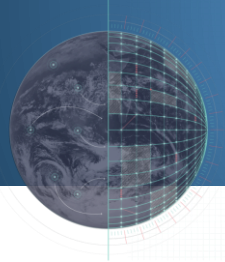
DESTINATION EARTH

DESTINATION EARTH CLIMATE DIGITAL TWIN: NEW CAPABILITIES FOR OPERATIONAL KM-SCALE CLIMATE SIMULATIONS

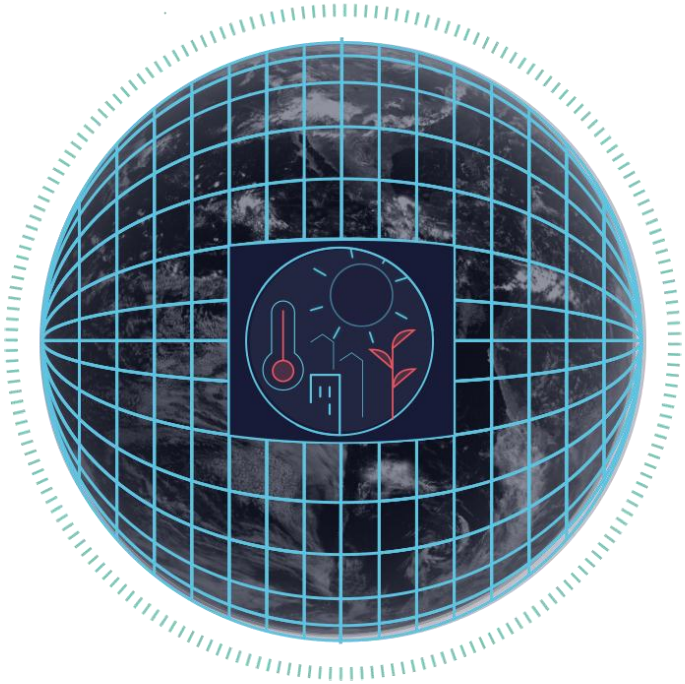
Funded by the European Union
Destination Earth implemented by ECMWF esa EUMETSAT



CONTENT

- **Overview of Destination Earth Climate DT** – *Jenni Kontkanen, CSC*
- **AQUA tool for monitoring and evaluation** – *Silvia Caprioli, Polito*
- **Results from the first operational simulations** – *Matteo Nurisso, CNR-ISAC*
- **Storyline simulations** – *Amal John, AWI*

OVERVIEW OF DESTINATION EARTH CLIMATE DT



CLIMATE DT TEAM

Climate DT is implemented by a partnership led by CSC, involving several European organizations, in close collaboration with ECMWF.

CSC

ALFRED-WEGENER-INSTITUT
HELMHOLTZ-ZENTRUM FÜR POLAR- UND MEERESFORSCHUNG

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

DKRZ
DEUTSCHES KLIMARECHENZENTRUM

UFZ HELMHOLTZ
Centre for Environmental Research

Hewlett Packard Enterprise

ILMATIETEEN LAITOS
METEOROLOGISKA INSTITUTET
FINNISH METEOROLOGICAL INSTITUTE

ISAC

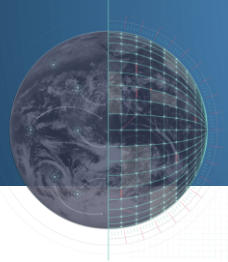
MAX-PLANCK-INSTITUT
FÜR METEOROLOGIE

UNIVERSITY OF HELSINKI

Politecnico di Torino

Federal Office of Meteorology and Climatology MeteoSwiss

JÜLICH
Forschungszentrum



DESTINATION EARTH CLIMATE ADAPTATION DIGITAL TWIN (CLIMATE DT)

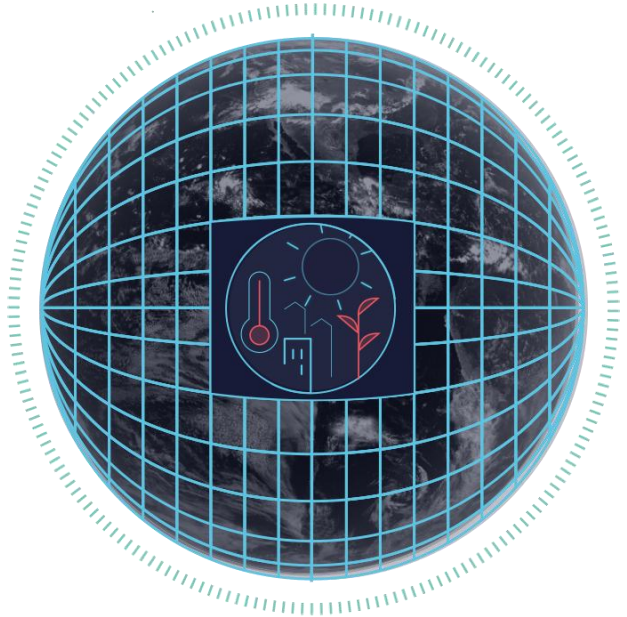
Destination Earth Climate DT delivers an operational simulation framework, which combines km-scale global climate models with impact-sector applications to produce climate information supporting climate adaptation

Phase 1 (Sep 2022 - April 2024) developed **the first prototype** of Climate DT.

Phase 2 (May 2024 – Apr 2026) focused on **operationalization** of the Climate DT and **further developing** its scientific and technical capabilities.

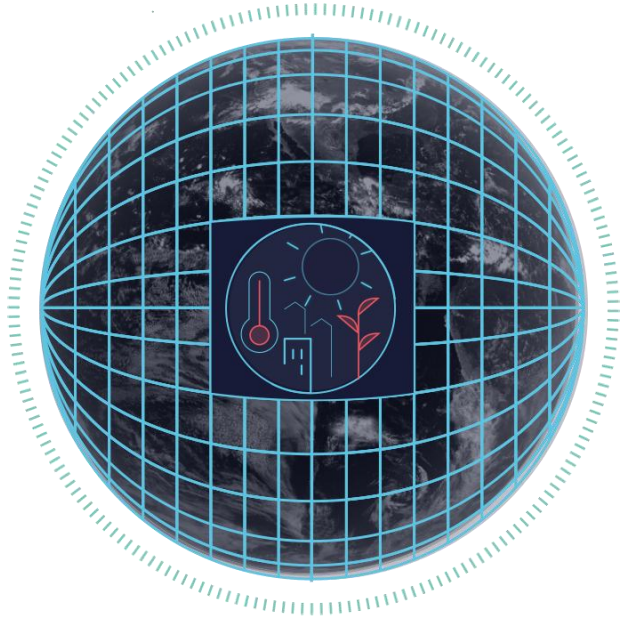
Phase 3 (May 2026 – Apr 2028) focuses on **maintaining, operating and upgrading** Climate DT as well as further developing its capabilities.

KEY NOVELTIES OF CLIMATE DT



KEY NOVELTIES OF CLIMATE DT

- **Multi-decadal global climate projections at 5-10 km resolution** with three coupled climate models (IFS-NEMO, IFS-FESOM, ICON) and **storyline simulations at 10 km** with IFS-FESOM



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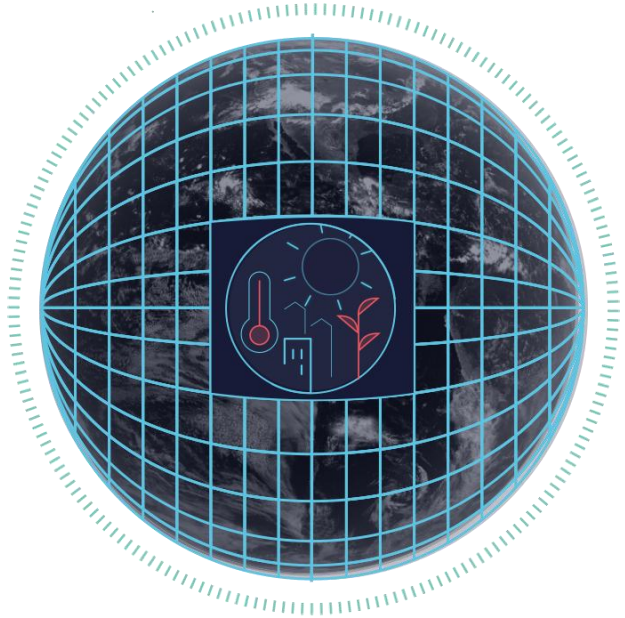
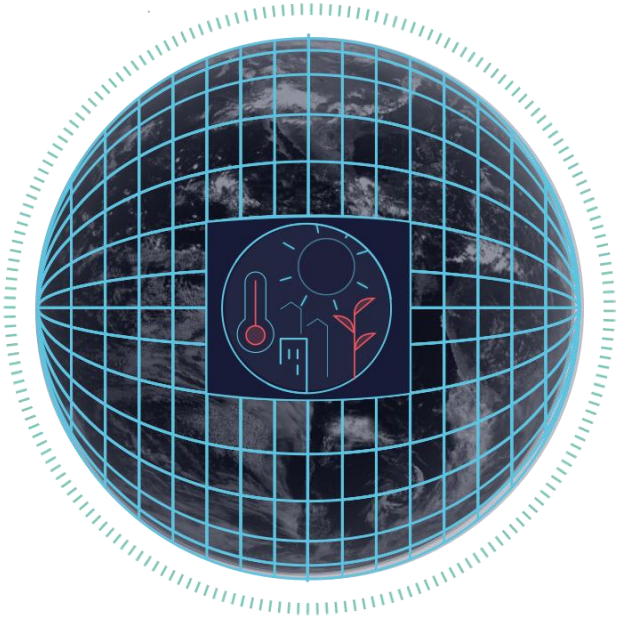
- **Multi-decadal global climate projections at 5-10 km resolution** with three coupled climate models (IFS-NEMO, IFS-FESOM, ICON) and **storyline simulations at 10 km** with IFS-FESOM

- **First ever operational capability** for climate projections & capabilities for addressing **'what-if' questions**



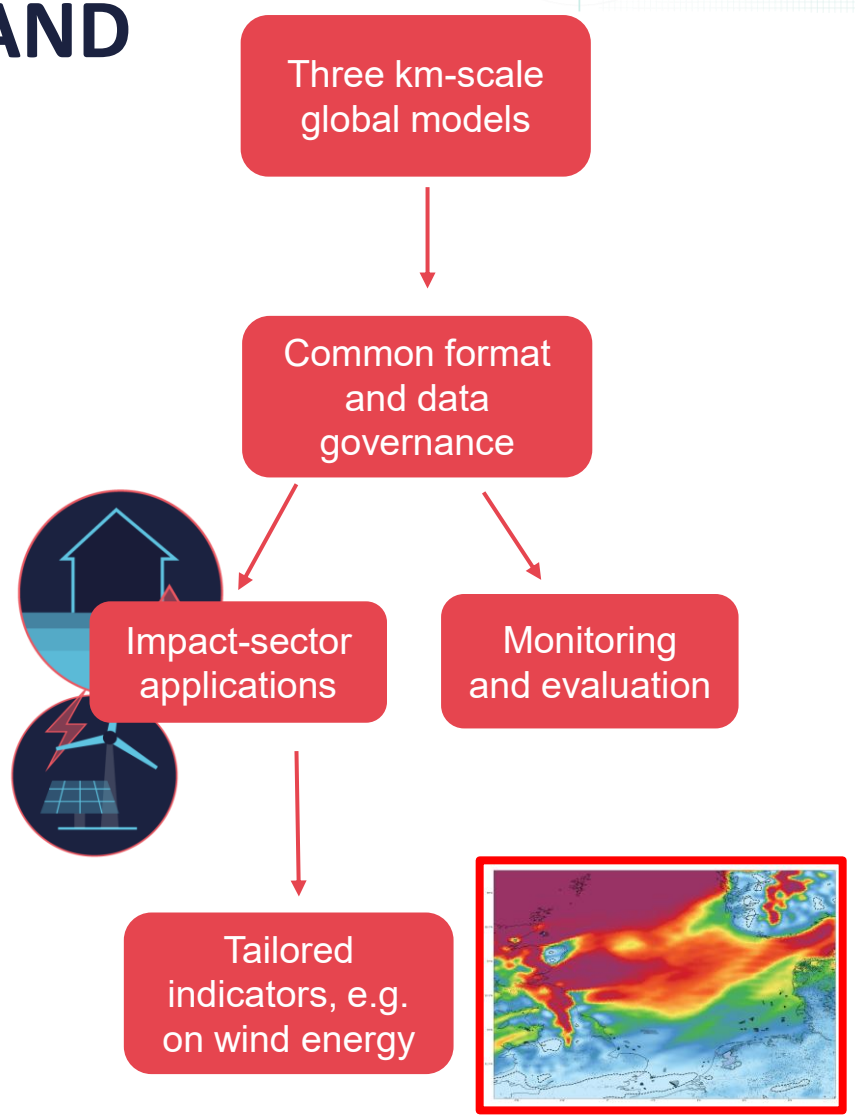
KEY NOVELTIES OF CLIMATE DT

- **Multi-decadal global climate projections at 5-10 km resolution** with three coupled climate models (IFS-NEMO, IFS-FESOM, ICON) and **storyline simulations at 10 km** with IFS-FESOM
- **First ever operational capability** for climate projections & capabilities for addressing **'what-if' questions**
- **Actionable information for different sectors** by bringing climate models and impact sector models within the same workflow

