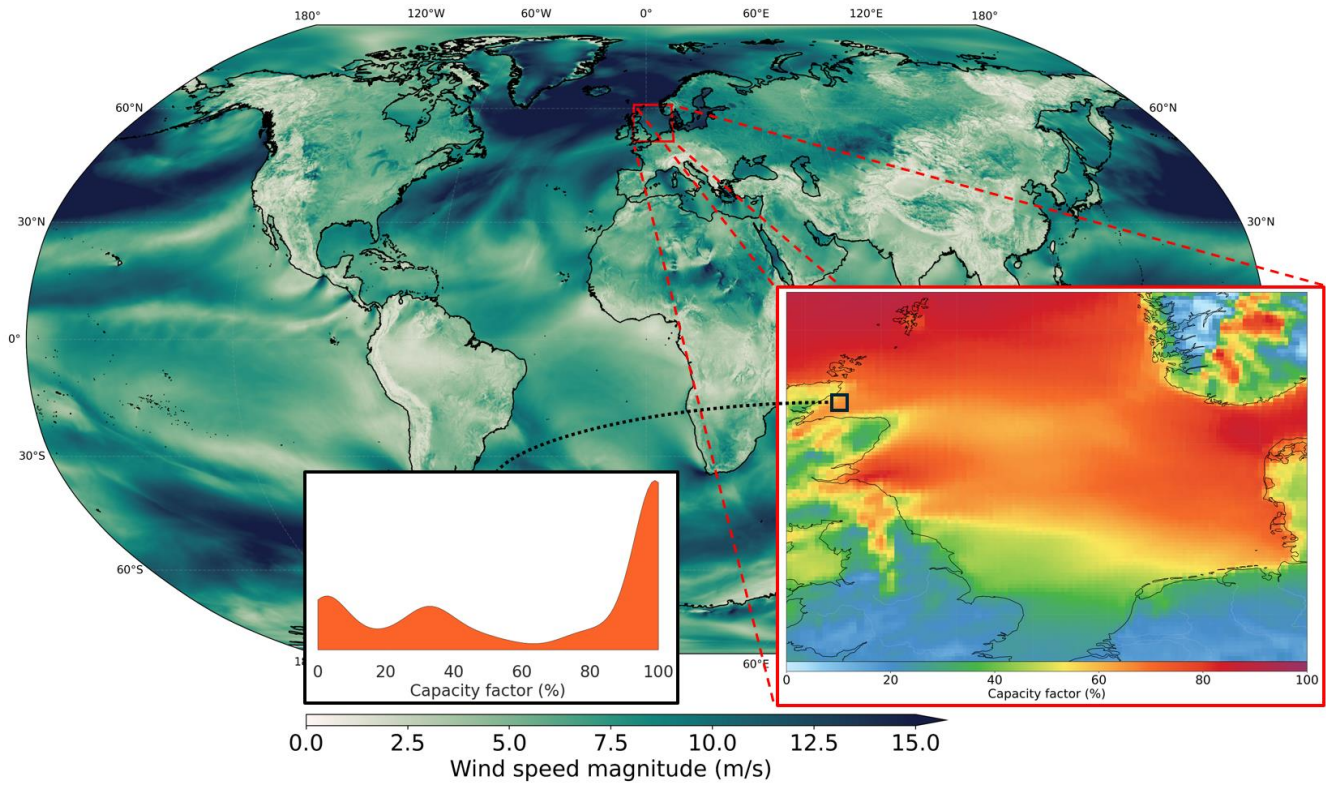
507 can be generated by making use of the full climate model state described above, while more traditional asynchronous access
508 to the resulting data included in the DestinE portfolio is still possible for those applications that are not embedded in the
509 workflow by accessing data in the data bridge.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

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

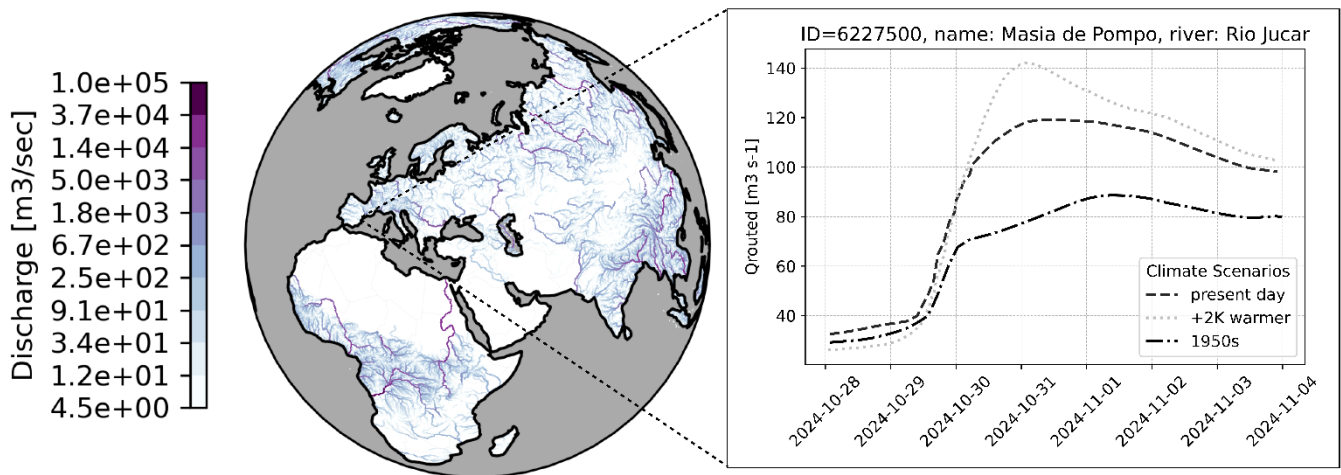
- 512 ● Wind-energy management and energy demand: This application illustrates the value of the Climate DT for informing
513 the near- to mid-term investment and management strategies of the wind energy sector (Lacima-Nadolnik et al.,
514 2026). Wind-energy generation is particularly sensitive to sudden variations in resource availability. This application
515 provides global indicators, such as high- and low-wind event frequency (Rapella et al., 2023), capacity factors, and
516 annual energy production estimates, among others, for a range of turbine types (Lledó et al., 2019), at global scale
517 with high resolution from high-frequency wind data (Fig. 7). These indicators have been selected in collaboration
518 with a company that provides estimates of the wind resource to energy producers. In addition, for specific areas with
519 offshore installations, the application provides indicators relevant to the construction and maintenance that require
520 high-frequency data, such as sea-ice occurrence, ice-related stress to structures, and expected navigability conditions.
- 521 ● Freshwater availability and flood occurrence: This application, named HydroLand, provides global estimates of river
522 runoff at the same spatial scale as the climate simulations. This is an improvement over current hydrology information
523 systems for climate time scales. The HydroLand application is based on the mesoscale Hydrologic Model (mHM;
524 Samaniego et al., 2010) and the multiscale Routing Model (mRM; Thober et al., 2019). mHM uses Climate DT data
525 at the highest spatial and temporal resolution available and mRM provides a wide range of hydrological variables and
526 indicators depicting global freshwater availability to support insights about the requirements for climate adaptation
527 anywhere in areas of particular interest (Fig. 7). The application can also take advantage of the simultaneous bias-
528 adjustment of the climate simulations. Cumulative distribution functions used for the statistical adjustment can be
529 estimated on-the-fly using the method available in the OPA package (Grayson et al., 2025).
- 530 ● Characteristics of hydrometeorological extreme events: The HydroMet application summarises user-selected
531 statistics of hydrological extremes by identifying extreme rainfall events over Germany. This leads to information
532 about the spatial and temporal extent, precipitation amounts, return time, and the frequency of extreme events. The
533 application is based on KOSTRA-DWD-2020 (Junghänel et al., 2022), a solution for the evaluation of precipitation
534 levels, duration, and the annual return interval, and on the Catalogue of Radar-based heavy Rainfall Events (CatRaRE;
535 Lengfeld et al., 2021) software package that detects spatially and temporally independent heavy precipitation events
536 leading to flash floods. High global spatial and temporal data frequency is required to estimate these indicators with
537 the level of detail required by the range of users that collaborate with the developers.
- 538 ● Fire weather and wildfire spread: This application focuses on wildfire management strategies. The high-resolution
539 Fire Weather Index (FWI) identifies where meteorological drivers of fire weather conditions are conducive to the
540 occurrence and persistence of fires (Abatzoglou et al., 2019). Additionally, the fire spread model Wildfire Safety

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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 (Hetzler et al., 2024).