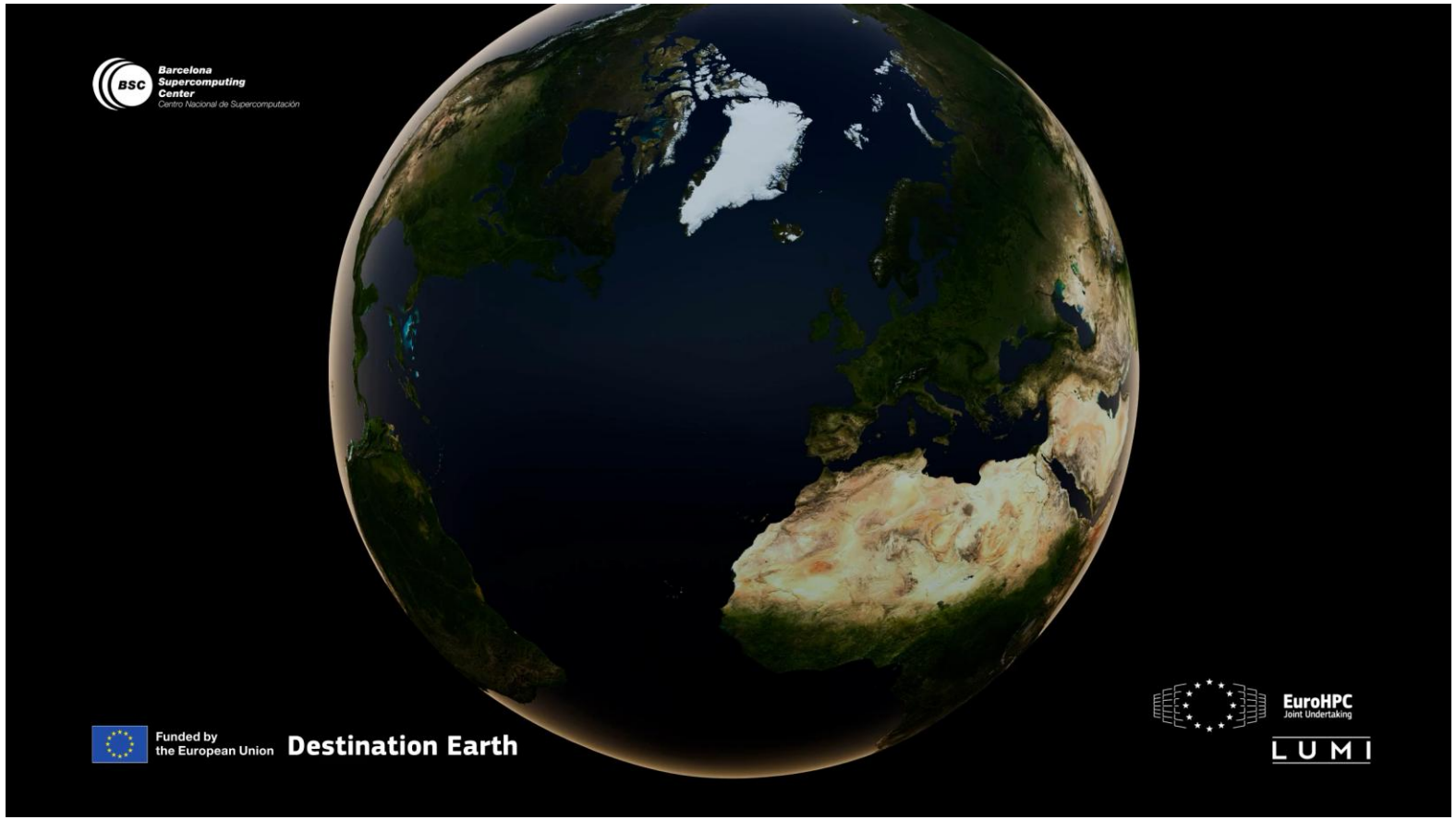


CLIMATE DT INTEGRATES CLIMATE MODELS AND APPLICATIONS IN THE SAME WORKFLOW

- **Common format (Generic State Vector, GSV) and data governance** for the three climate models
- Impact-sector applications produce **tailored user-relevant indicators** on the fly
- **Monitoring, evaluation** and **bias adjustment** on the fly
- Possibility to access data via DestinE Platform for **offline processing**



CLIMATE DT SIMULATIONS - ENHANCED SPATIAL AND TEMPORAL RESOLUTION



Simulations with **three coupled global climate models** (IFS-NEMO, IFS-FESOM and ICON) at **5-10 km resolution including multi-decadal projections and storyline simulations** (with IFS-FESOM).

CLIMATE DT OPERATIONAL CYCLE ENABLES REGULAR PRODUCTION OF NEW SIMULATIONS

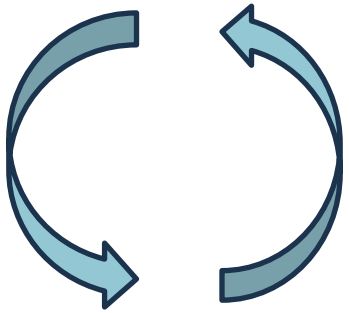
Technical and scientific updates of climate models, applications and workflow

Operational simulations: Multi-decadal simulations with online monitoring

Scientific verification: 5 years at 5 km resolution

End-to-end testing: running models end-to-end with applications

Workflow integration of updated components



- **Full operational cycle takes ~1 year,** first simulations with newly defined operational workflows completed and available via the DestinE Platform.
- New approach – **other climate modeling activities run through research efforts** with 7-10 years update cycles

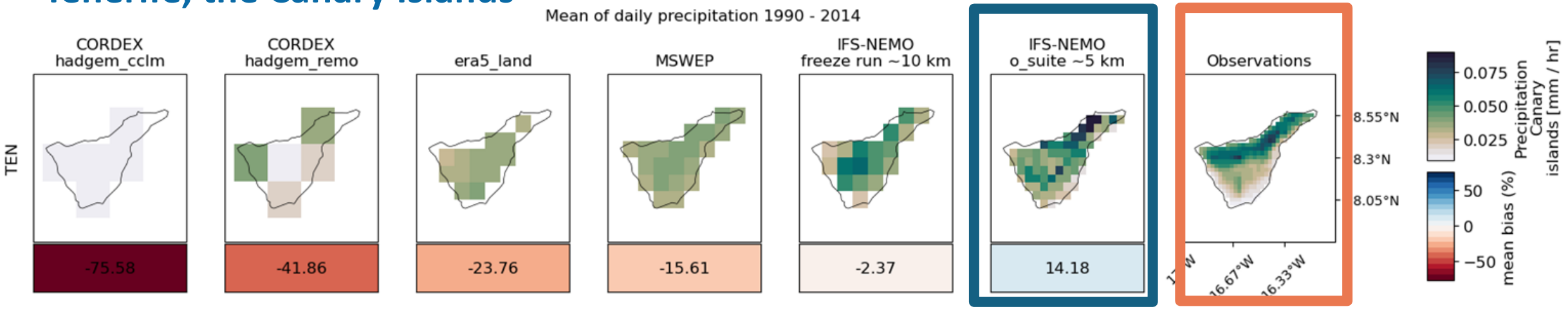
ANALYSIS OVER SMALL ISLANDS DEMONSTRATES THE ADDED VALUE OF GLOBAL KM-SCALE DATA

Comparison of CORDEX simulations, re-analysis and Climate DT simulations show improved capability to capture observed precipitation over small islands

Tenerife, the Canary Islands

Climate DT operational simulations

Observations



Figures by BSC team.

IMPACT SECTOR APPLICATION PRODUCE USER-RELEVANT INFORMATION FOR DIFFERENT SECTORS

Climate DT involves a set of impact sector applications operating as part of the same workflow with climate models.

Energy
- Wind energy supply and demand

Hydrometeorology
- Extreme event statistics

HydroLand
- Fresh water availability & floods

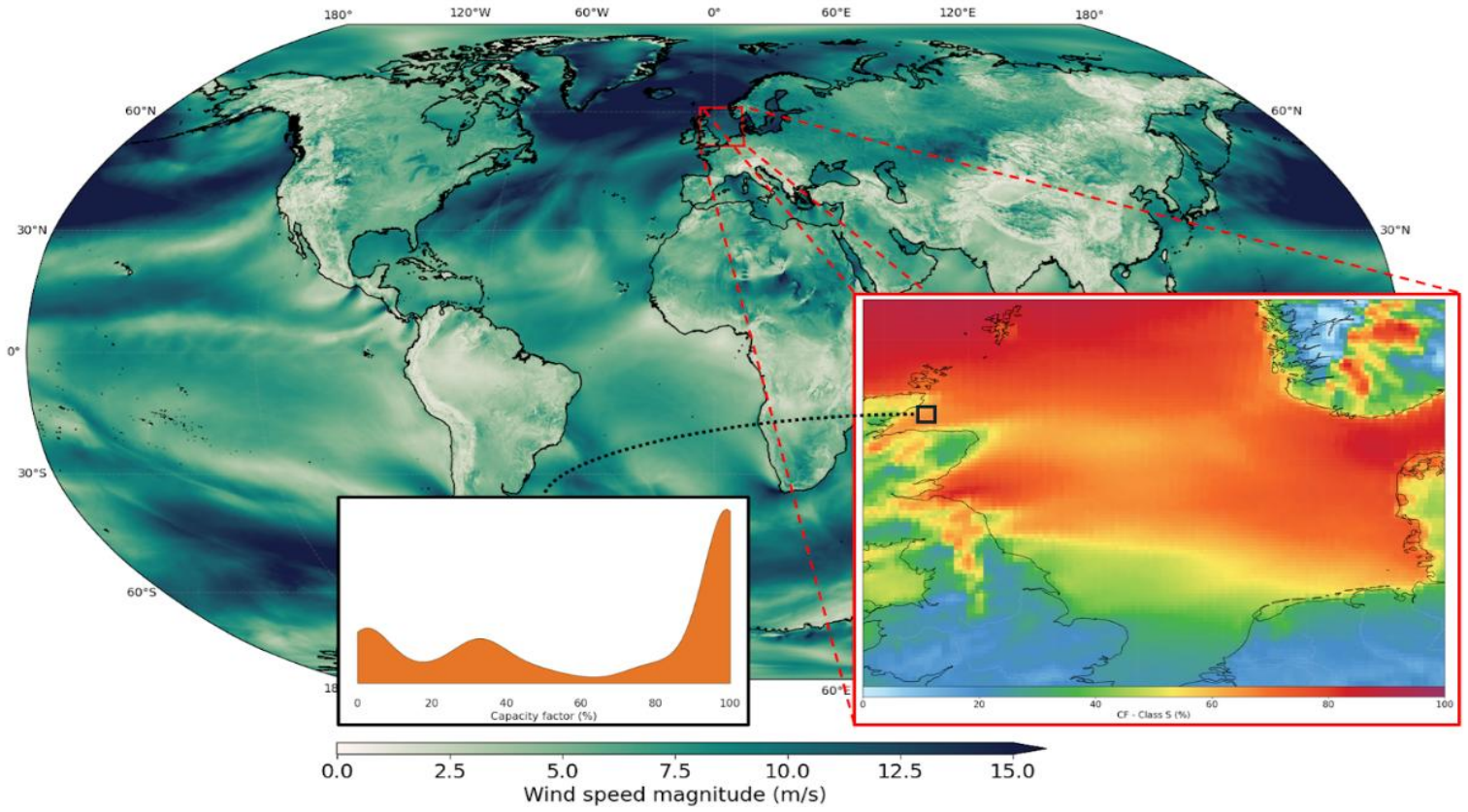
Fire and carbon
- Wild fire risk and emissions

WIND ENERGY APPLICATION

On-the-fly calculation of user-relevant indicators on wind energy.

Users from **grid operators** to **renewable energy providers** can **assess changes** in energy production or consumption.

User story



Figures by BSC team.