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547

548 **Figure 7: (Top panel) Global map with a snapshot of wind speed at 100 metres from the 10-km IFS-NEMO historical simulation.**
549 **The regional zoom, highlighted with a red rectangle, shows the capacity factor averaged over a week for a class S Vestas V164 wind**
550 **turbine over the North Sea computed from 1-hourly wind components (zonal and meridional 100-metre wind). The black square**
551 **marks the location of the Moray East wind farm, off the coast of Scotland, which operates this specific type of turbine. The curve**
552 **represents the distribution of the hourly capacity factor for Moray East during the week. (Bottom panel) The HydroLand application**
553 **provides global estimates of terrestrial hydrological processes like river discharge over small areas (~80 km²), soil moisture deficits,**
554 **and extreme flooding events. The time series represent the river discharge values over the Jucar River in the Valencia region (Spain)**
555 **during the period of the storm event at the end of October 2024 using climate data from the 1950s, present-day, and future climate**
556 **(+2K global warming level) IFS-FESOM storyline simulations.**

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

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

566 **7 Consolidating the Climate DT**

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

574 **7.1 Operational framework**

575 The Climate DT lays out the basis for the operationalisation of user-oriented, multi-decadal, multi-model global climate
576 projections. This is an initiative complementary to the existing CMIP and CORDEX international efforts and to the activities
577 of national climate services and the Copernicus Climate Change Service in the provision of future climate information sources.
578 The regular production of climate simulations at this scale can only be maintained by ensuring that the computational
579 performance of all elements is monitored, analysed, and optimised as the underlying HPC platforms evolve. Moreover, a
580 protocol will be developed to decide how other climate models may be incorporated and benefit from the operational
581 framework. The Climate DT simulations are not time-critical, compared to weather forecasts, but the operational context

582 requires that they are regularly performed to address continuously emerging data consumer requirements. The production
583 should be flexible enough to continue in alternative HPC systems whenever needed. This requires data consumers embedded
584 in the workflow to use containers and integrate and schedule their own restarting mechanisms. The development team supports
585 data consumers to develop these capabilities.

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

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

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

599 **7.2 Increasingly flexible data management**

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

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

613 **7.3 Penetration of artificial intelligence solutions**

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

- 617 ● enhancing the user experience through the development of chatbots that make the Climate DT data more accessible
618 to decision-makers by including it into context-relevant reports (Koldunov and Jung, 2024; Kuznetsov et al., 2025)
619 using fine-tuned large language models with the help of a climate-adaptation specific corpus;
- 620 ● exploiting the wealth of the unprecedented high-resolution, high-frequency global data produced by the Climate DT
621 models for AI model training to build emulators³² of the physical climate models; the emulators will be used for
622 uncertainty quantification of the simulated trajectories, for the fast reconstruction (Kadow et al., 2020) of the
623 simulated trajectories as reruns for selected time slices (Rackow et al., 2024) that can provide high-frequency data on
624 demand as described in the “AI on top” concept (Bauer et al., 2023), and for the exploration of the climate evolution
625 for a range of emission scenarios not sampled by the physical models.

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

627 **7.4 Interactivity to address user needs**

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

639 **8 Summary and conclusions**

640 The Climate DT is a pioneering effort to build an operational climate information system based on a digital infrastructure to
641 support climate change adaptation. It provides globally consistent multi-decadal climate simulation data with very high

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

642 temporal (hourly) and spatial resolution (between 5 and 10 km) and considers user needs in terms of the output variables,
643 access patterns, data processing, and simulation design. It benefits from the convergence of hardware and software
644 infrastructure, dedicated resources, digital innovation, and domain experts with the adequate knowledge, perspectives, and
645 experience, in a transdisciplinary endeavour. The Climate DT supports tackling some of the existing challenges (Stevens et
646 al., 2024) in providing climate-vulnerable communities with timely, decision-oriented global climate information. It
647 complements existing sources of climate information for adaptation focusing on the need for salience, equitability, and
648 credibility. Besides, the Climate DT, while computationally more expensive than existing climate simulation approaches, is a
649 trailblazer for the use of computational resources so far largely unused by the climate community, such as GPU-based
650 platforms.

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

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

676 apply strict access rules and it has been designed to be run by dedicated operators. However, users able to use the
677 workflow and the system software in their own environments.

- 678 ● Unified data handling: The Climate DT introduces a harmonised data framework, including the GSV concept and the
679 use of the HEALPix grid for all climate outputs. This ensures homogeneity, consistency, and interoperability. A
680 common list of variables is delivered by all models at high frequency and near-native resolution under strict data
681 governance that follows FAIR data principles (Wilkinson et al., 2016). Data are made available using either streaming,
682 allowing data consumers embedded in the workflow to exploit quality-controlled full climate model output as the
683 models run, or storage in the data bridges. In the former option data and workflow become closely linked together
684 with full traceability. OPAs offer efficient data processing, supporting the translation of climate data into impact-
685 sector information, and improve responsiveness to the data consumer requirements.
- 686 ● AI integration: AI technologies are an emerging component of the Climate DT. Their use aims at improving
687 interactivity and user experience, inspired by the Earth Virtualization Engines initiative (Stevens et al., 2024) ideas.
688 AI-powered chatbots are being developed to ease the exploitation of Climate DT data. In addition, the DTE supports
689 the creation of AI-ready datasets, enabling the development of data-driven climate emulators.
- 690 ● Real-time monitoring and model evaluation: The Climate DT workflow integrates online model evaluation through
691 the AQUA and OBSALL frameworks. AQUA provides real-time diagnostics of key climate aspects, including model
692 biases, performance metrics, and variability indices. OBSALL delivers full-resolution comparisons in observation
693 space using multiple observational networks. The results are summarised in a dashboard used by operators and climate
694 model developers to assess the quality of the simulations as they are running.
- 695 ● Action-oriented climate information: Climate-impact applications are embedded within the workflow to generate both
696 global and regional indicators relevant for climate adaptation, such as renewable energy, water, and forest
697 management. Co-designed with selected users, the applications exploit the high spatial and temporal resolution of
698 Climate DT data and its streaming capabilities to support the system salience. Further work is required to advance
699 uncertainty quantification beyond the current multi-model estimates.

700 The Climate DT ambitions respond to many of the objectives of the World Climate Research Programme and WMO's
701 Scientific Advisory Panel³³ strategic vision. The Climate DT is an effort complementary to the sources offered by initiatives
702 like CMIP and CORDEX, among others. These initiatives have different business models and governance, while they provide
703 invaluable opportunities to exchange experiences and solutions with. The exchanges can follow the WMO concept of research
704 to operations and operations to research transfers.

³³ <https://community.wmo.int/en/activity-areas/scientific-advisory-panel>

705 **9 Acronyms and project names**706 **Table 1. Acronyms employed in the Climate DT description.**

707

Acronym	Description
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

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709

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

710

711 **Code and data availability**

712 Except where specifically noted, the software used is open source under the licences listed in the relevant software archive.
713 The Climate DT dataset is accessible via <https://doi.org/10.21957/d3f982672e>. There is a unique semantic data access for the
714 data that allows users to clearly delineate the contributing models, experiment, dates, and variables, among other parameters.
715 The availability policy of datasets in the data lake is defined in [https://destine-data-lake-docs.data.destination-](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)
716 [earth.eu/en/latest/dedl-discovery-and-data-access/DestinE-Data-Policy-for-DestinE-Digital-Twin-Outputs/DestinE-Data-](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)
717 [Policy-for-DestinE-Digital-Twin-Outputs.html](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).
718 The ICON source code is available under <https://gitlab.dkrz.de/icon/icon-model> with doi:10.35089/wdcc/iconrelease2025.04,
719 including all modifications used for this study. The version of FESOM2.5 used in the Climate DT simulations is available at
720 <https://doi.org/10.5281/zenodo.10225420>. The FESOM2.5 model is also available from GitHub
721 <https://github.com/FESOM/fesom2>. The IFS source code is available subject to a licence agreement with ECMWF. ECMWF
722 member-state weather services and approved partners have granted access. The IFS code without modules for data assimilation
723 is also available. IFS used version cycle 48r1, available under an openIFS licence
724 (<http://www.ecmwf.int/en/research/projects/openifs>, OpenIFS licence, 2024) for educational and academic purposes, with
725 corresponding modifications available at <https://doi.org/10.5281/zenodo.10223577>. The NEMO4.0 source code version used
726 in the Climate-DT is available at <https://doi.org/10.5281/zenodo.5566313>. The interfaces to NEMO can be obtained from
727 ECMWF on request under the licence described above. Autosubmit is available at <https://github.com/BSC-ES/autosubmit> and
728 the version used in the manuscript is available at <https://doi.org/10.5281/zenodo.1559052>. The Climate DT workflow is
729 available in <https://github.com/DestinE-Climate-DT/Workflow>, and the version used is archived available at
730 <https://doi.org/10.5281/zenodo.15607598>. The AQUA code is available at <https://doi.org/10.5281/zenodo.14906075>. The
731 OBSALL, OPA, and BA versions used are available at <https://doi.org/10.5281/zenodo.15628903>,

732 <https://doi.org/10.5281/zenodo.14591827>, and <https://doi.org/10.5281/zenodo.18755253>, respectively. The code for the mHM
733 model version used in the HydroLand application is available at <https://doi.org/10.5281/zenodo.8279545>, while the code for
734 the energy application is at <https://doi.org/10.5281/zenodo.15609171>. The code developed for the wildfire FWI application is
735 available from <https://doi.org/10.5281/zenodo.15610494>.