CLIMATE DT WORKFLOW IS RUN ON LEADING EUROHPC SYSTEMS

Climate DT workflow is run on **EuroHPC LUMI** and **MareNostrum5** systems – in Phase 3 the system will be ported to also include **JUPITER.**

We acknowledge the EuroHPC Joint Undertaking (JU) for awarding this project access to the EuroHPC supercomputer LUMI and MareNostrum5 through a EuroHPC JU Special Access call

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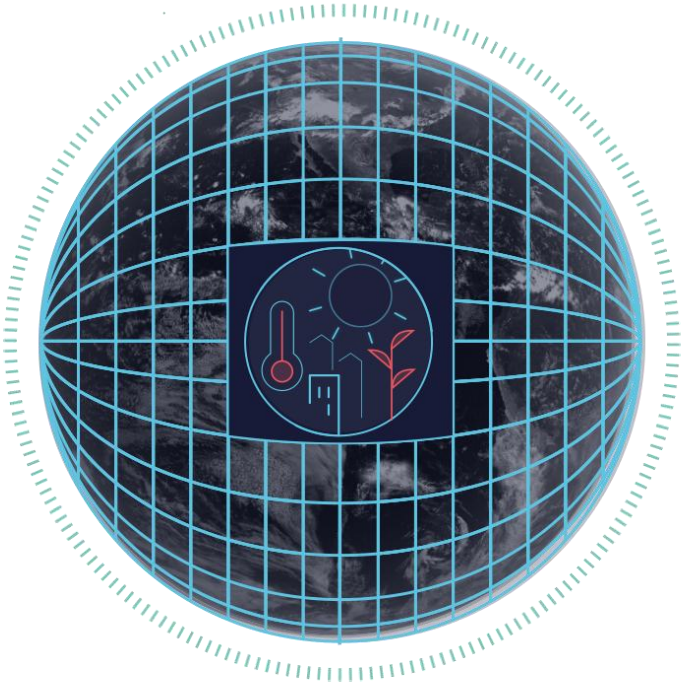
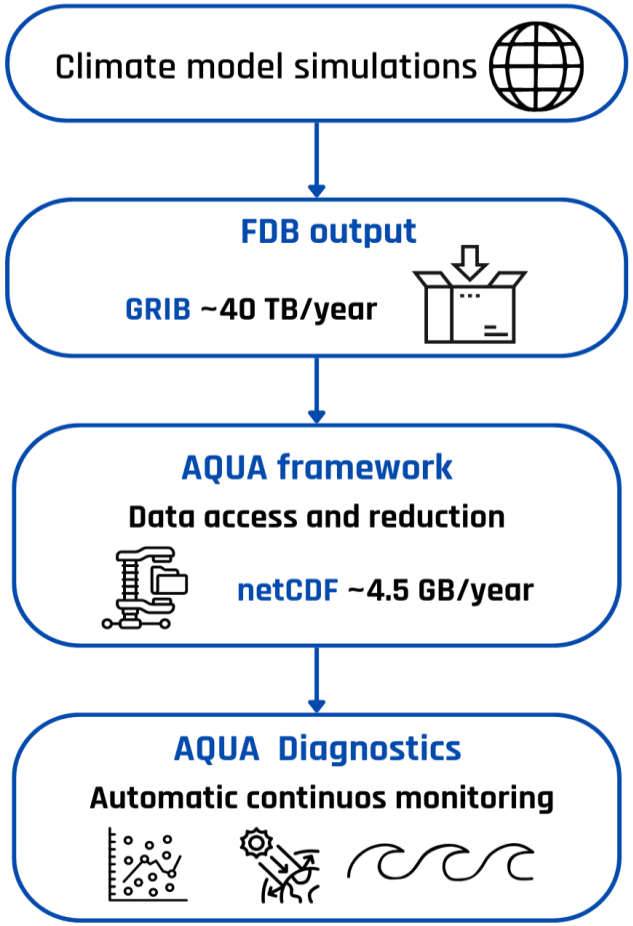
AQUA TOOL FOR MONITORING AND EVALUATION



MODEL EVALUATION IN THE CLIMATE DT: AQUA

Many tools are available for model analysis (ESMValTool, PMP/CMEC, …).
However, in the ClimateDT:

- **Amount of data** for a single simulation is critically high
  (DE Climate DT: 5km/hourly data = 36 TB of output per simulated year.)
- **Data access** not only to netCDF/zarr files, but to GRIB via FDB software, with data both locally on HPC and remote on the Data Bridge
- **Scalability** is crucial for even being able to open data
- Monitoring needs to be continuous and automatic in an **operational framework**



THE PHILOSOPHY OF AQUA

AQUA provides a framework to **access**, **process** and **analyze** vast volumes of climate data

AQUA-core and AQUA-diagnostics both available on Pypi!

Python3 library package based on **xarray**, **dask** and **intake**

Homogeneity: smooth interface to the user, despite differences in data formats metadata conventions

Modularity: data processing tools available as independent python classes

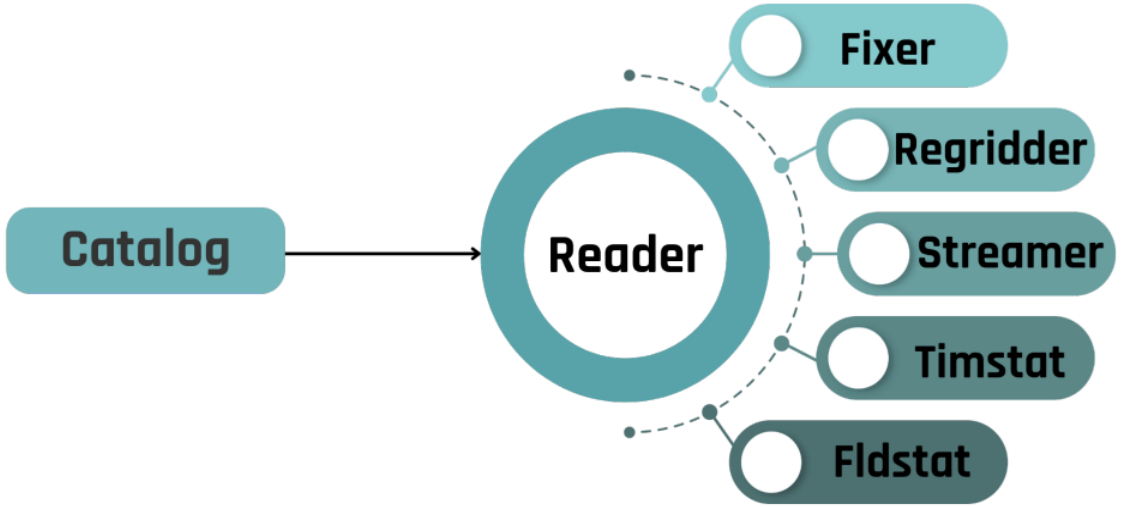
Efficiency: parallelization and lazy access to data

Fully containerized: portability on multiple HPC infrastructures

AQUA-CORE

Set of tools to open and process high resolution climate data

Once a catalog is added the user can retrieve the dataset with two lines of code! 🎉



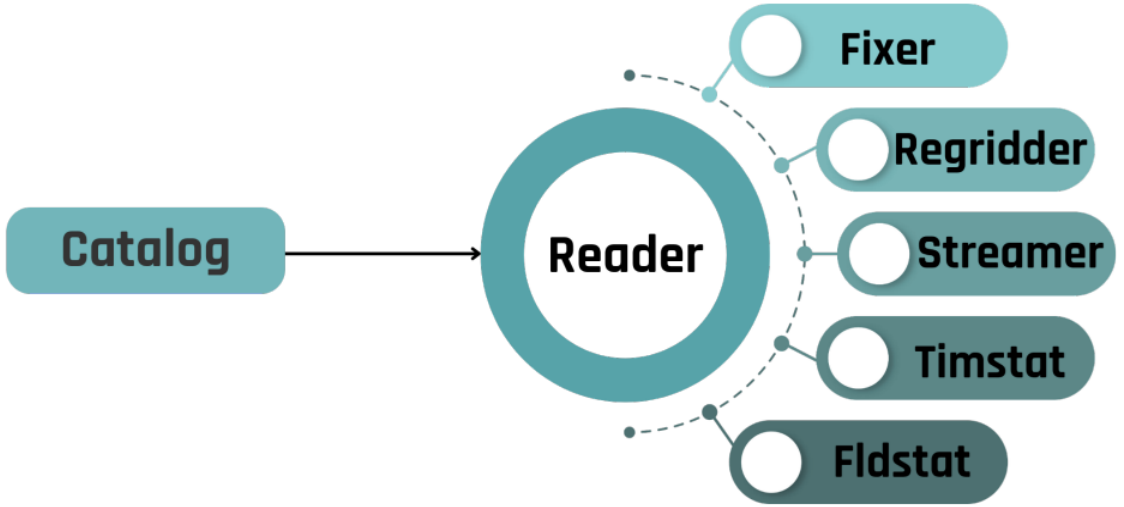

```
from aqua import Reader
reader = Reader(model='IFS-NEMO-5km', exp='baseline-
hist', source='hourly-hpz10-sfc', regrid='r005')
data = reader.retrieve()
```

→ Lazy dask array
Standardized metadata!

GitHub repo: https://github.com/DestinE-Climate-DT/AQUA
Preprint: https://doi.org/10.5194/egusphere-2026-1115

AQUA-CORE

Set of tools to open and process high resolution climate data



Users can interact with AQUA at three different levels:

- as a data retriever
- by applying AQUA's built-in methods

  (e.g., spatial regridding, temporal averaging)
- by performing a complete analysis through the **AQUA diagnostic suite**

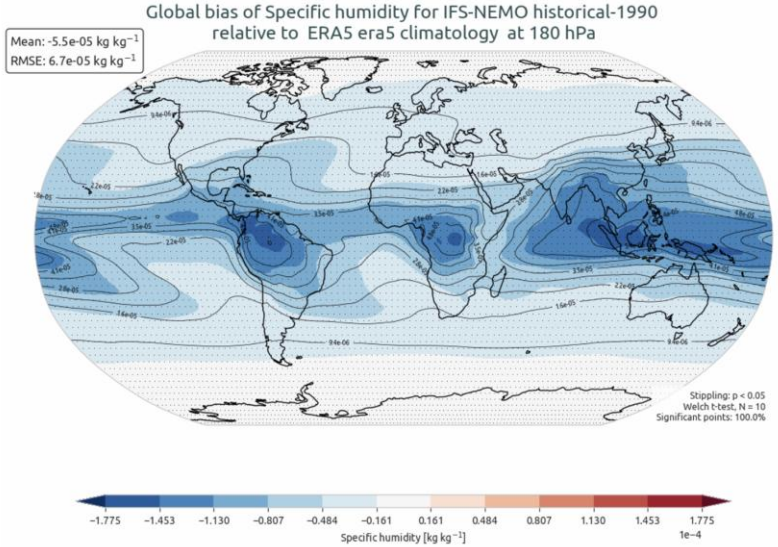
GitHub repo: https://github.com/DestinE-Climate-DT/AQUA
Preprint: https://doi.org/10.5194/egusphere-2026-1115

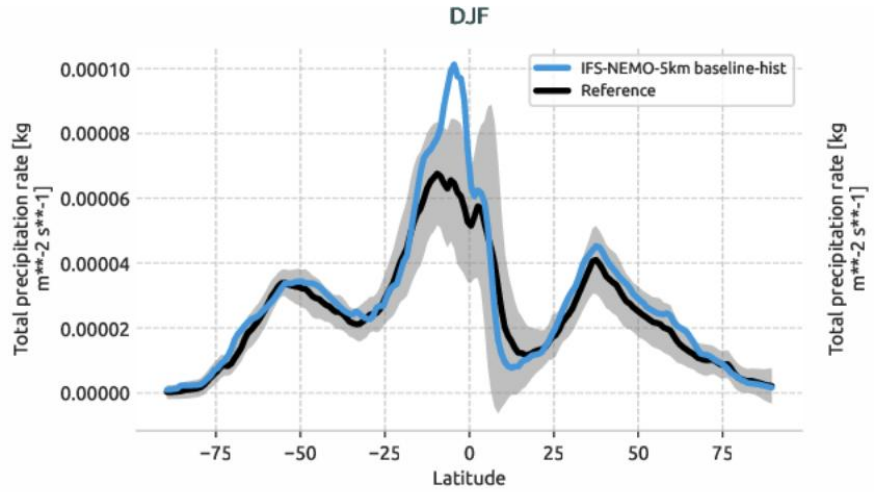
Funded by the European Union Destination Earth implemented by ECMWF esa EUMETSAT