736 Scripts and data to reproduce the figures of this manuscript can be found at <https://zenodo.org/records/15680547>.

737 **Author contributions**

738 AM, AS, BF, BS, CH, CS, DK, FD, FZ, HJ, IS, JH, JKon, KK, MAc, MC, NK, NW, PB, PBr, PD, PM, PO, PP, RR, SCa,
739 SMi, ST and UH contributed to conceptualization; AC, ALu, AS, BF, CH, CS, DK, FD, FR, HJ, HT, IS, JH, JKon, KK, MAc,
740 MC, NK, NW, PBr, PM, PO, PP, RR, SCa, SMi, SN, SP and UH contributed to project administration; AA, AC, AJ, AL,
741 AMe, AN, BJ, BR, CA, CF, CH, CHa, CPe, DB, DN, DS, ED, EV, FD, FR, HJ, HT, IA, IH, IG, IS, IW, JE, JJ, JKo, JKon,
742 JRa, KK, KG, LK, LKo, LT, MAc, MC, MG, MK, MM, MN, MR, NK, NN, PBr, PD, PG, PO, PR, PS, RR, SCa, SG, SMi,
743 SMu, SN, SP, ST, SW, TC, UB, UH, UTi, VW and VG contributed to the software; AC, AJ, AL, AMe, AN, BJ, BR, CF, CPe,
744 DS, EV, FR, HP, IA, IH, IW, JE, JKo, KK, KG, LK, LKo, LT, MAc, MC, MG, MN, NK, PBr, PR, SCa, SMi, ST, SW and
745 VG contributed to investigation; AA, BJ, BN, CA, FR, HJ, IG, JH, JRa, JSu, KG, KK, MN, MR, NK, NN, PD, PG, PO, SCa,
746 SG, SMi and SS contributed to validation; AJ, AL, FD, HJ, JW, JKon, JRa, KG, LT, MC, MM, MN, OS, PD, PO and ST
747 contributed to visualization; AA, AM, BN, CH, DN, ED, FD, HJ, IA, JH, JT, LK, LKo, LT, MAc, MC, MG, MN, NW, PBr,
748 SMi and SW contributed to data curation; AN, FD, HJ, HT, JKon, KG, SN and SP contributed to writing – original draft; AL,
749 AN, BF, CS, FD, FR, HJ, HT, IG, JKon, JRa, KG, LT, MAc, MC, NK, NW, PB, PBr, PD, PO, SMi, SN and ST contributed
750 to writing – review & editing. All authors read and approved the final manuscript.

751 **Competing interests**

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

753 **Acknowledgements**

754 The authors would like to thank all their colleagues of the different participating institutes listed at
755 <https://destine.ecmwf.int/provider> and from ECMWF for their collaboration to make this ambitious endeavour a reality. We
756 also acknowledge the EuroHPC Joint Undertaking (JU) for awarding this project access to the EuroHPC supercomputer LUMI
757 and MareNostrum5 through a EuroHPC JU Special Access call. The work presented in this paper has been produced in the
758 context of the European Union’s Destination Earth Initiative and relates to tasks entrusted by the European Union to the
759 European Centre for Medium-Range Weather Forecasts implementing part of this Initiative with funding by the European
760 Union. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European
761 Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for

762 them. Ehsan Sharifi is acknowledged for his contribution to the initial development and delivery of the streaming bias-
763 adjustment component, including methodological evaluation, workflow integration, and validation. Juniper Tyree (University
764 of Helsinki) is acknowledged for her contribution to figure 4 and Zeynep Musoglu (ECMWF) for her invaluable help with
765 figures 1, 2, and 3. Helene Hewitt and Bryan Lawrence made valuable and thoughtful suggestions to a preliminary version of
766 the manuscript that helped improve the description of the context in which the Climate DT develops. We sincerely thank Pier
767 Luigi Vidale, Christian Jakob, and a third anonymous reviewer, for their evaluation of the manuscript and their constructive
768 comments. Some of the authors have received support from the EERIE project (Grant Agreement No 101081383) funded by
769 the European Union and some through WarmWorld (Better – 01LK2202A and Faster – 01LK2203A) funded by the German
770 Federal Ministry of Education and Research. Some of the authors have received support of the GLORIA project (TED2021-
771 129543B-I00) funded by the Spanish MICIN/AEI. This work was also supported by the S1 project: “Diagnosis and Metrics in
772 Climate Models” of the Collaborative Research Centre TRR 181 “Energy Transfer in Atmosphere and Ocean”, funded by the
773 Deutsche Forschungsgemeinschaft (DFG, German Research Foundation, project no. 274762653).

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