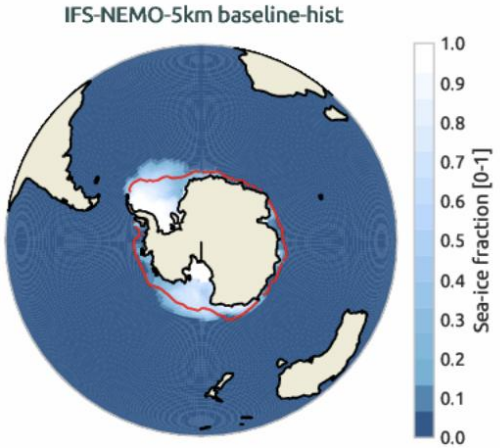
AQUA-DIAGNOSTICS

Set of diagnostic tools based on AQUA-core that can be combined for different scientific analyses:

Timeseries, Global Biases, Teleconnections, Performance Indices, Trends, Ocean drifts and stratification, Latitude-Longitude profiles, Boxplots, Histograms, Sea Ice



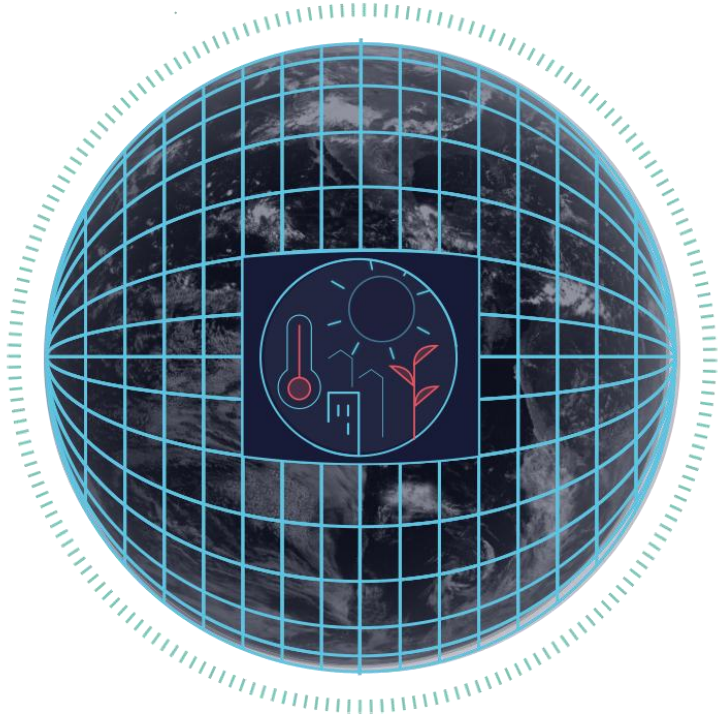




Real Time Monitoring: In the ClimateDT diagnostics are run automatically while the simulation is running and published real-time on a dedicated Dashboard

GitHub repo: https://github.com/DestinE-Climate-DT/AQUA-diagnostics
Paper in preparation

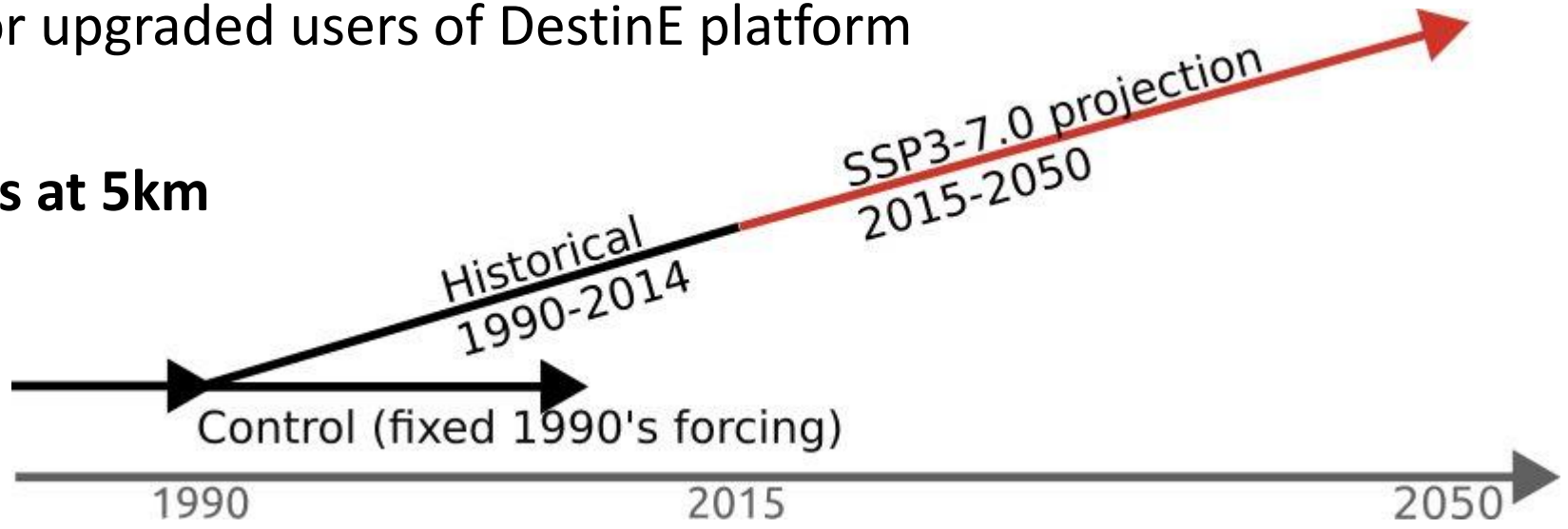
RESULTS FROM THE FIRST OPERATIONAL SIMULATIONS



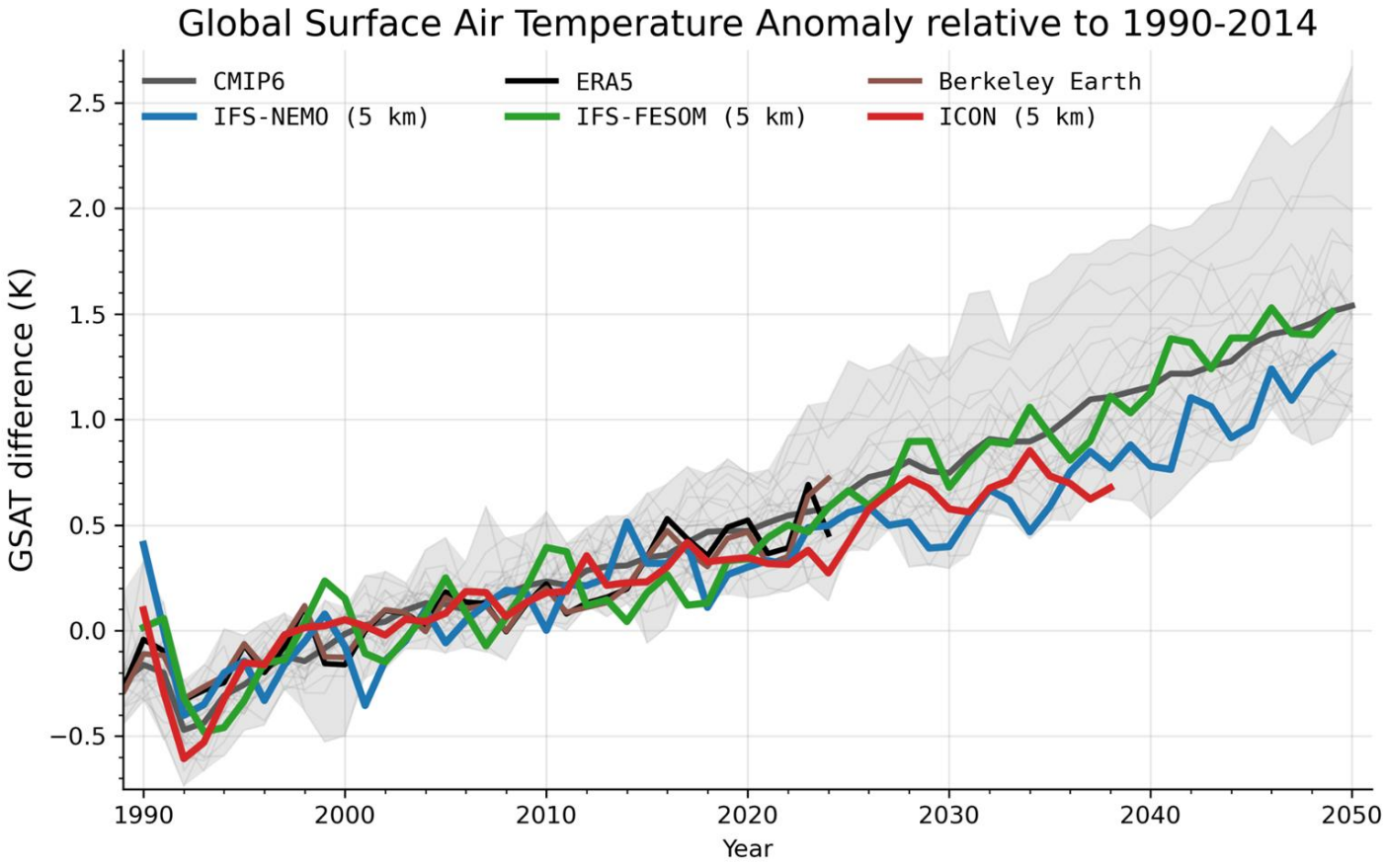
GENERATION 2 SIMULATIONS

- Coupled ocean and atmosphere
- Three models: IFS-FESOM, IFS-NEMO, ICON
- Using CMIP6 forcings
- Data are available for upgraded users of DestinE platform

Multi-decadal simulations at 5km with all models:

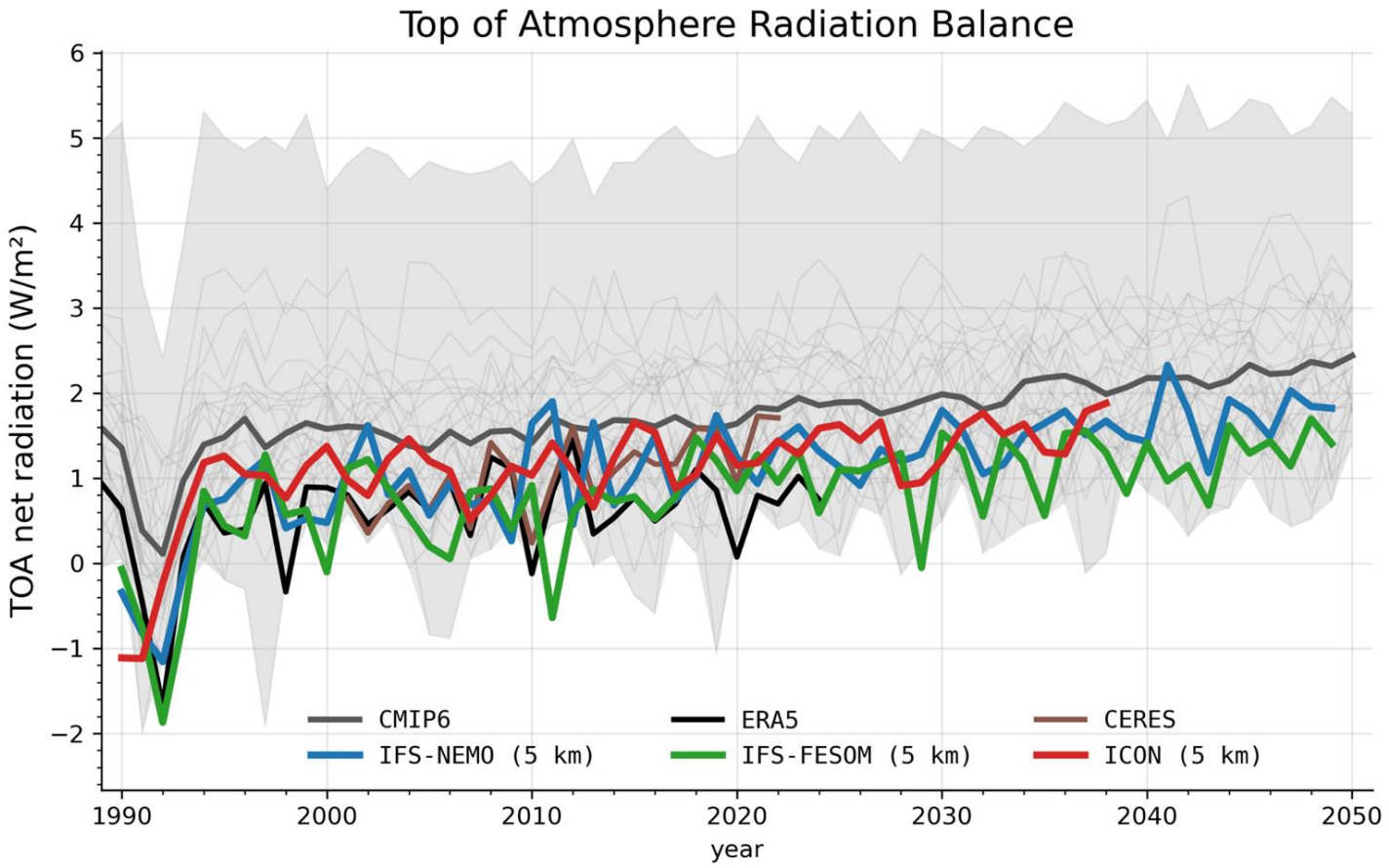


TIMESERIES



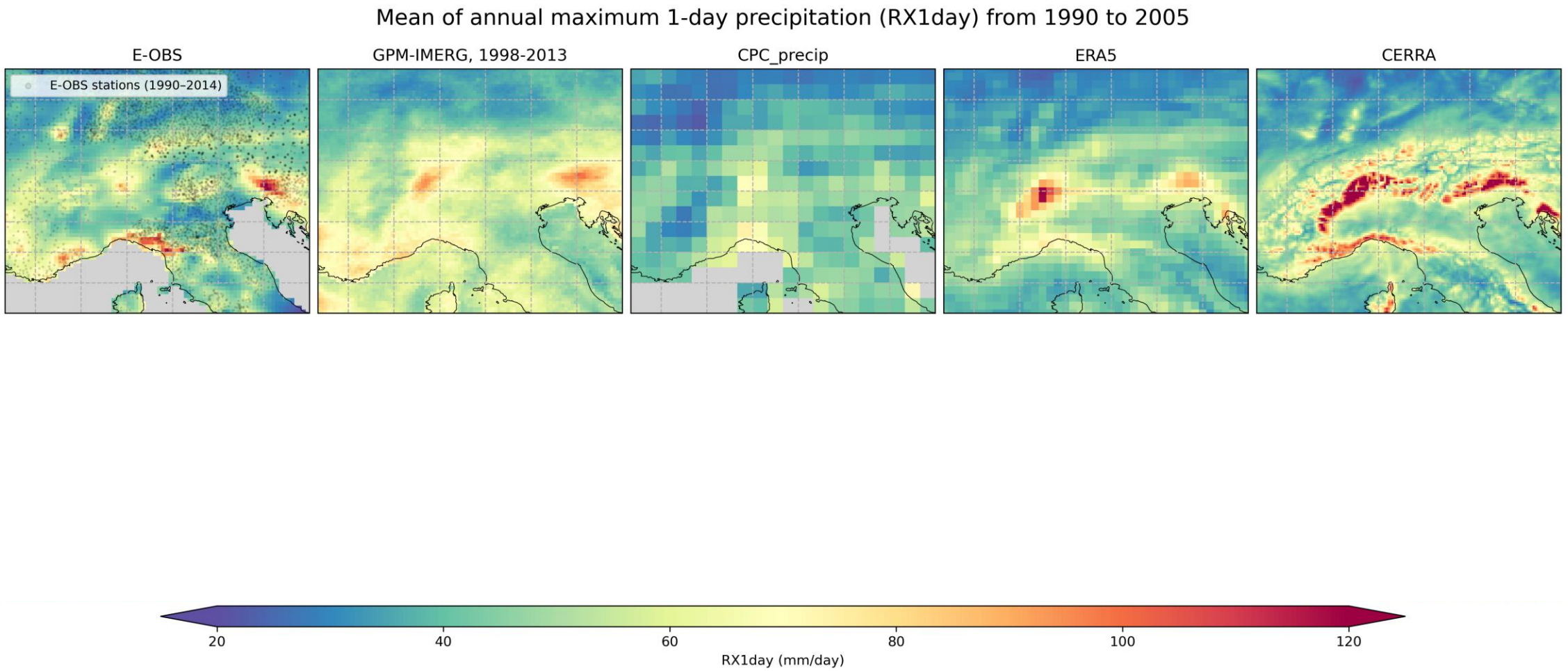
- IFS-FESOM follows closely the warming rate of the CMIP6 multi-model mean.
- IFS-NEMO and ICON show a warming rate at the lower end of the CMIP6 ensemble.

TIMESERIES

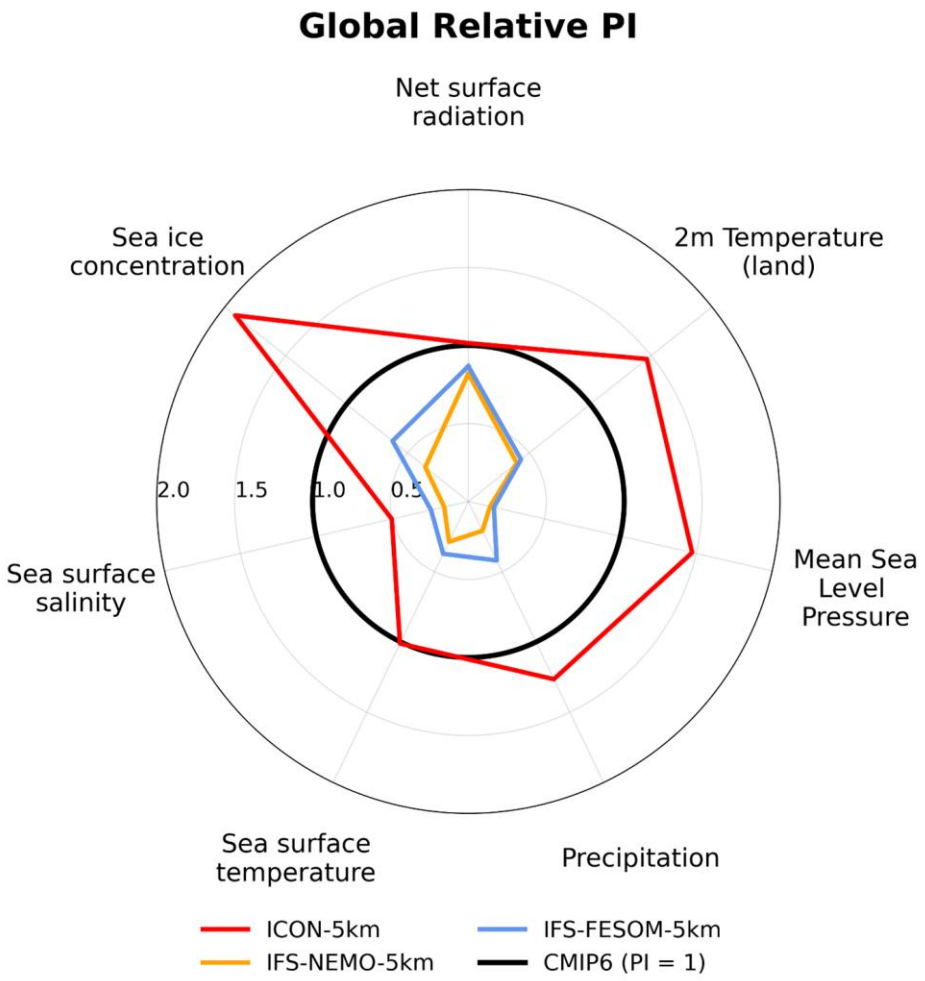


- CERES satellite observations indicate a TOA imbalance of around 1 W m^{-2}.
- Many CMIP6 models exceed this value (grey shaded area in the figure)
- The three ClimateDT models well represent the TOA imbalance

LOCAL GRANULARITY – extreme rainfall



PERFORMANCE INDICES



Reichler and Kim (2008) Performance Indices (PI).
They provide a measure of the climate mean state of the model evaluating several 2D variables against observations

PIs can be **normalized** toward an "average" value which in our case is CMIP6 **model multi model mean**.

We run PI on the **historical runs** to provide a comprehensive assessment.

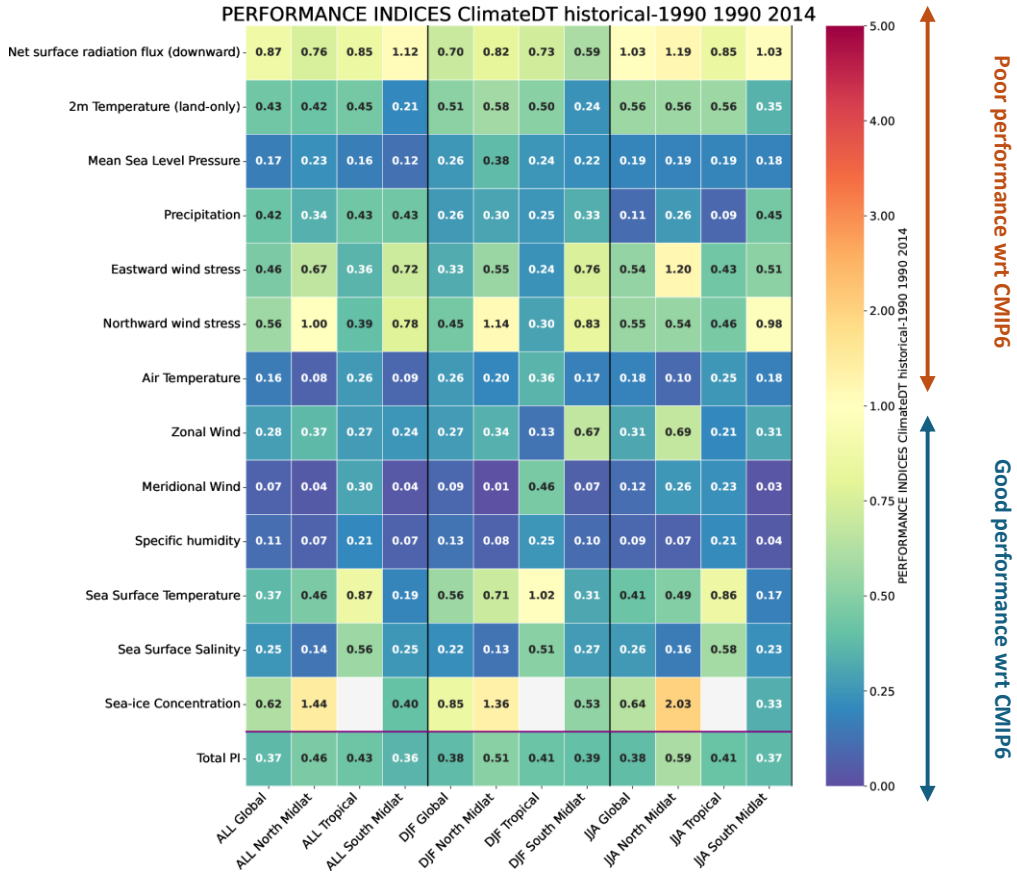
$$\sum \frac{\text{Model climatology} - \text{Observation climatology}}{\text{Observation variance}}$$

PI < 1: the model is doing a good job compared to CMIP6 models

PI > 1: the models is doing worse than the average of CMIP6 models

PERFORMANCE INDICES

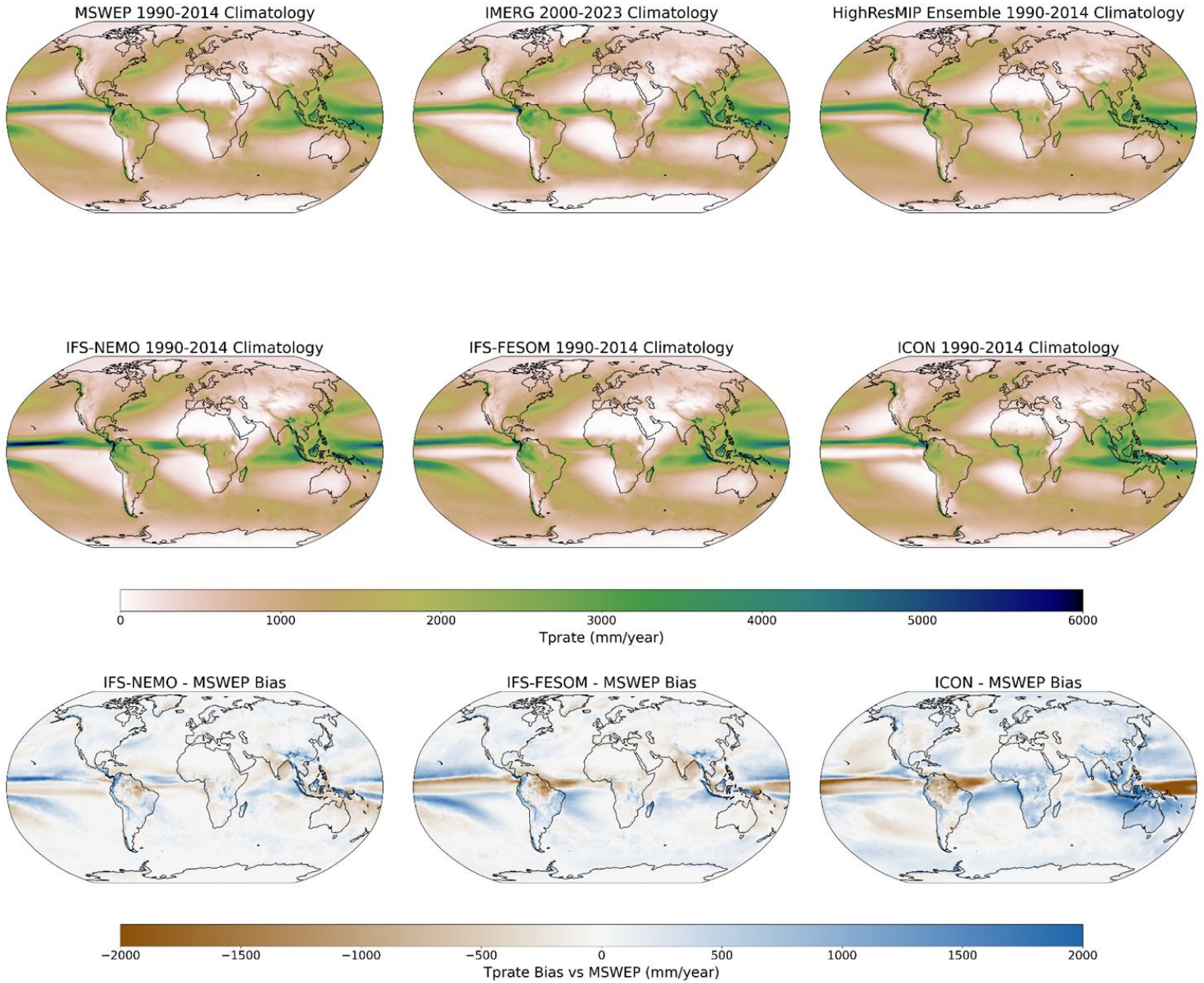
IFS-FESOM vs CMIP6



The Performance Indices evaluation is part of the automatic monitoring provided by AQUA.

PRECIPITATION BIAS

- **IFS-NEMO** and **IFS-FESOM**: good performance.
- Double ITCZ or ITCZ displacement in the tropical pacific.
- **ICON**: double ITCZ structure in the Pacific
- Shift of the Atlantic rainband reduces precipitation over the Amazon

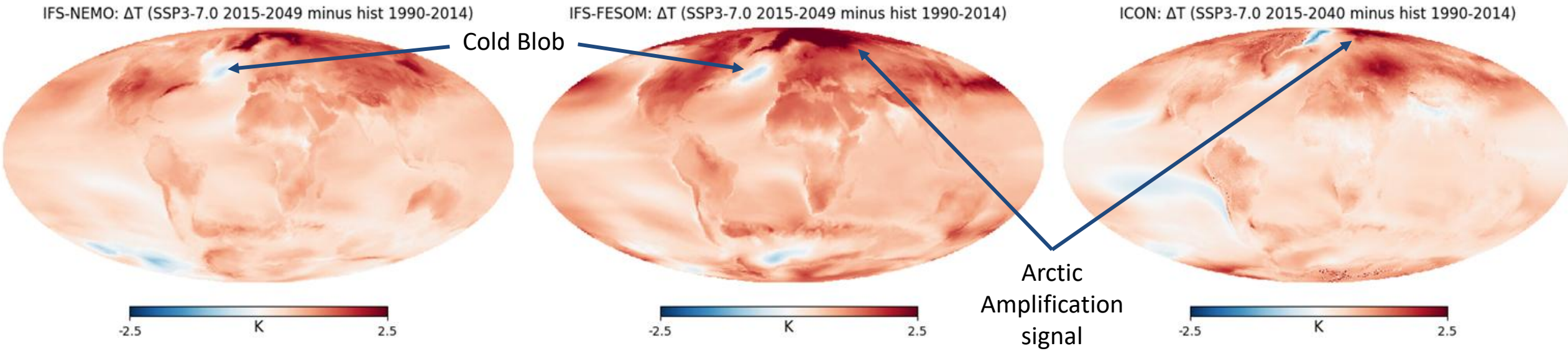


TEMPERATURE TREND

IFS-NEMO

IFS-FESOM

ICON

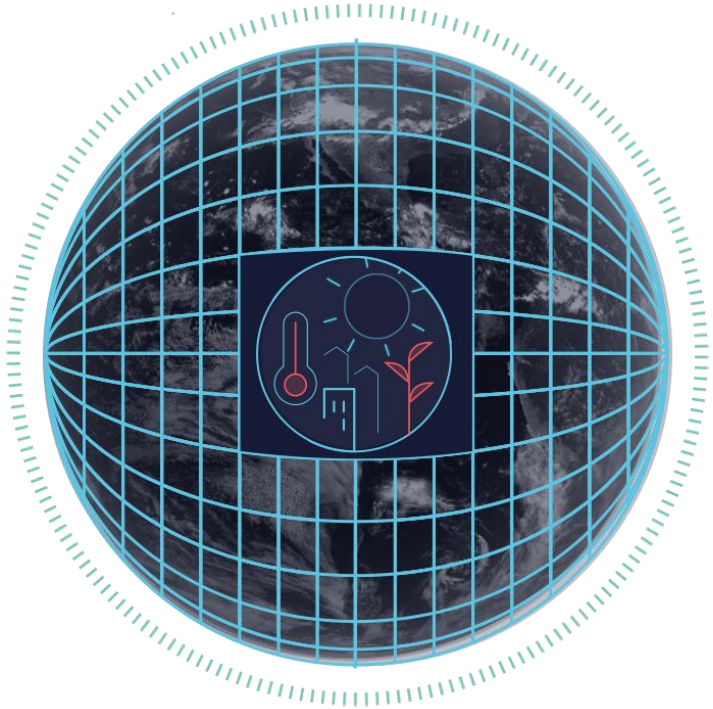


Temperature differences between the historical (1990-2014) and the scenario SSP3.7-0 (IFS-NEMO and IFS-FESOM 2015-2049; ICON 2015-2040) for all models.

MORE INFO ON DATA ACCESS AND MODEL EVALUATION

- A landing page for the climateDT is available at https://platform.destine.eu/climate-dt/
- A **climateDT user guide** is also available, containing more details on model evaluation and how to access the Generation 2 data. https://platform.destine.eu/services/documents-and-api/doc/?service_name=climate-dt-user-guide
- Upgraded users can check the Evaluation chart, showing the scientific quality assessment diagnostics produced by AQUA during the online monitoring.

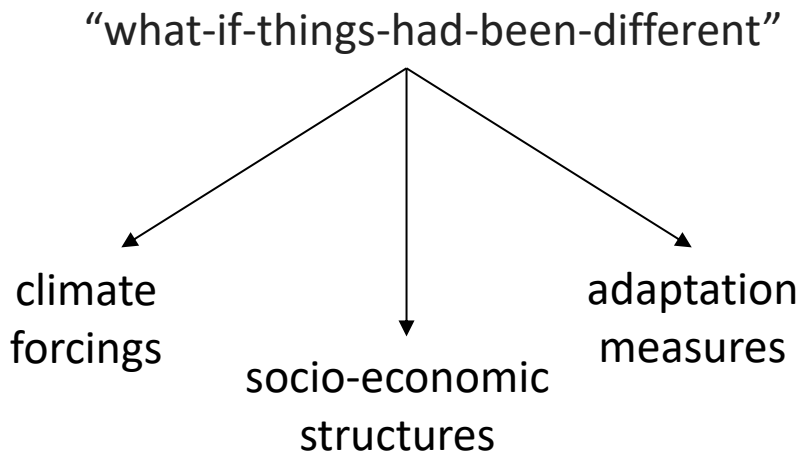
STORYLINE SIMULATIONS



CLIMATE STORYLINES

A physically self-consistent unfolding of past events, or of plausible future events or pathways

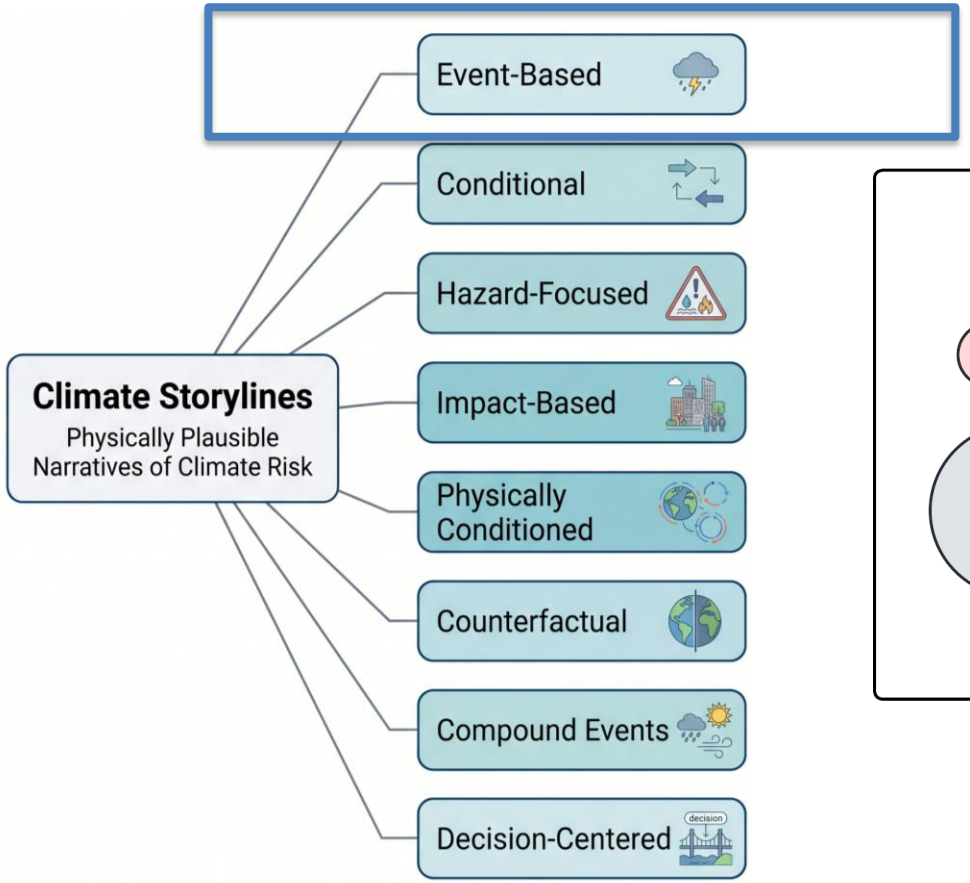
- Shepherd, 2018

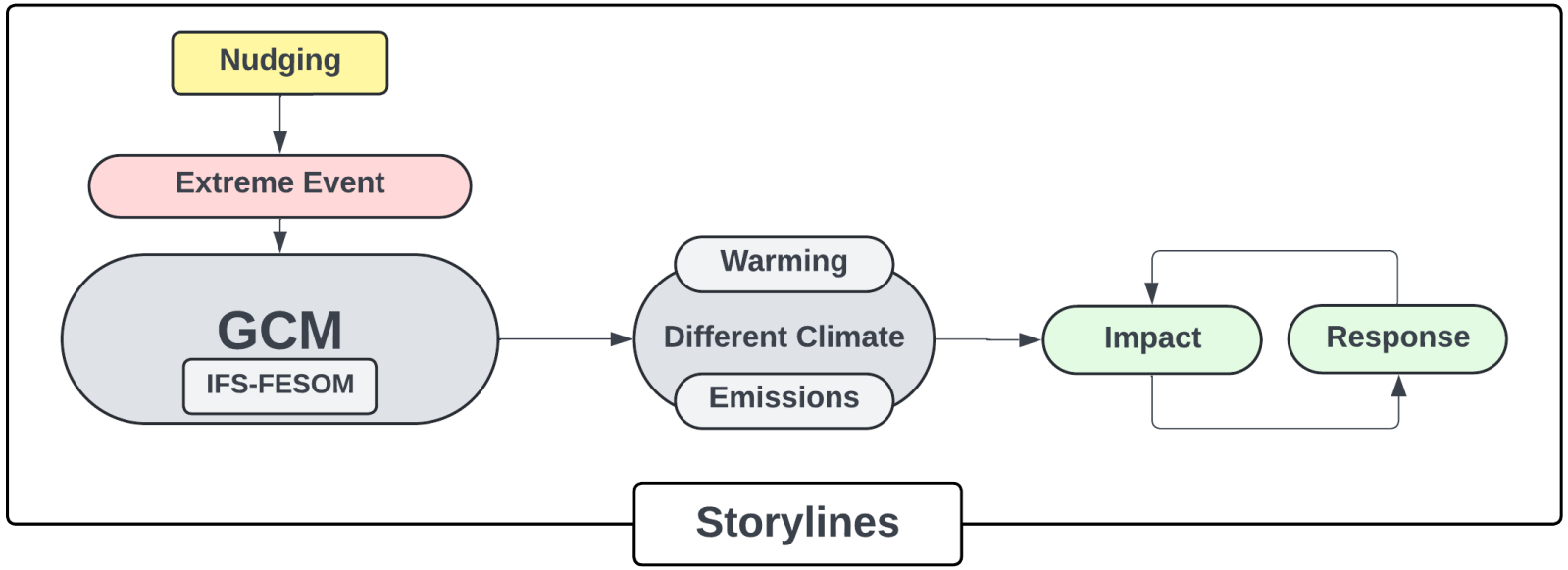


Storylines make the climate change information

Meaningful | Tangible | Engaging

TYPES OF STORYLINES



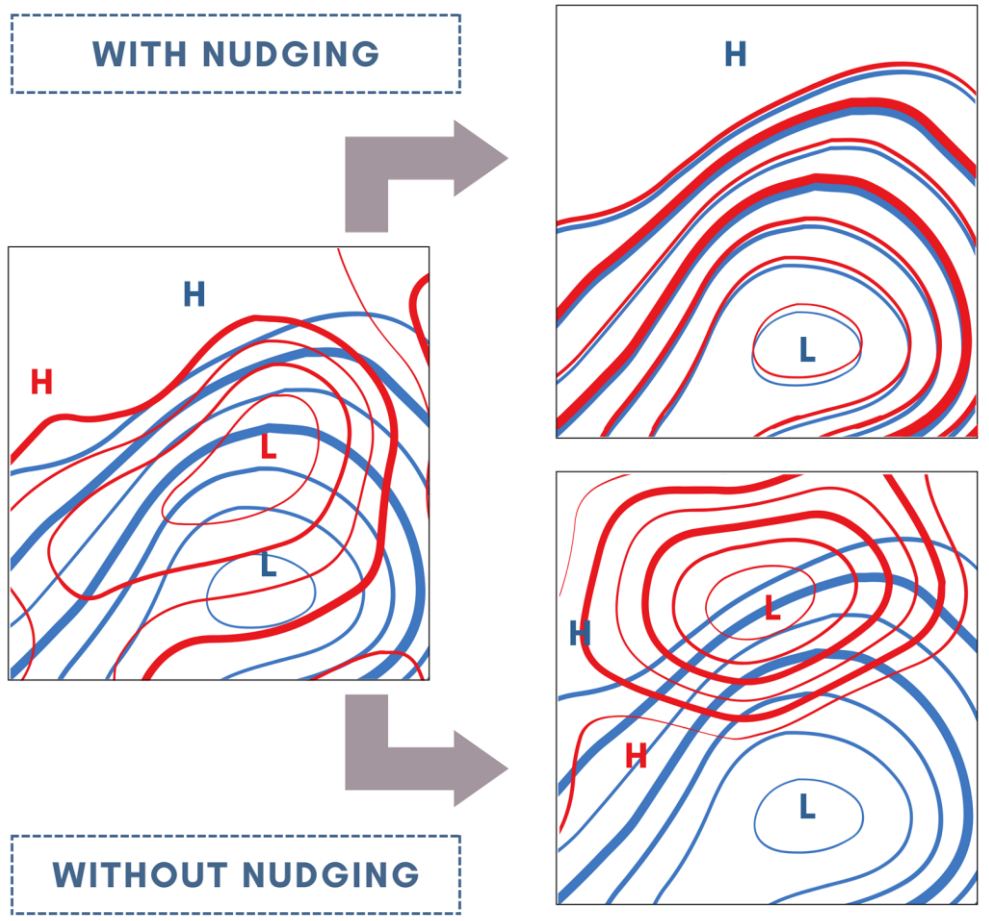


NUDGING

Nudging constrain the large scale model dynamics to follow a reference data

The reference data can be an observational product or reanalysis data.

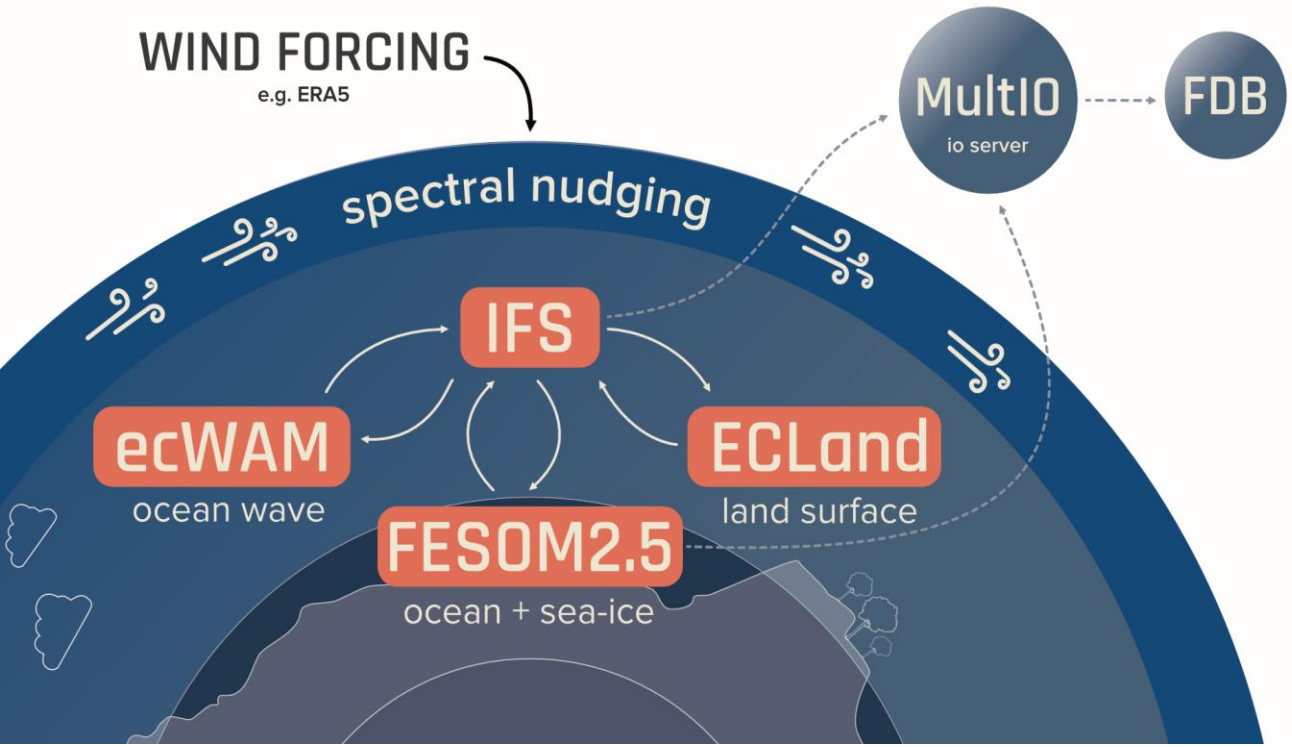
eg., ERA5



keeps large-scale weather patterns close to real data

weather patterns deviate from real-world data

THE APPPROACH: COUPLED IFS-FESOM



John, A., et al. (2026)

Our storyline framework global coupled setup:

- **Global Atmosphere (IFS):**
  - **TCo1279** octahedral grid, achieving a nominal resolution of **≈9 km** globally.
- **Global Ocean (FESOM2):**
  - **Unstructured NG5** multi-resolution grid ranging from **12 km** down to **4.5 km**

- **Vorticity and divergence** are constrained upto **T60** between model levels **between 100 and 700 hPa** with **e-folding time of 1 hr**

- Only large-scale atmospheric circulation is constrained while **thermodynamic and small-scale dynamical processes evolve freely**

CLIMATE DT STORYLINES COVER ALL EVENTS BETWEEN 2017-2025

Cont (a.k.a control, circa 1950)

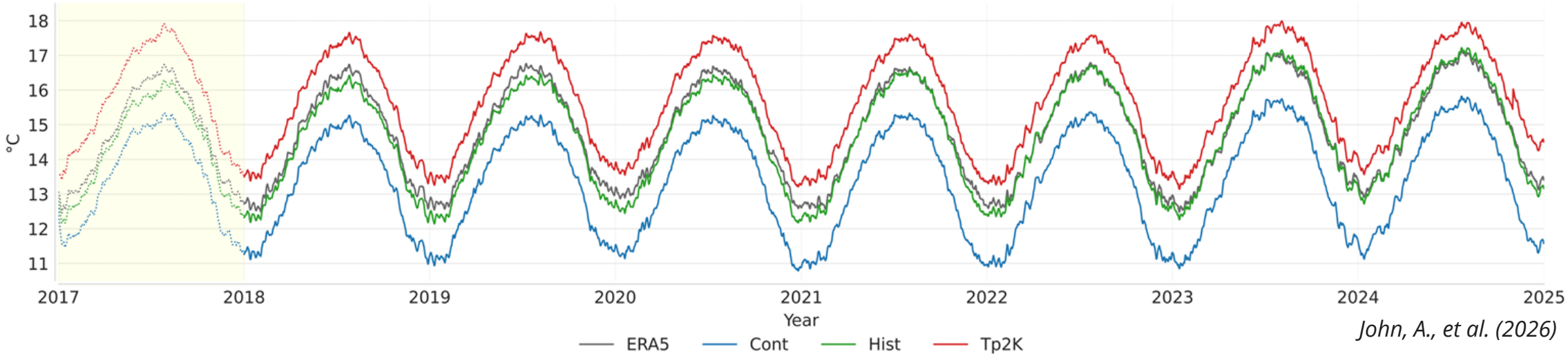
Hist (a.k.a historical, present day)

Tplus2.0K (a.k.a 2K, circa 2050)-

BOUNDARY CONDITIONS (FORCING)	INITIALIZATION (ATM & OCEAN)	
	Atmosphere	Ocean
CMIP6-historical	EERIE 1950	EERIE 1950
Fixed (1950)		
CMIP6-SSP245	EERIE 2017-01-01	EERIE 2017-01-01
Transient (2017-2024)		
CMIP6-SSP245	EERIE 2050-01-01	EERIE 2050-01-01
Fixed (2050)		

Additional experiments, Tplus3.0K, Tplus4.0K -planned

5 Ensemble members each



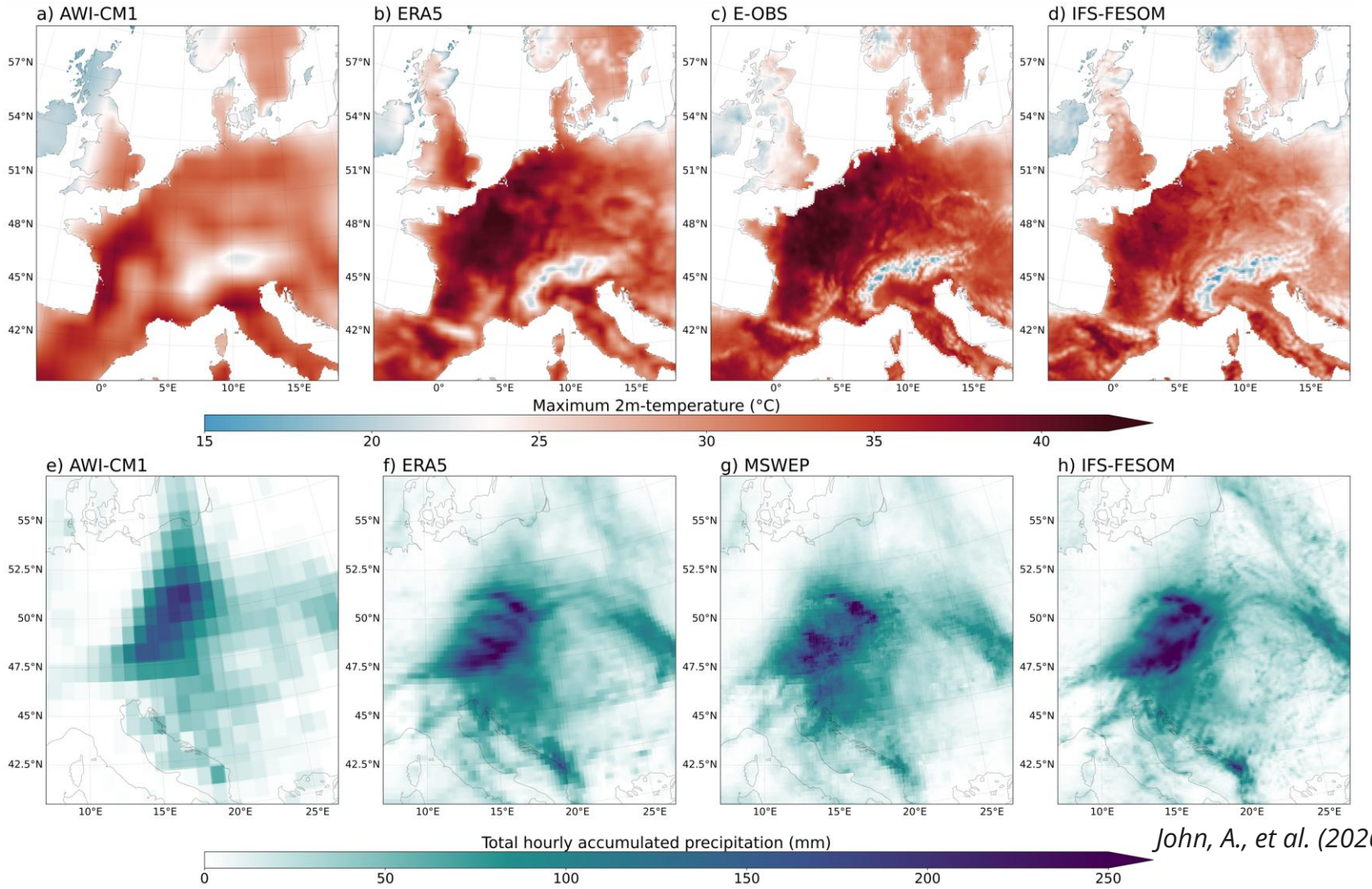
John, A., et al. (2026)

All are nudged -> same weather events at different climate

CAPTURING EXTREMES

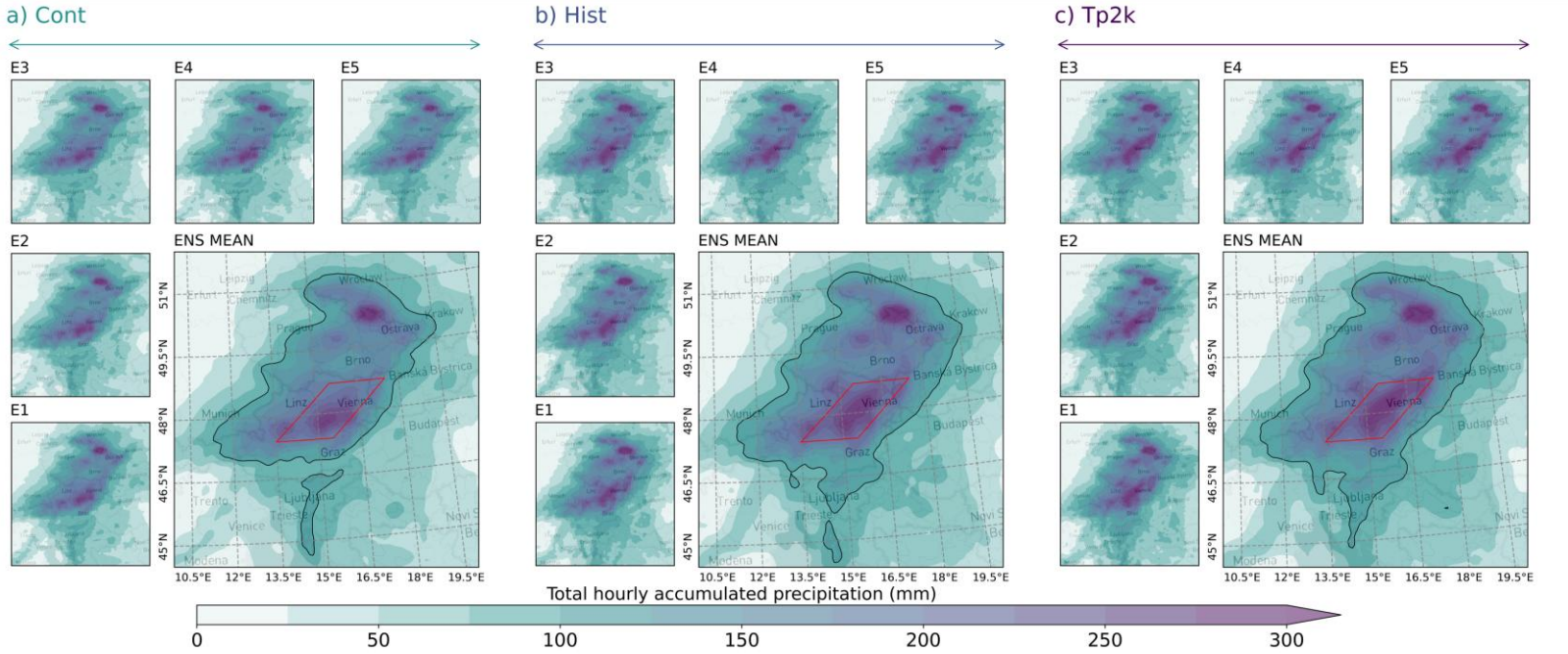
Paris heatwave: 2019

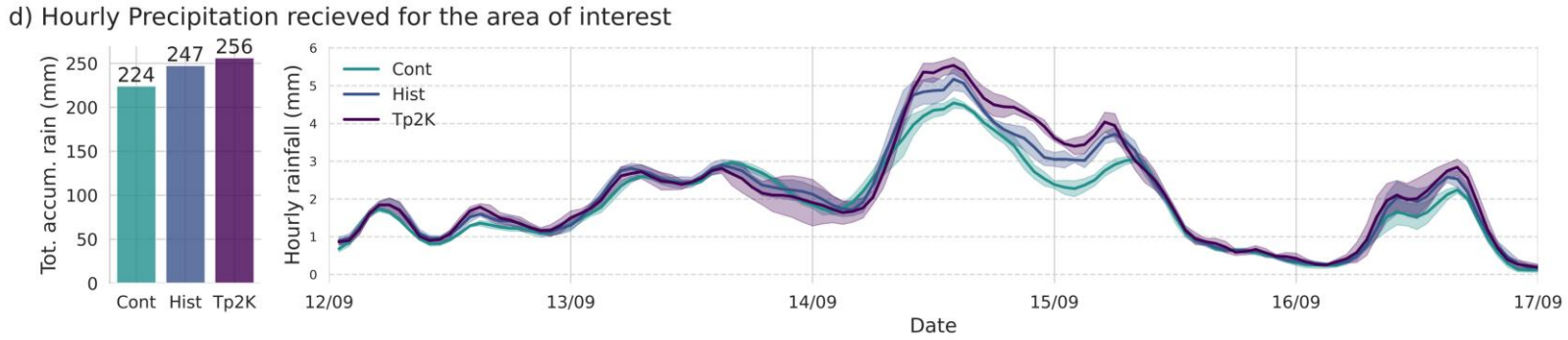
Storm Boris: 2024



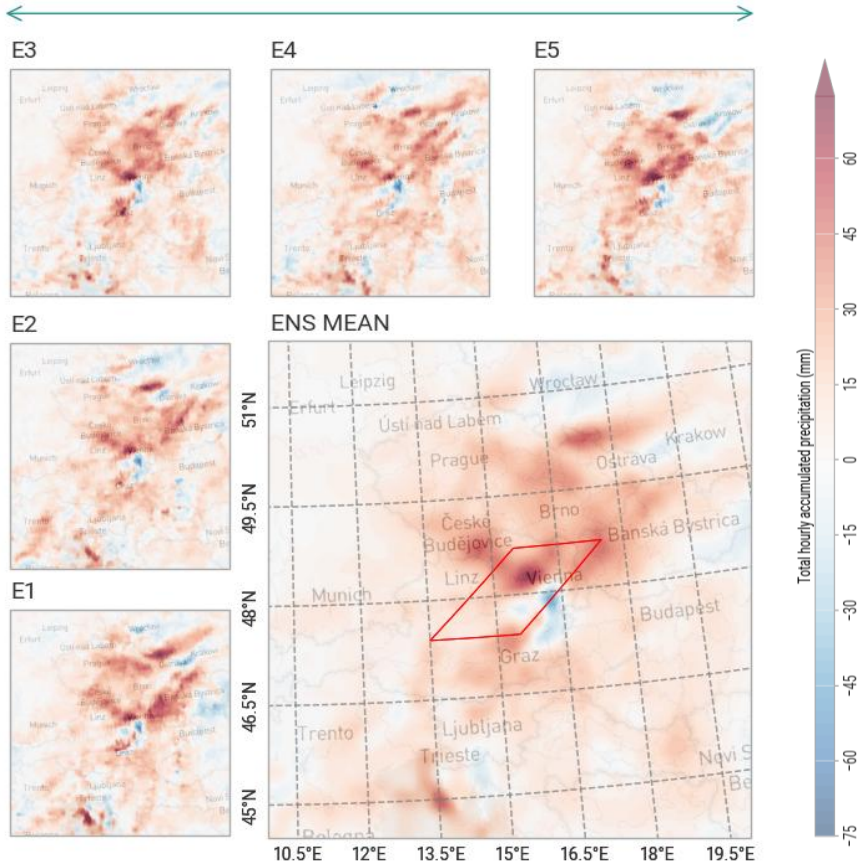
John, A., et al. (2026)

STORYLINES: BORIS IN DIFFERENT CLIMATES





How does it change?



John, A., et al. (2026)

WHY THIS MATTERS?

"Storylines unravel the 'DNA' of high-impact disasters"

They illustrate how climate change alters extreme events, enabling to contextualise specific event intensification to anthropogenic forcing and the plausible effects.

"Not just the 'what,' but the 'why' and 'who' of disasters."

Climate storylines translate climate data into tangible "what-if" narratives, making the risks relatable.

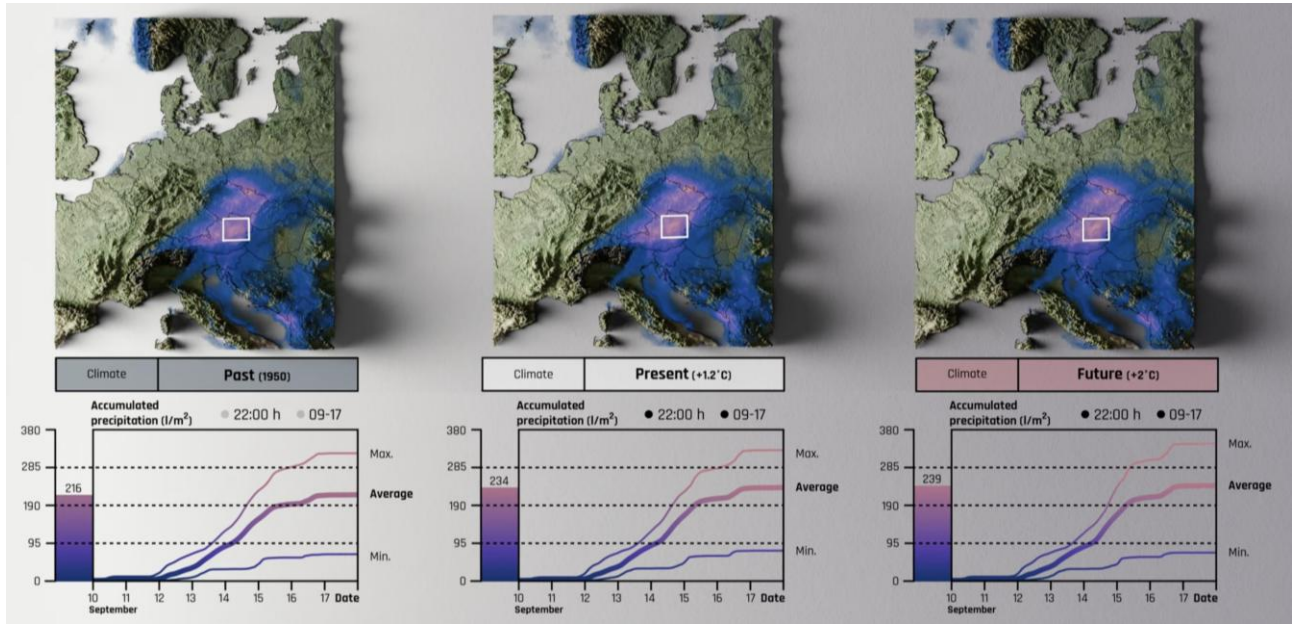


Illustration by Jan Wehner

Building a Catalogue :
A future-ready resource that allows users to explore how specific extreme events may change

ACCESS THE DATA & PUBLICATION

JAMES | Journal of Advances in Modeling Earth Systems

RESEARCH ARTICLE
10.1029/2025MS005326

Global Kilometer-Scale Climate Storylines Using Spectral Nudging

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Key Points:

- Combines the storylines approach using spectral nudging with km-scale modeling
- km-scale storylines deliver localized and granular information on extreme events

Supporting Information:

Supporting Information may be found in the online version of this article.

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CLIMATE DIGITAL TWIN – MORE INFORMATION

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https://doi.org/10.5194/gmd-19-2821-2026

Geoscientific Model Development Open Access EGU

The Destination Earth digital twin for climate change adaptation

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Data access & user guide on DestinE platform: