DESTINATION EARTH

DIGITAL TWINS OF THE EARTH SYSTEM

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WGNE, November 2022

Funded by the European Union

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EU's Destination Earth (DestinE) initiative

Towards a Digital Twin Earth

Entrusted entities

ECMWF esa EUMETSAT

Key elements

- Digital Twin Engine
- Digital Twins
- Data lake
- Core platform

A European Green Deal (2019)

A European strategy for data (2020)

Shaping Europe's digital future (2020)

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2021-2023

- Operational cloud-based platform
- First two digital twins

2023-2025

Platform integrates the next operational digital twins and offers services to public sector users

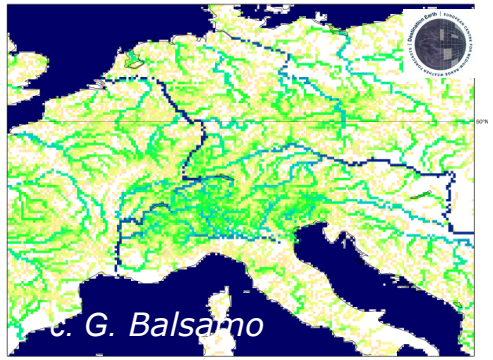
2025-2027+

Towards a full "digital twin of the Earth" through a convergence of multiple digital twins on the platform

Funded by the European Union

DestinE's Digital Twins: Quality + Impacts + Interaction

1. **Better simulations** based on **more realistic models**
2. **Better ways of combining all observed and simulated information** from entire Earth system = physical + food/water/energy/health **supporting action scenarios**
3. **Interactive and configurable access to all data, models and workflows**



More realistic at *global* scale

More realistic at *local* scale

Include impacts where they matter

Trial different adaptation and mitigation scenarios

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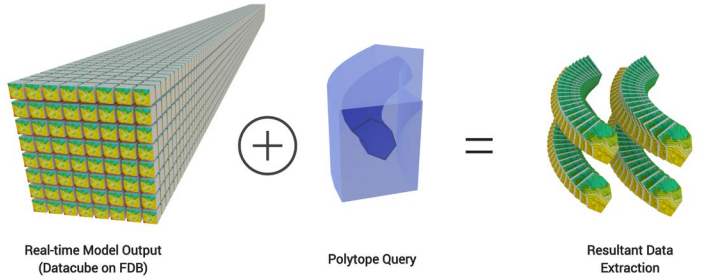
DestinE's Digital Twins: functionalities



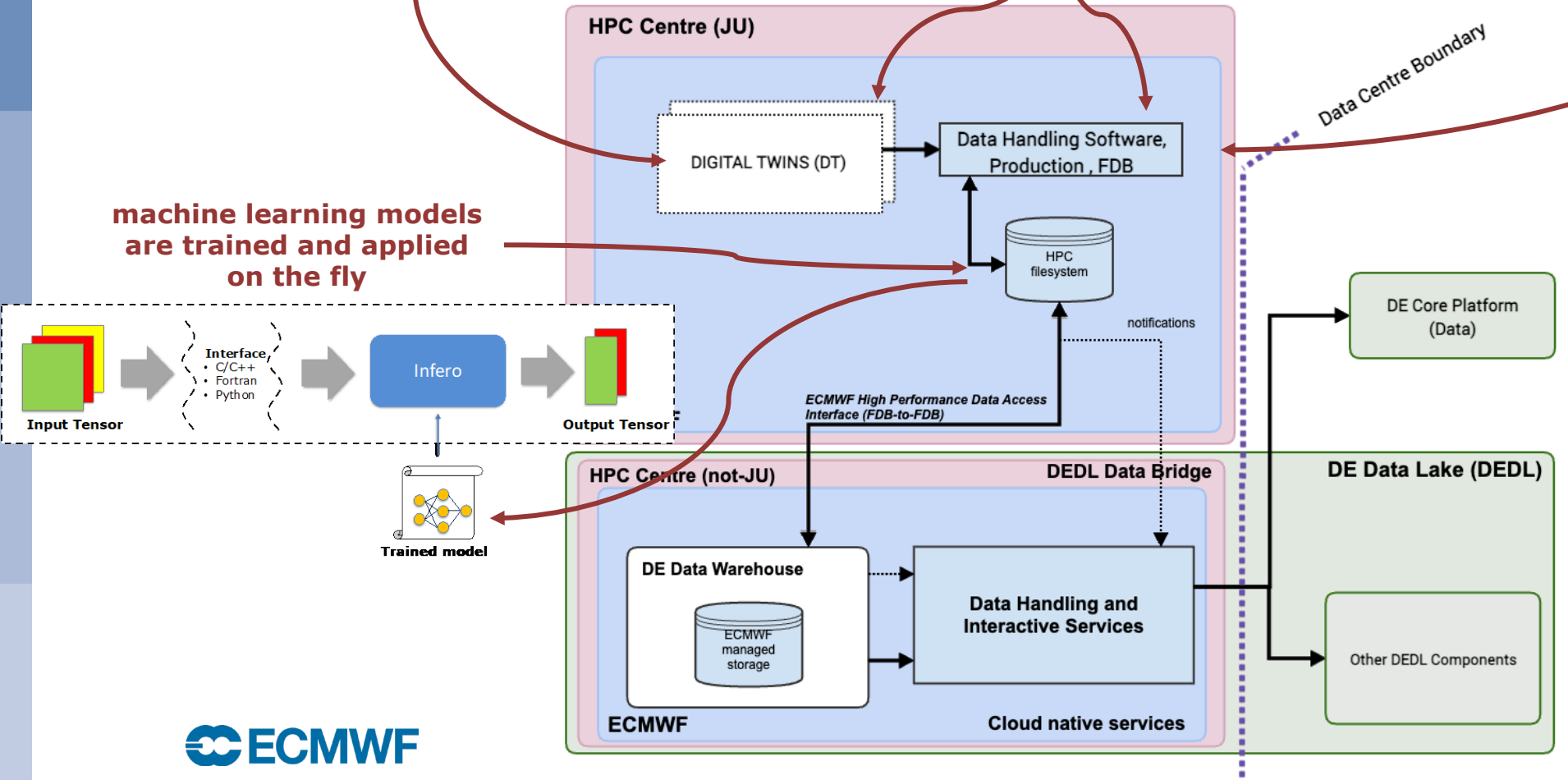
data is streamed at full 4D-resolution and coupled with applications (water, food, energy) on the fly

simulation-observation production can be run in continuous or on-demand modes
(and deployed across distributed HPC)

applications can operate in fully immersive data spaces

machine learning models are trained and applied on the fly

Workflows incl. models and observations can be configured



Data handling architecture becomes scalable

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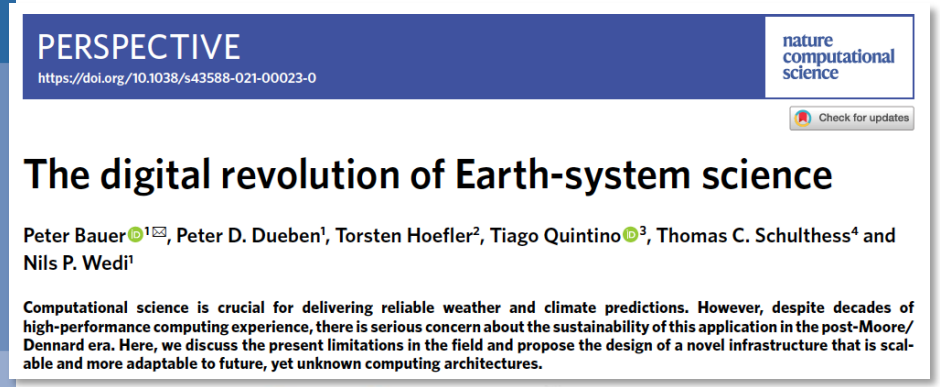
DestinE's Digital Twins: need extreme computing



PERSPECTIVE
https://doi.org/10.1038/s43588-021-00023-0

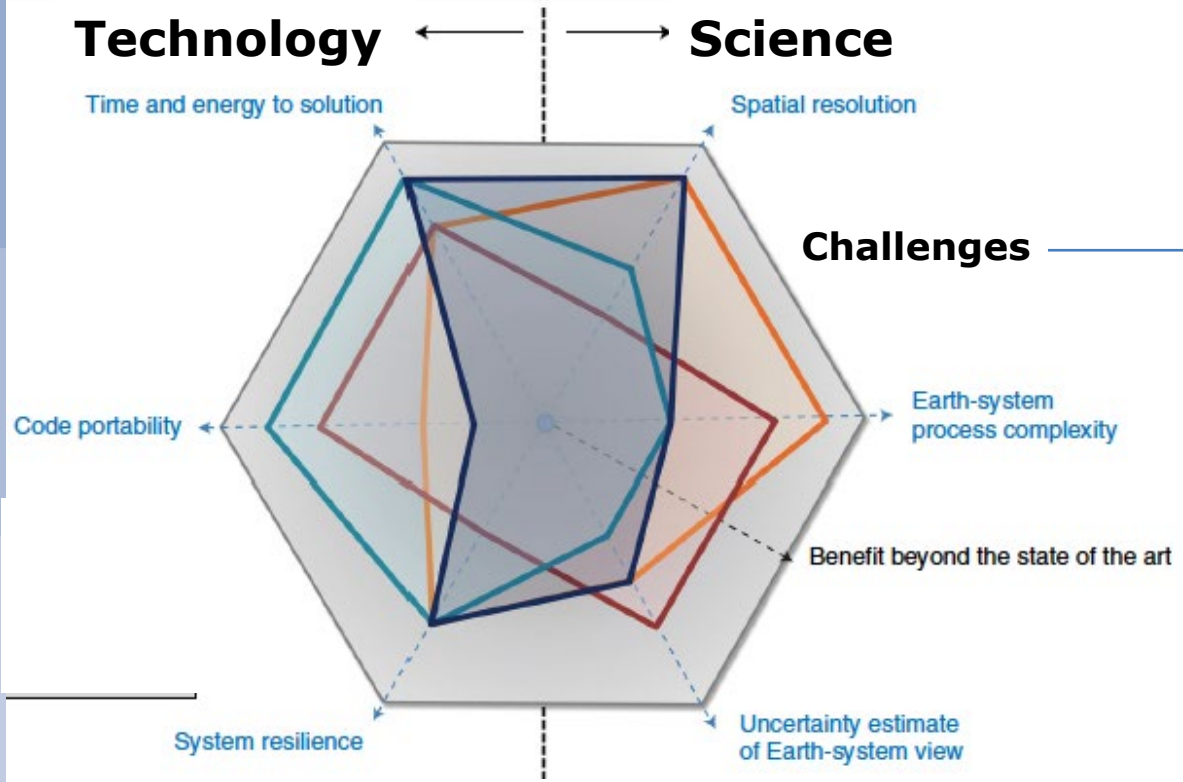
nature computational science

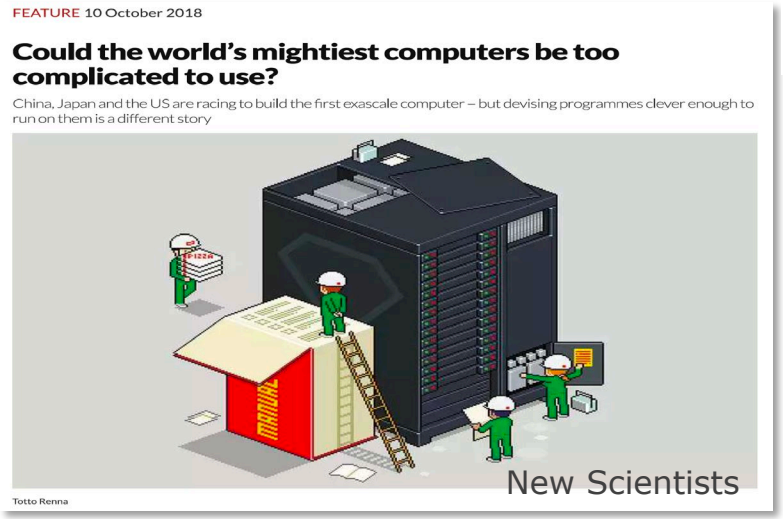
Check for updates

The digital revolution of Earth-system science

Peter Bauer[1], Peter D. Dueben[1], Torsten Hoefler[2], Tiago Quintino[3], Thomas C. Schulthess[4] and Nils P. Wedi[1]

Computational science is crucial for delivering reliable weather and climate predictions. However, despite decades of high-performance computing experience, there is serious concern about the sustainability of this application in the post-Moore/Dennard era. Here, we discuss the present limitations in the field and propose the design of a novel infrastructure that is scalable and more adaptable to future, yet unknown computing architectures.





FEATURE 10 October 2018

Could the world's mightiest computers be too complicated to use?

China, Japan and the US are racing to build the first exascale computer – but devising programmes clever enough to run on them is a different story

Totto Renna

New Scientists

Challenges → **Solutions**

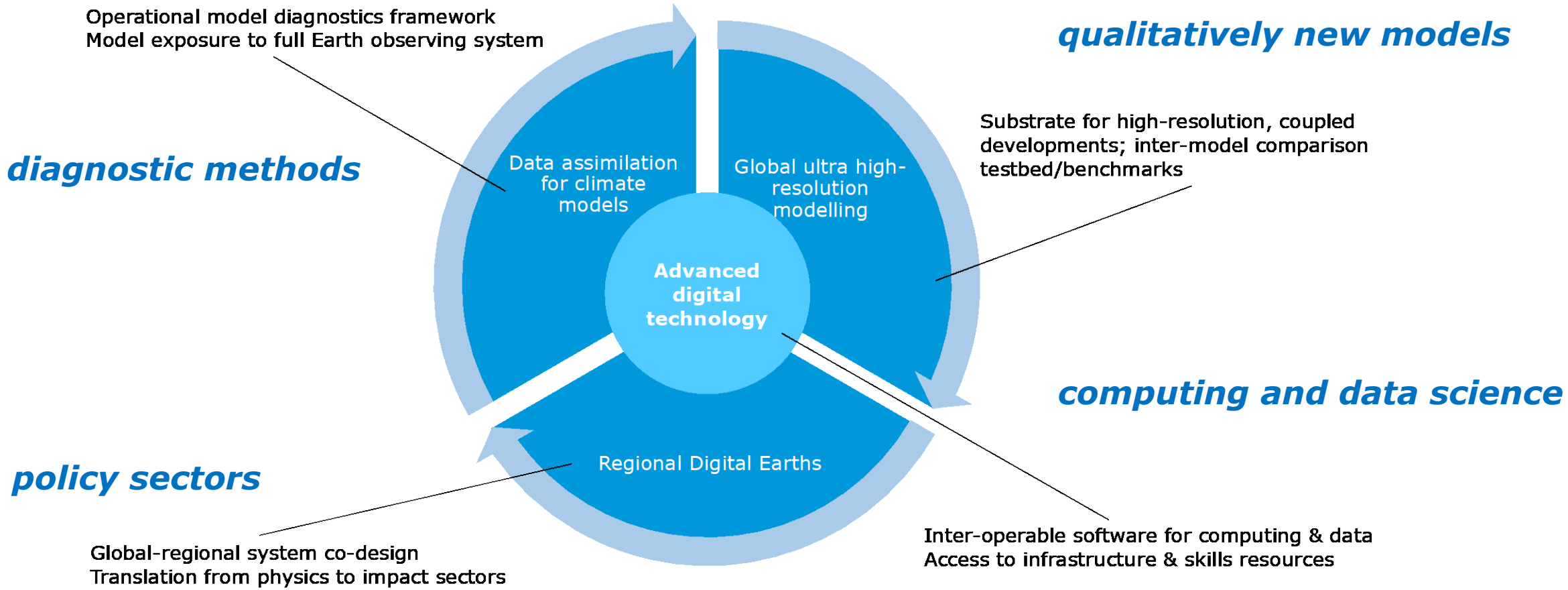
- Numerical methods, algorithms, data structures
- Machine learning
- Programming models
- Heterogeneous processing, memory, interconnect technology

EuroHPC Joint Undertaking

… make sure that technology is not running away from us!

DestinE's Digital Twins: build on increasing consensus

WCRP Lighthouse Activity 'Digital Earths'



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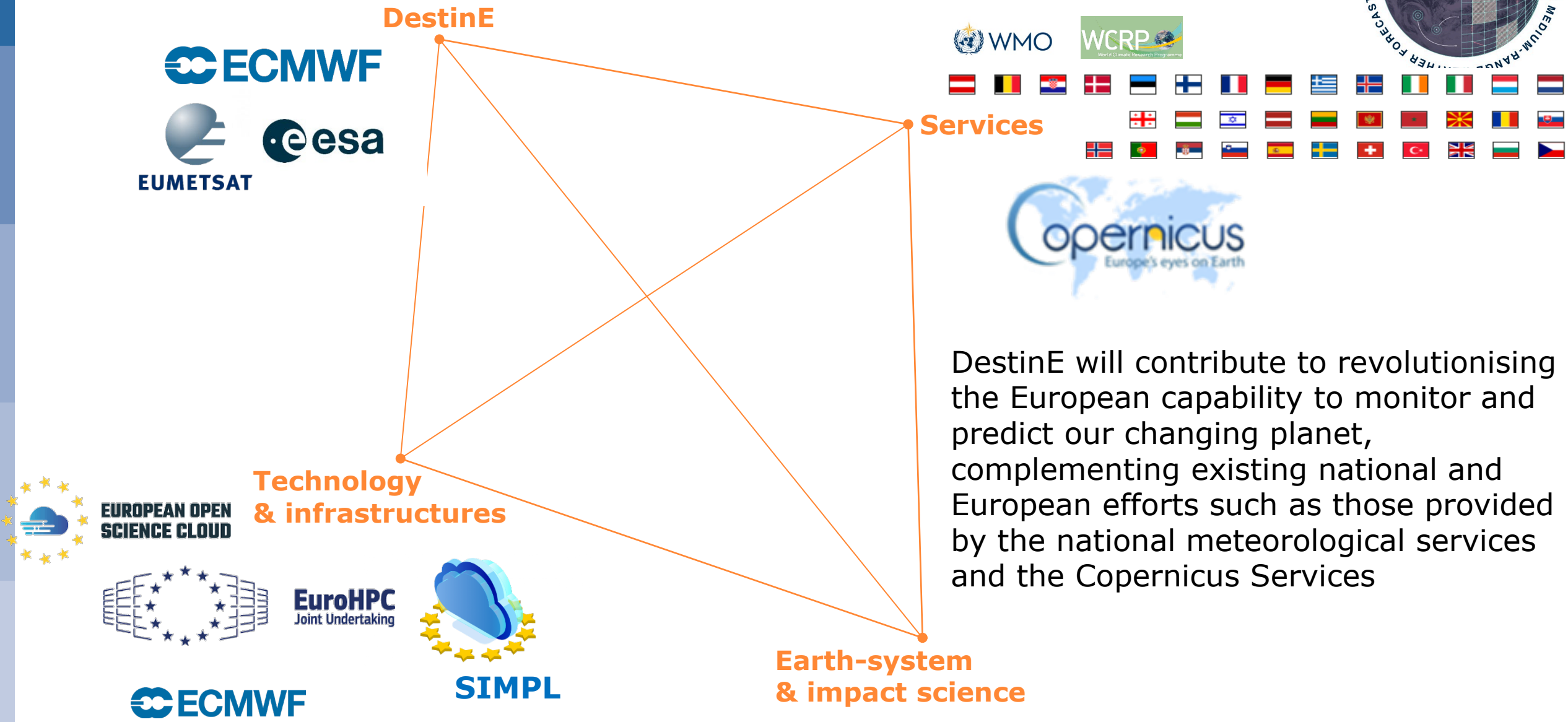
WMO

WCRP World Climate Research Programme

A service-science-technology synergy



DestinE will contribute to revolutionising the European capability to monitor and predict our changing planet, complementing existing national and European efforts such as those provided by the national meteorological services and the Copernicus Services

ECMWF's role in EU's DestinE initiative

Towards a Digital Twin Earth

ECMWF is responsible for the delivery of:

The DestinE **Digital Twin Engine** (DTE):

- common approach for a unified orchestration of Earth-system simulations and their fusion with observations, requiring **large-scale HPC** and data handling resources

Weather-induced and Geophysical **Extremes Digital Twin**:

- capabilities and services for the assessment and prediction of **environmental extremes**

Climate Change Adaptation **Digital Twin**:

- capabilities and services in support of climate change **adaptation policies and mitigation scenario** testing

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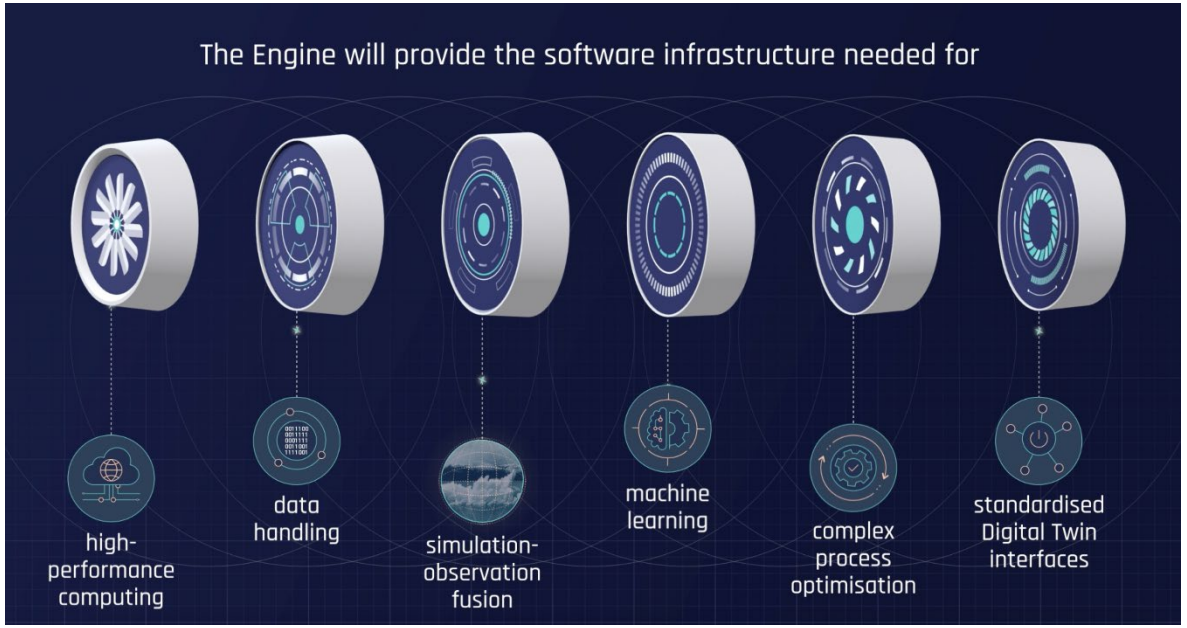
EuroHPC Joint Undertaking

Funded by the European Union

Digital Twin Engine: framework for Digital Twins workflows



- HPC adaptation /DT optimisation
- IO and data workflows
- Software management, controlling workflows, cloud environments, visualization
- Collection of API's and Services
- Opt-in initial components portfolio in DestinE

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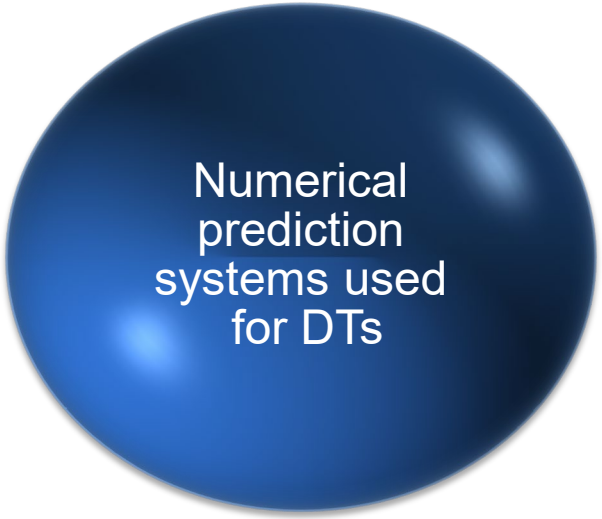
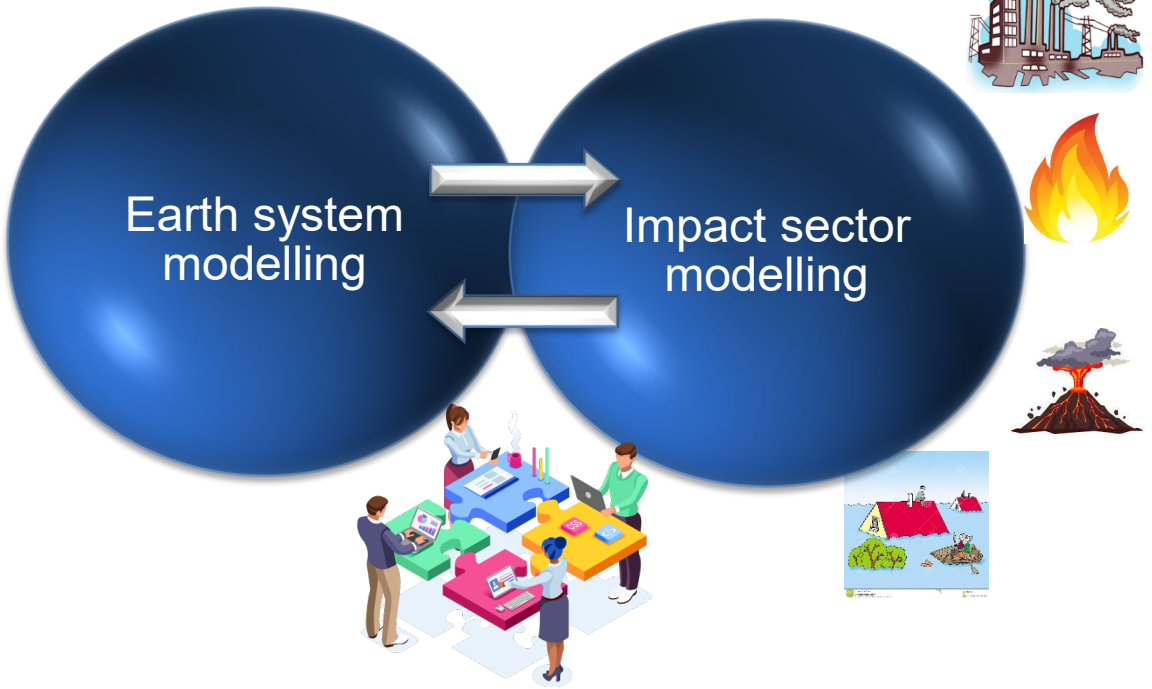
DestinE's Extremes and Climate Digital Twins: scientific vision

Stronger convergence of weather & climate prediction systems



Shared infrastructure, data assimilation, km-scale resolution

Integrated Earth-system & impact-sector modelling



Codesign with users

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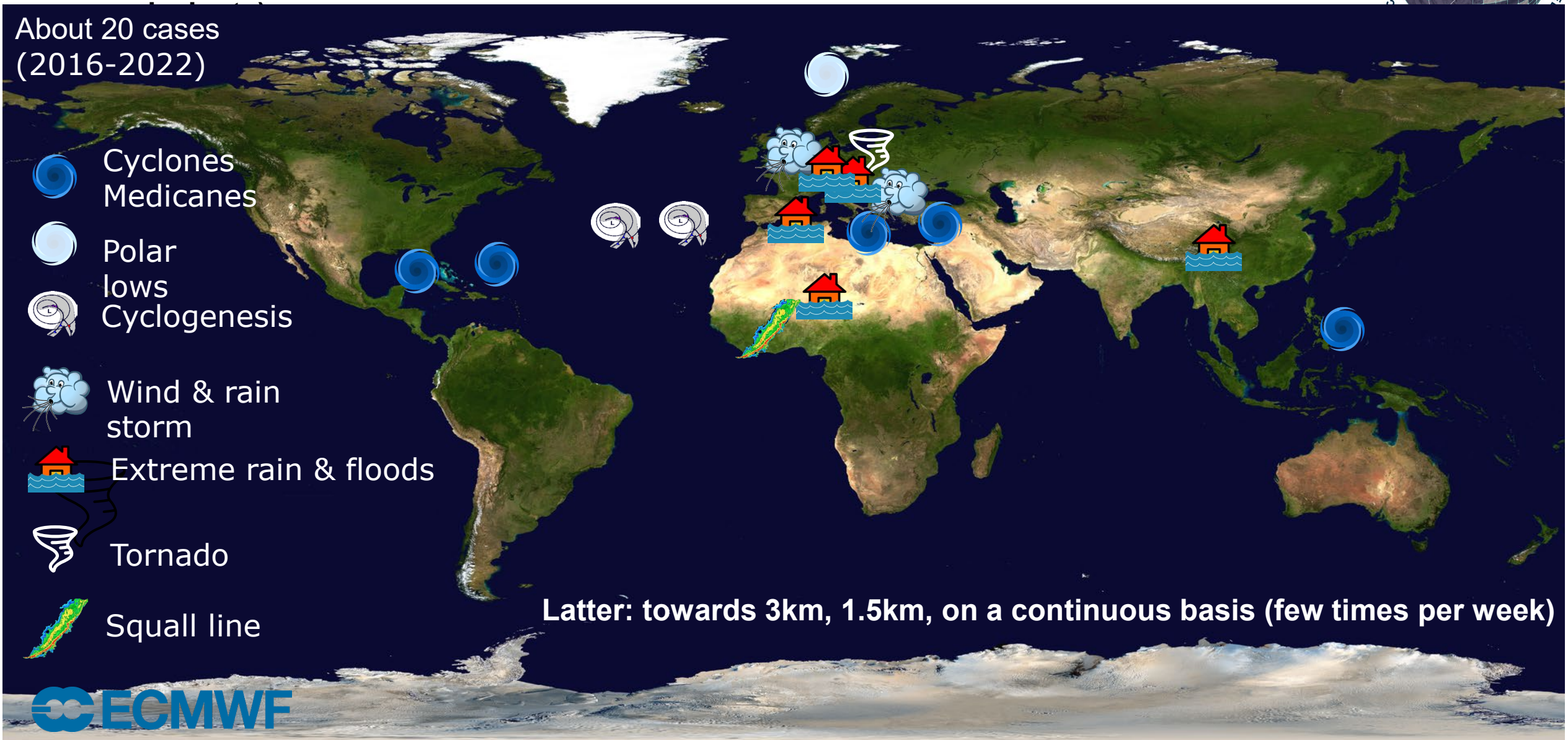
DestinE's Extremes and Climate Digital Twins: content

- Earth-system observation fusion/assimilation and initialization
- Earth-system modelling and simulations at storm-resolving scale, a few days ahead/multi-decadal
- On-demand/configurability
- Use cases for selected impact-sectors (water, air pollution, renewable energy, etc)
- Evaluation and uncertainty quantification
- Workflow set-up and monitoring on pre-exascale euroHPC systems
- End-to-end demonstration at scale with timely delivery

Continuous Extremes DT (ECMWF) – initial extreme events cases

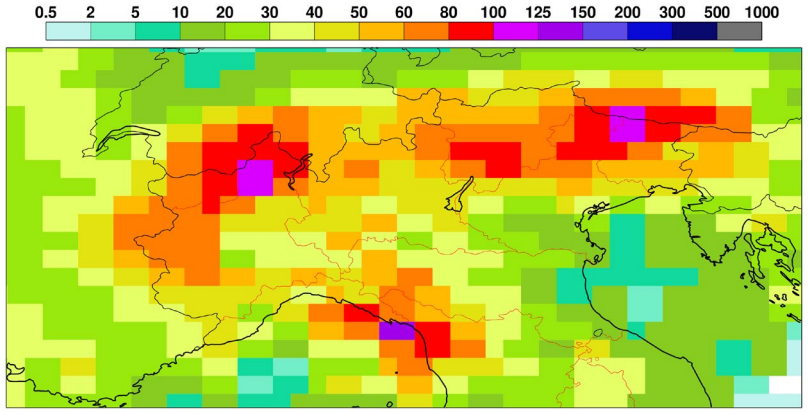
For now: 5 days global forecasts at 4.5 km with ECMWF IFS (and 9 and 29km)



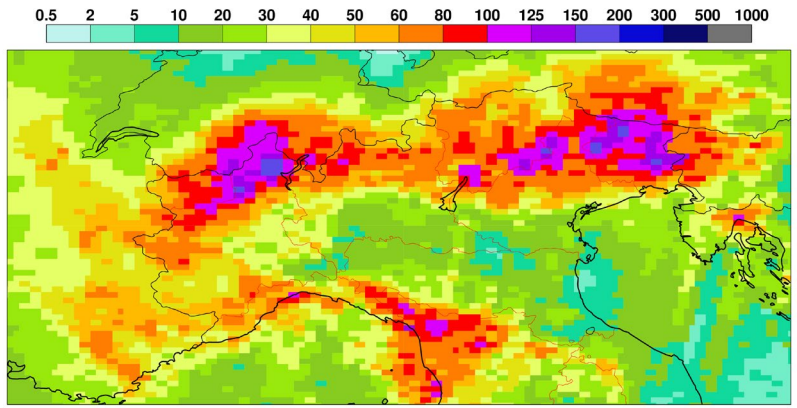
ECMWF

Continuous Extremes DT simulations : storm Adrian (oct 2018)

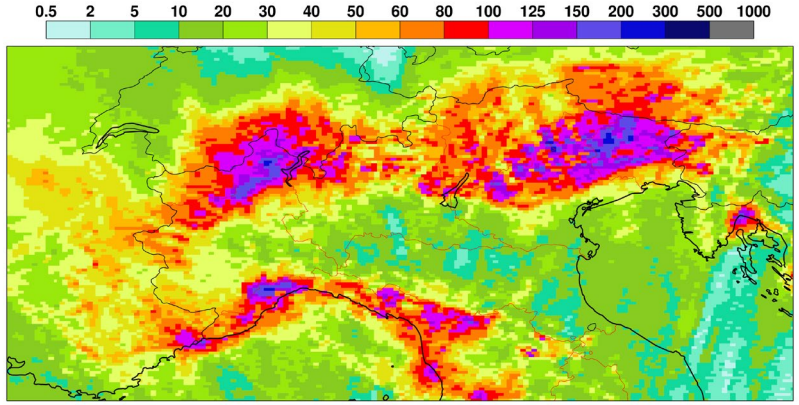
24h accumulated precipitation (T+54h - T+78h)



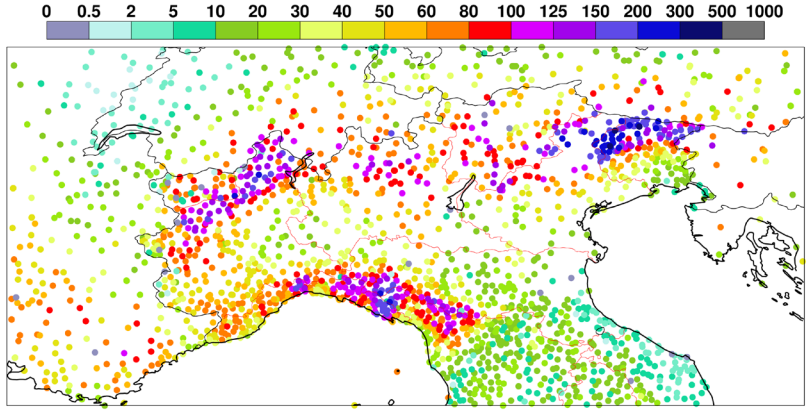
IFS 48r1 29 km



IFS 48r1 9 km



IFS 48r1 4.5 km

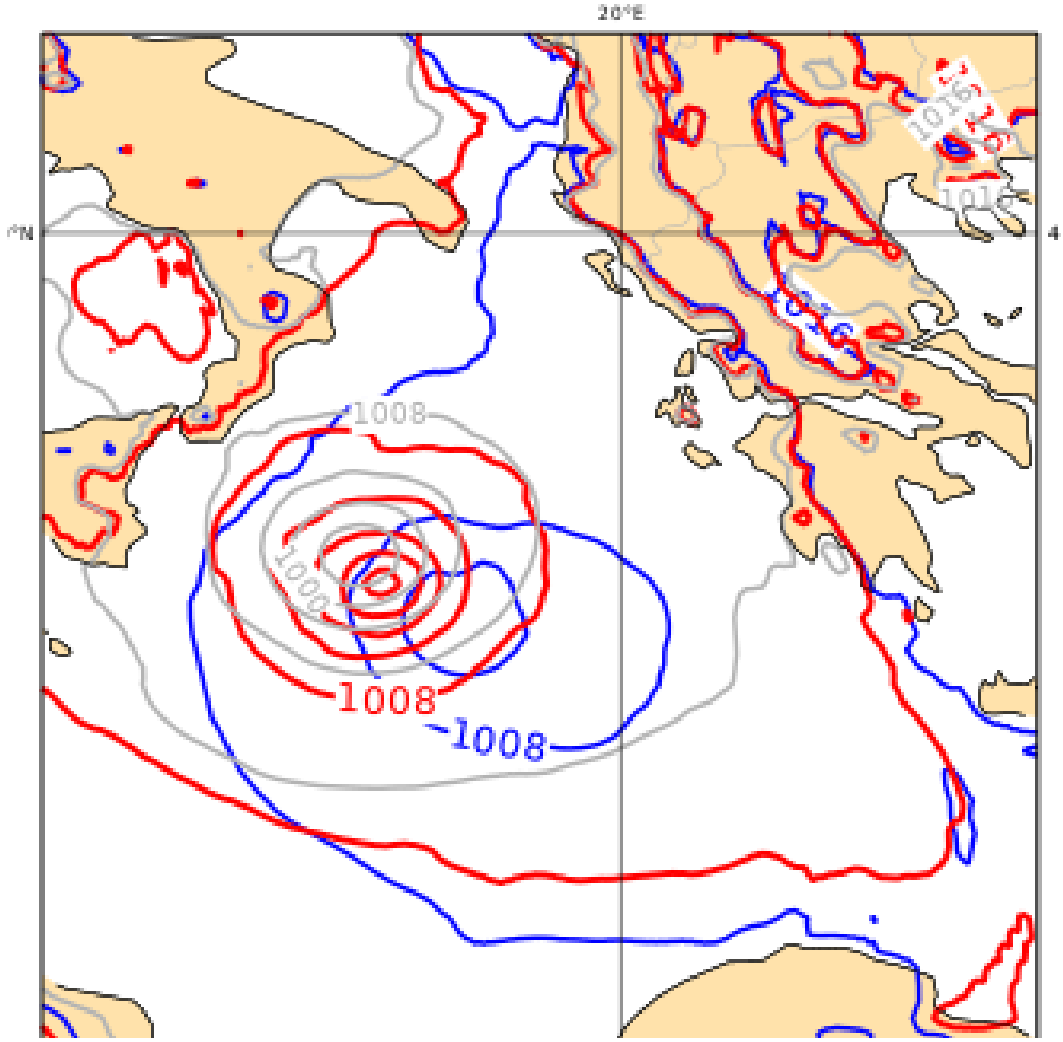


Observations

Continuous Extremes DT simulations : medicane Ianos (Sep 2020)

Mean sea level pressure (T+48h)

48r1 9km
48r1 4.5km
analysis

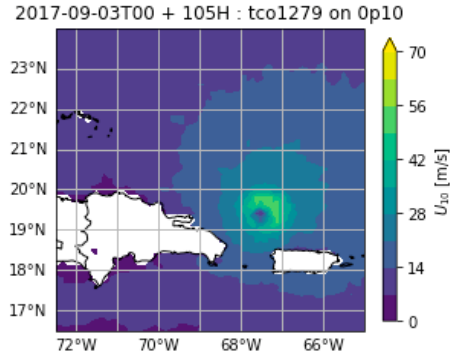


BT:2020-09-15 00:00:00. VT: T+48
minimum MSLP (blue, 48r1 9km): 1000 hPa
minimum MSLP (red, 48r1 4km): 990 hPa
minimum MSLP AN (grey): 993 hPa

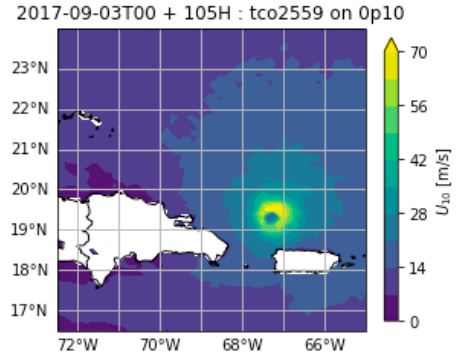
Wind and wave extremes in TC Irma

WIND, U_{10} (snapshot) (vs. SAR)

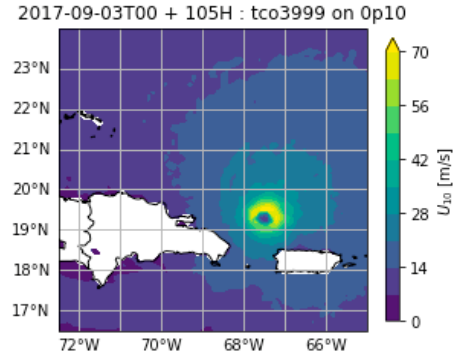
IFS 9 km



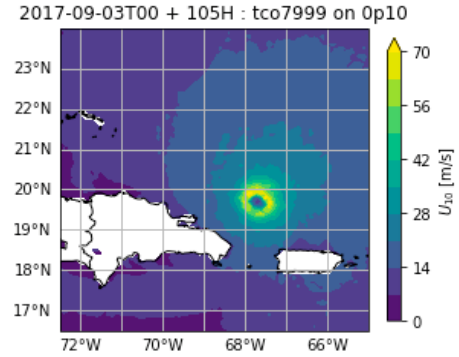
IFS 4.5 km



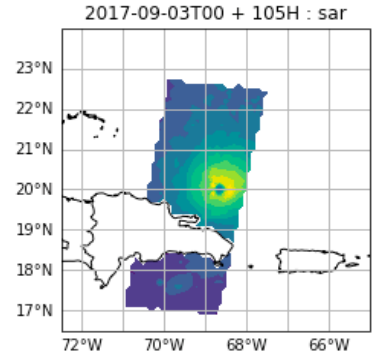
IFS 3 km



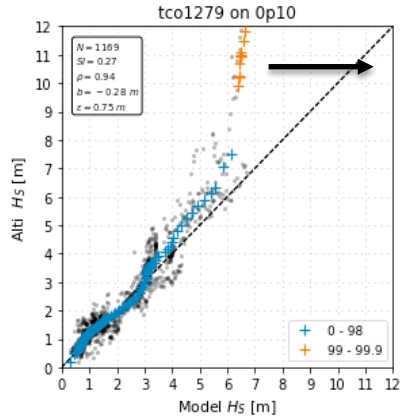
IFS 1.5 km

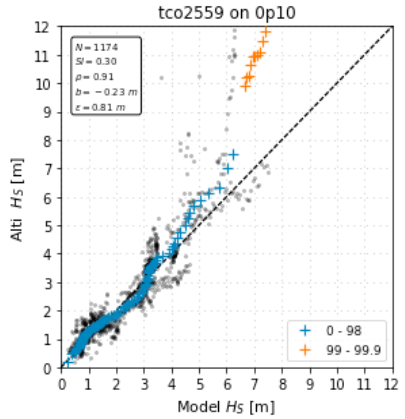


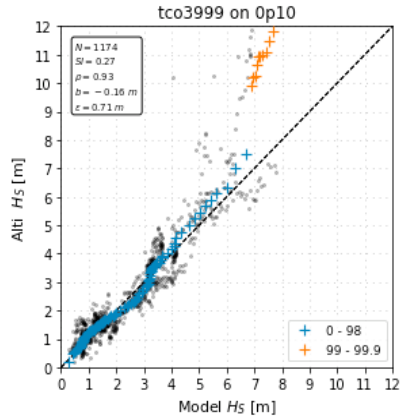
SAR

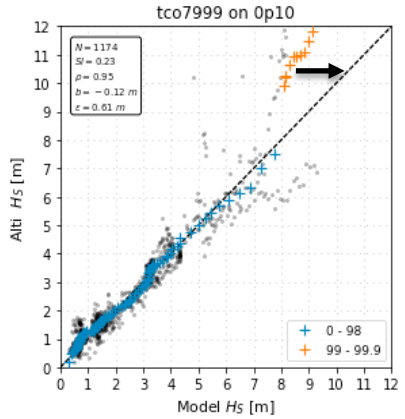


WAVES, H_S (vs. altimeter)









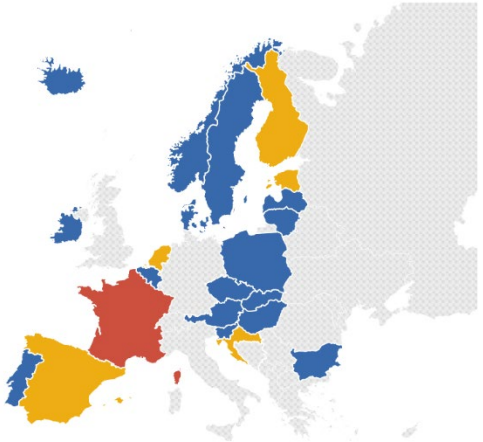
On-demand Extremes DT (procured)

Flexible and scalable workflows for the monitoring and short-range prediction of extremes at sub-km scales, that are configurable and operable on demand; builds on the ACCORD prediction system and selected impact models

Meteo-France led consortium

Participant countries and agencies from the ACCORD consortium

Sweden Spain Slovenia Slovakia Portugal Poland Netherlands Lithuania Latvia
Ireland Iceland Hungary Finland Estonia Denmark Czech Republic Croatia Bulgaria
Belgium Austria France Norway



Source: MeteoFrance • Hover in the countries to read the entities involved.
Yellow: Countries with another agency involved in addition to the National Meteorological service.

A Flourish map

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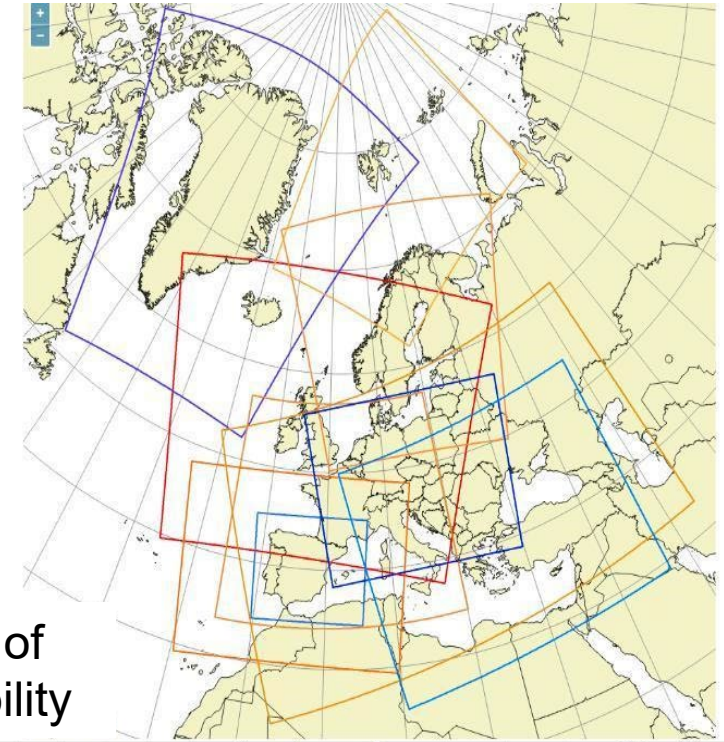
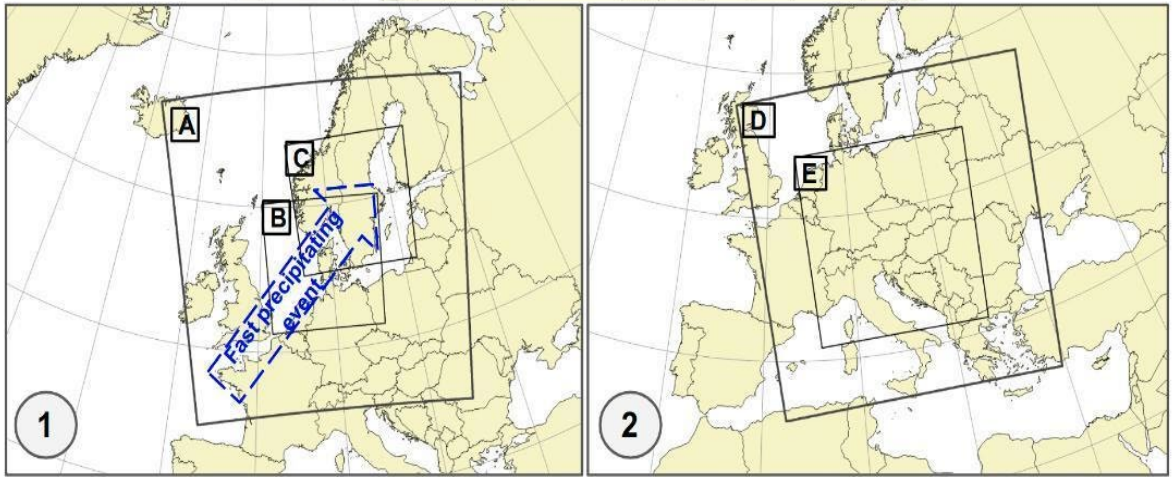
Today's prediction systems



Examples of configurability

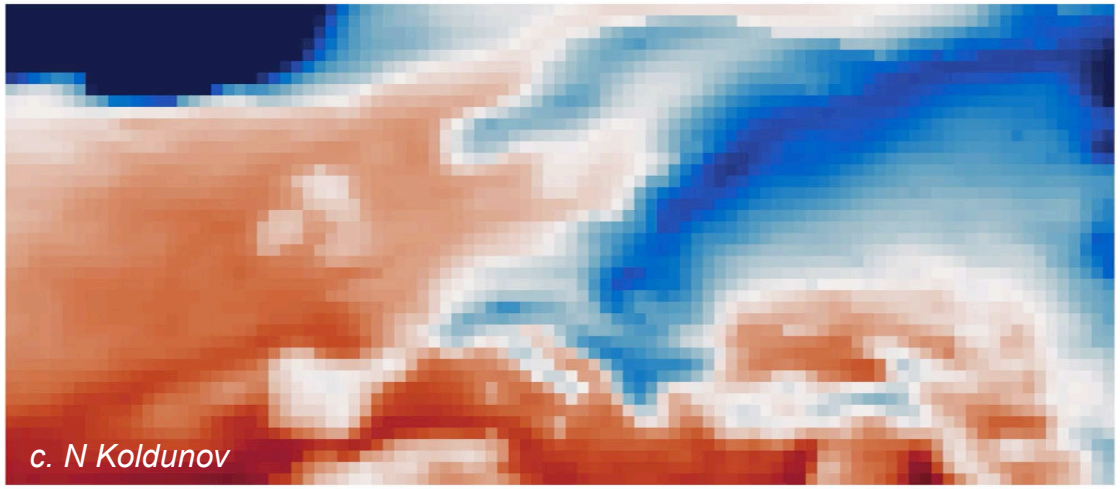


Climate DT (procured)

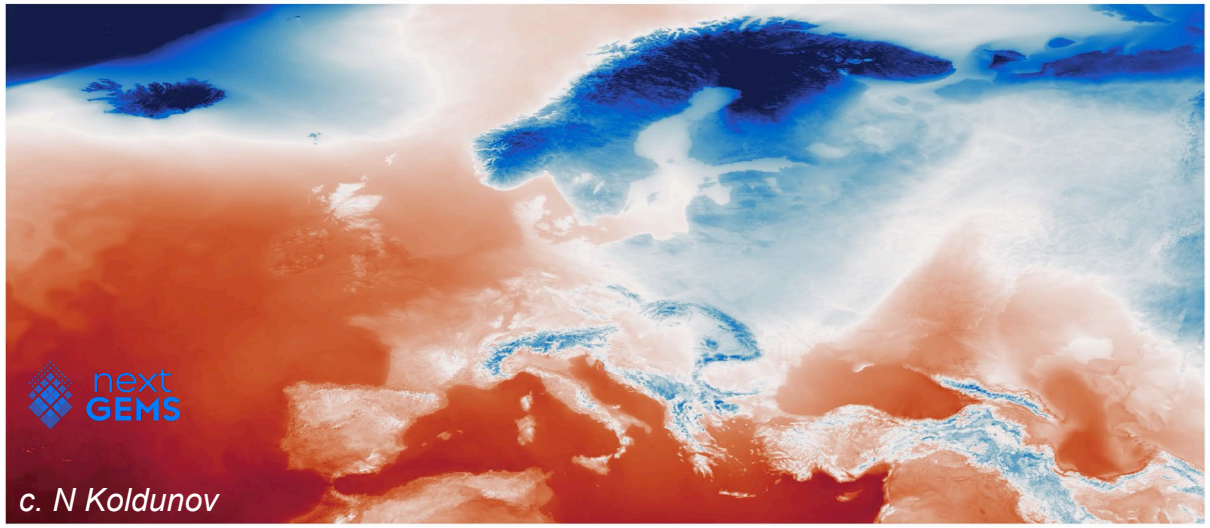
multi-decadal, global, storm/eddy-resolving numerical Earth-system simulation capability with the timely delivery of climate information for policy adaptation; observation based assessment framework; use cases for impact-sectors such as water, energy, food or health

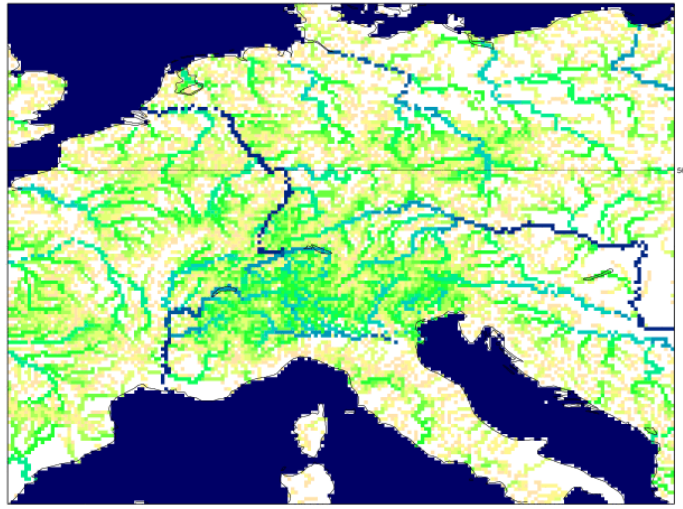
Today's global climate models

IPCC AR6 (2021)



Storm & eddy resolving simulations





Collocated weather, climate and impact-sector information on scales where impacts of climate change and extreme events are felt

Climate DT (procured)

multi-decadal, global, storm/eddy-resolving numerical Earth-system simulation capability with the timely delivery of climate information for policy adaptation; observation based assessment framework; use cases for impact-sectors such as water, energy, food or health

CSC led consortium

Climate Adaptation Digital Twin
List of participant institutions

Institution	Country
CSC - IT Center for Science	Finland
Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI)	Germany
Barcelona Supercomputing Center (BSC)	Spain
Institute of Atmospheric Sciences and Climate (CNR-ISAC)	Italy
German Climate Computing Centre (DKRZ)	Germany
National Meteorological Service of Germany (DWD)	Germany
Finnish Meteorological Institute (FMI)	Finland
Hewlett Packard Enterprise (HPE)	USA
Max Planck Institute for Meteorology (MPI-M)	Germany
Polytechnic University of Turin (POLITO)	Italy
Catholic University of Louvain (UCL)	Belgium
Helmholtz Centre for Environmental Research (UFZ)	Germany
University of Helsinki (UH)	Finland

Two storm-and-eddy-resolving Earth system models :

- ECMWF's IFS, coupled with two ocean models: NEMO, developed by the NEMO consortium, and FESOM, developed by the Alfred Wegener Institute (Germany)

- ICON, which is jointly developed by the Max Planck Institute for Meteorology and the German Weather service.

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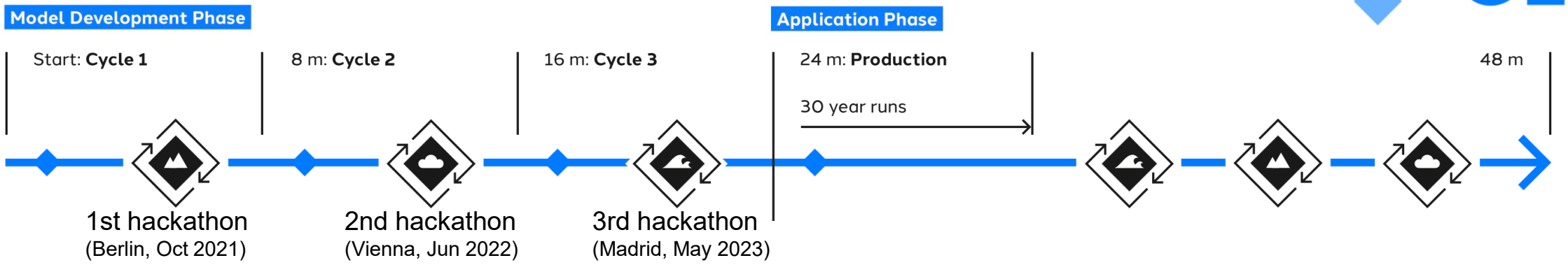
next GEMS

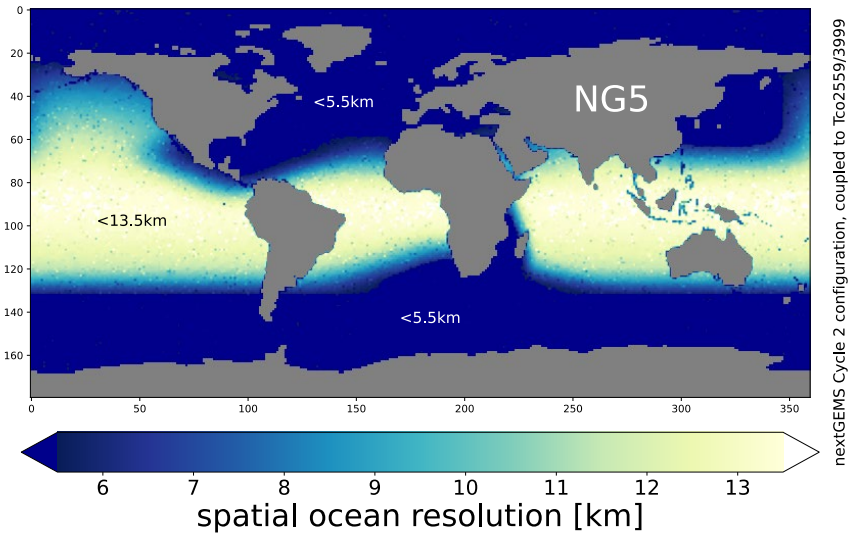
Different development cycles : IFS – NEMO/FESOM2



- **Cycle 1 and 2:** from **75 days to - 2 years**
- **Cycle 3:** **2 - 4 years**
- **Production runs:** **up to 30 years**

- **Atmosphere**: **9 km / 4.5 km / 3km**
- **Ocean**: **25km** NEMO; **4-13km** FESOM2 NG5 grid

*Ocean resolution of the **NG5** FESOM2 grid (Fig courtesy: T. Rackow)*



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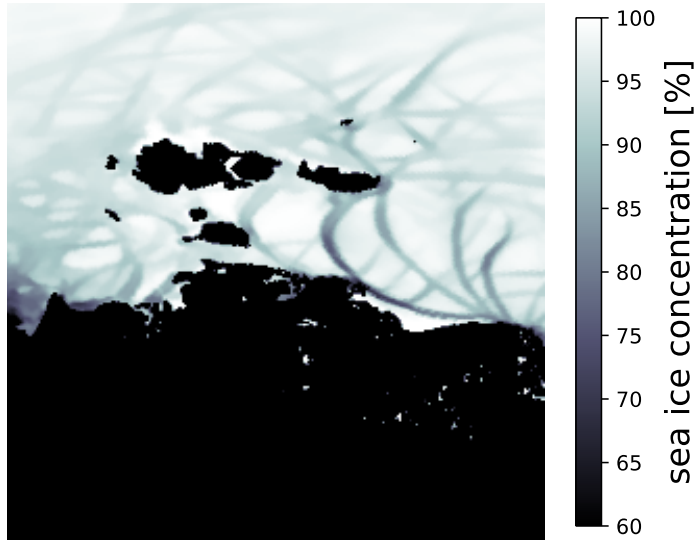
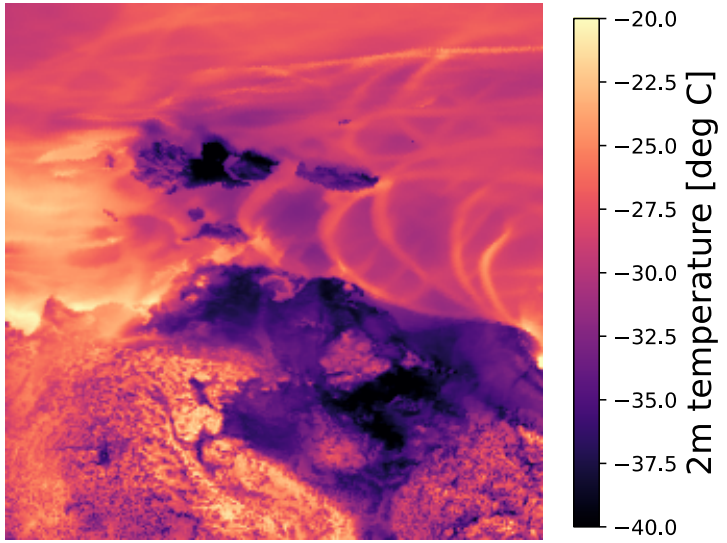
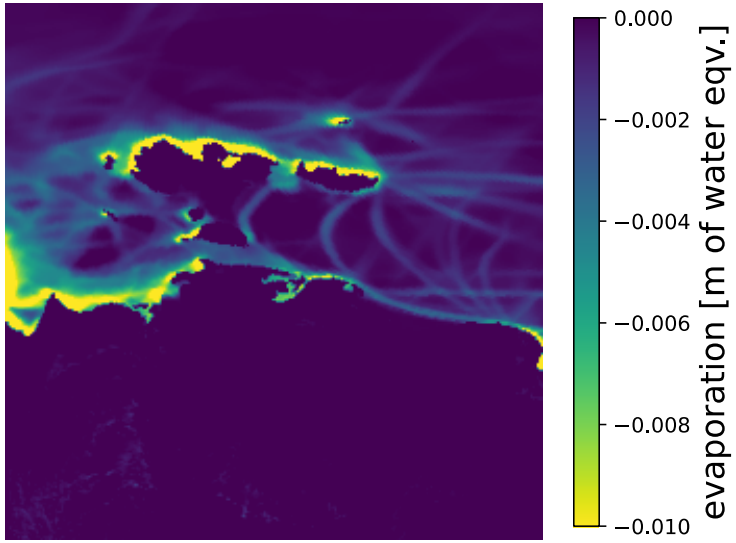
ALFRED-WEGENER-INSTITUT
HELMHOLTZ-ZENTRUM FÜR POLAR- UND MEERESFORSCHUNG

Sea ice imprint on atmospheric parameters in IFS-FESOM2 (TCo3999-NG5 resolution)







- First evidence of resolved linear kinematic **features in the sea ice** cover at 4-5 km resolution, **which can strongly modulate the atmospheric state above them (even low clouds)**

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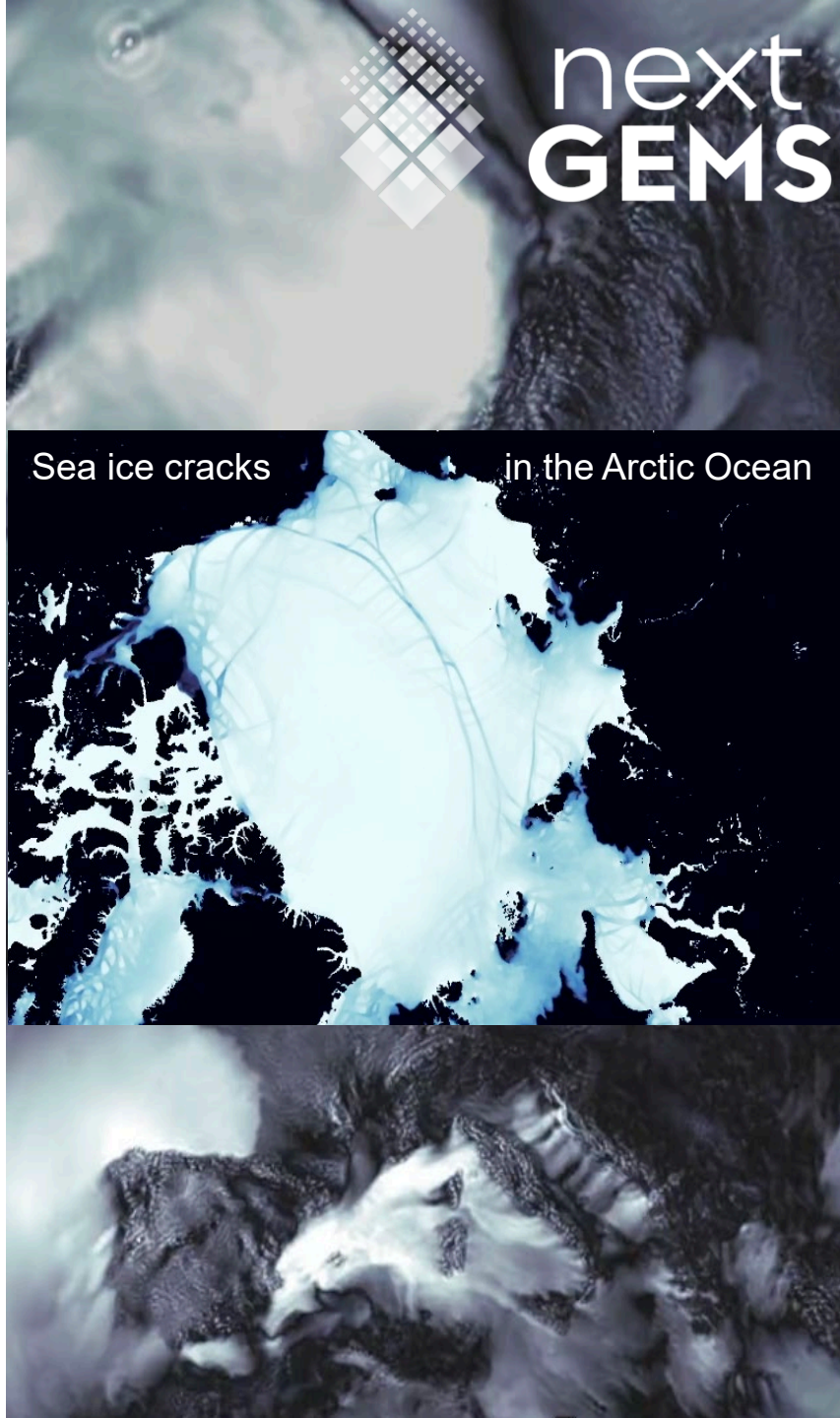
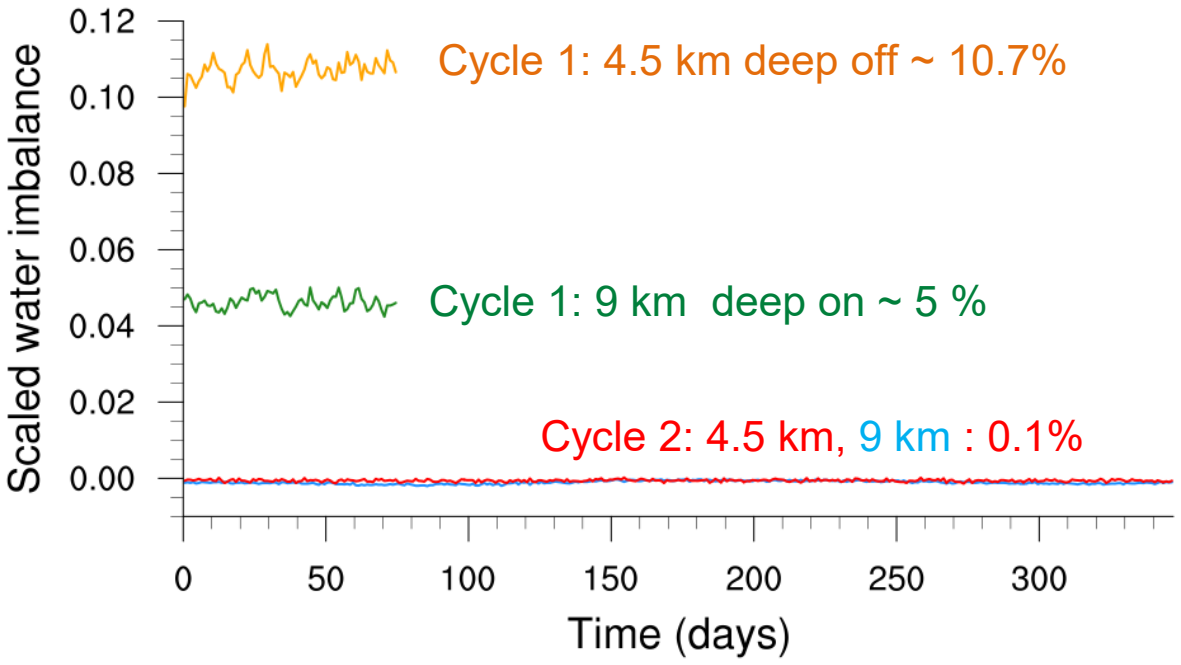
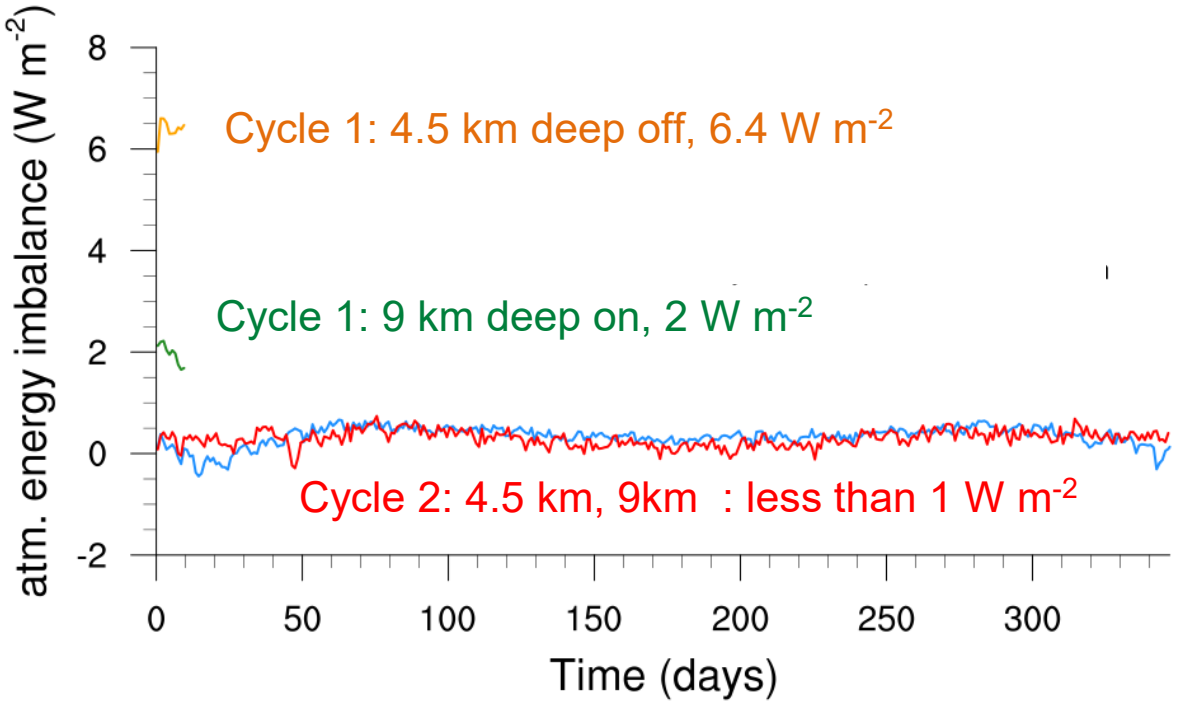
next GEMS



Lessons learned from storm resolving simulations: water and energy imbalance in IFS

IFS: semi-Lagrangian dynamics is non-conserving: to fix the water imbalance we activated the tracer mass fixer for all moist species





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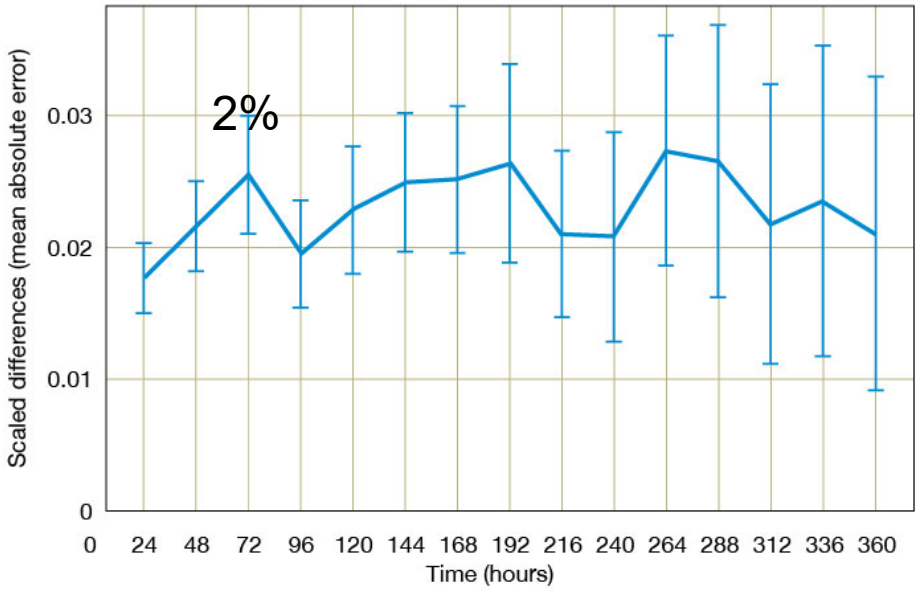
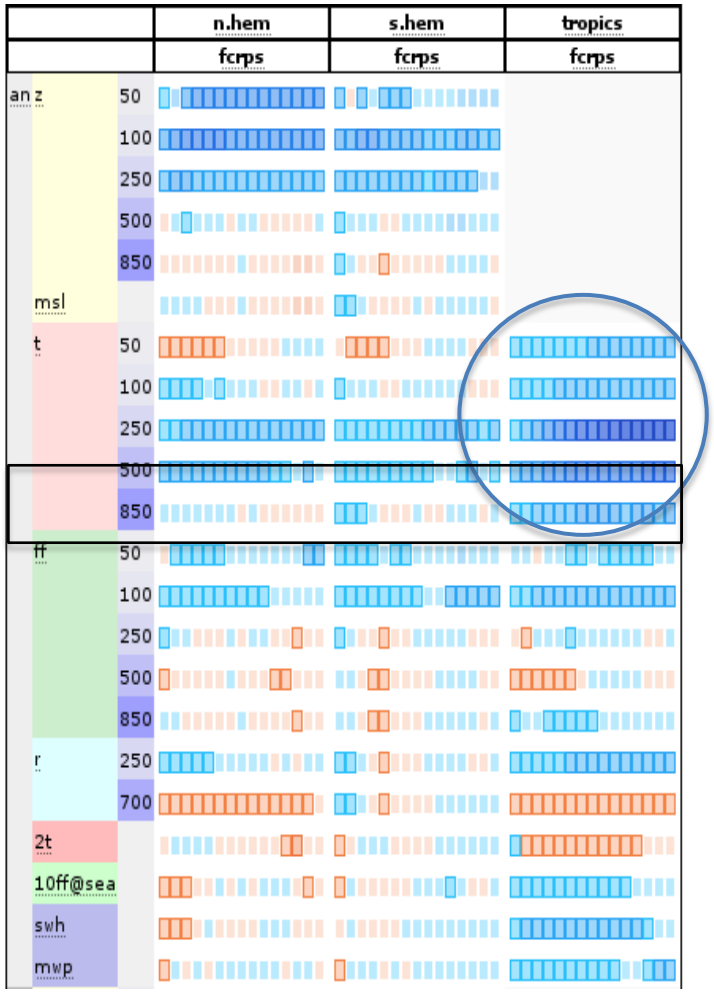
Impact of water conservation changes on forecast skill across resolutions

Precipitation mean absolute error



9km ENS



8-member d(fCRPS)

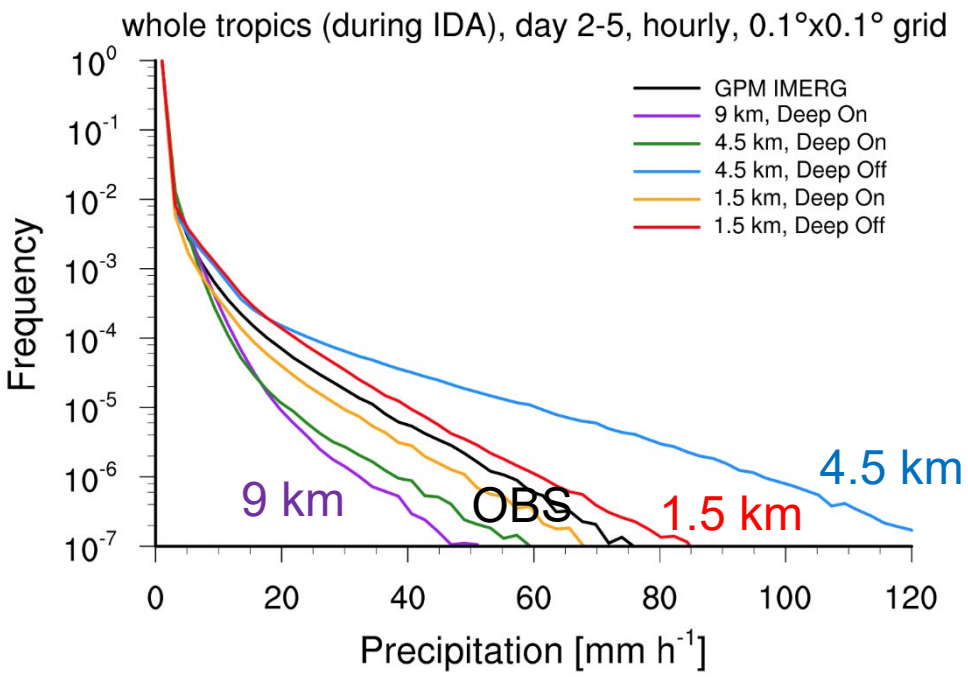
Monthly forecast (Tco 199)

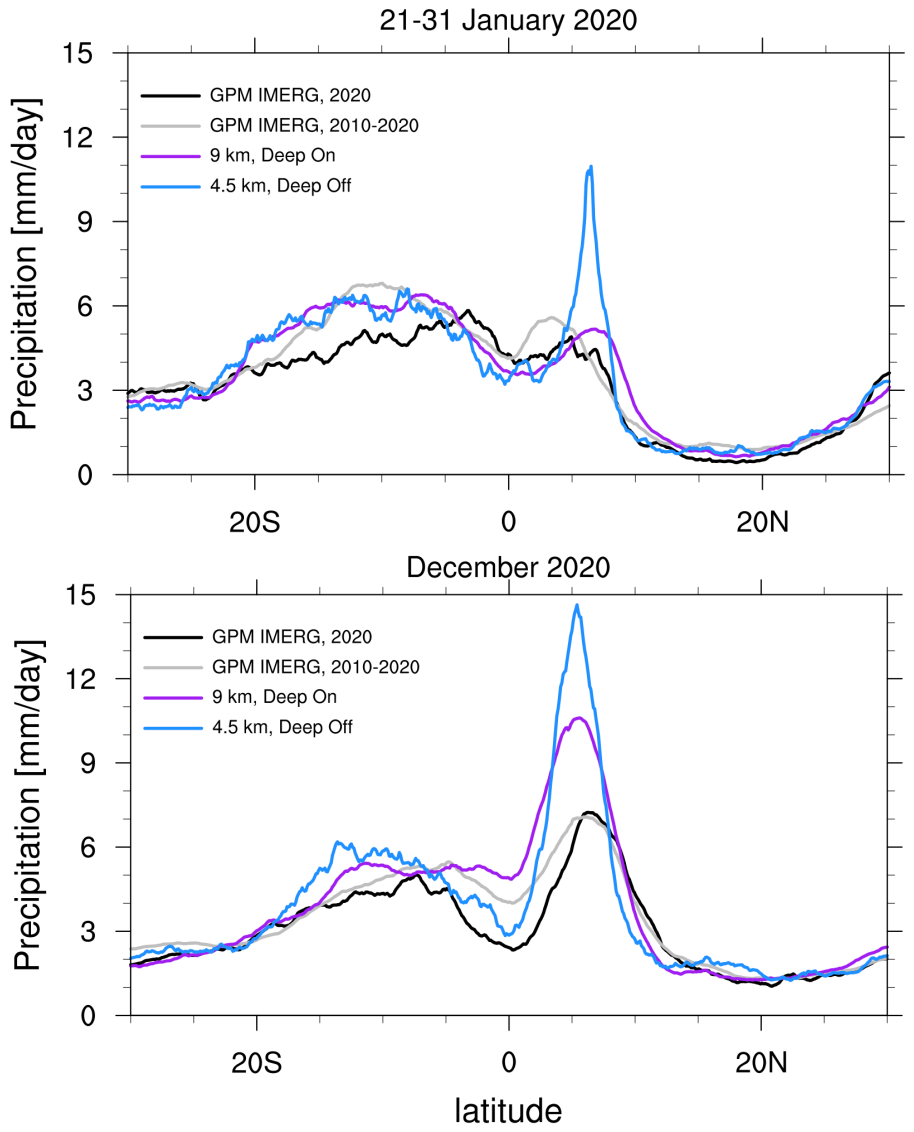
10 members , dCRPSS

ECMWF

Challenges in key science elements of the Digital Twins : systematic errors

Precipitation (extremes, MCS, etc)

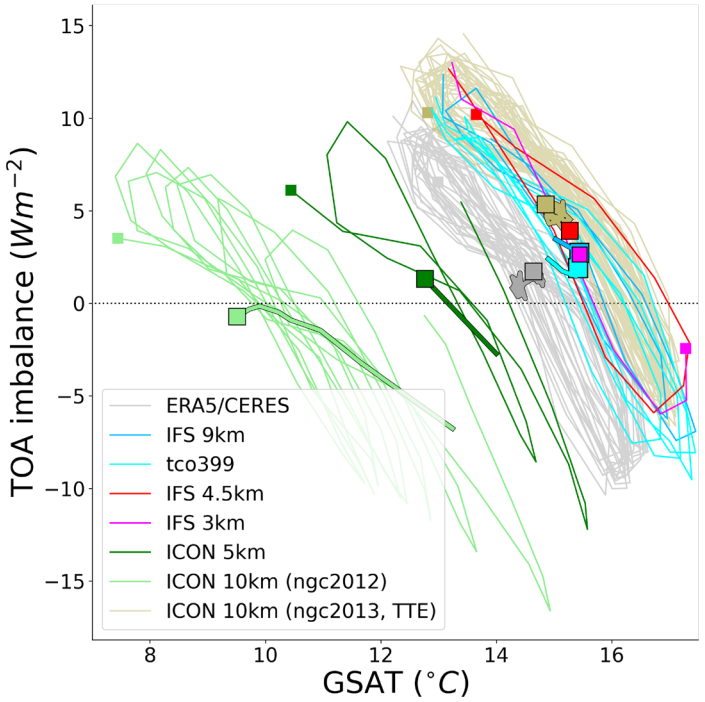


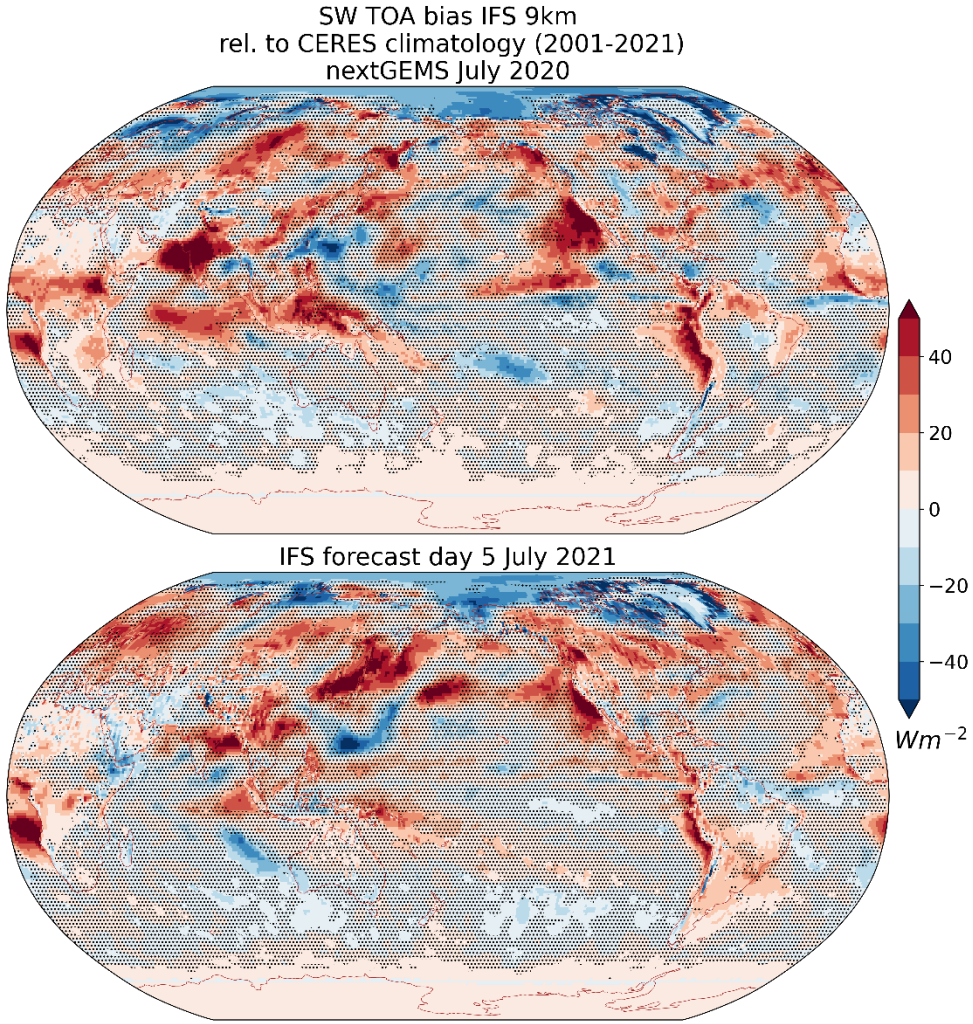


ECMWF

Challenges in key science elements of the Digital Twins : systematic errors

Radiative imbalance vs temperature

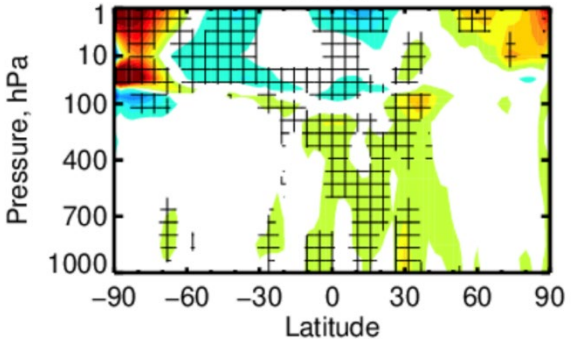




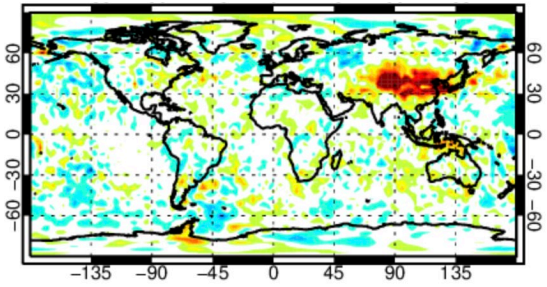
ECMWF

Challenges in key science elements of the Digital Twins : systematic errors

Geopotential RMSE
4.5 km - 9 km , T+72h

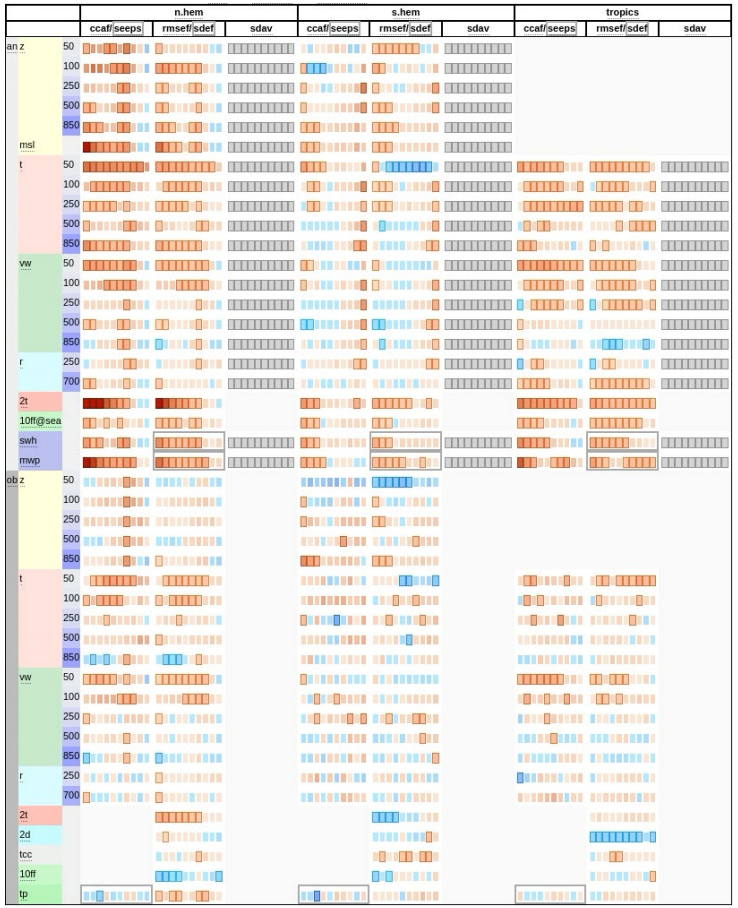


100 hPa wind vector RMSE
4.5 km - 9 km , T+48h

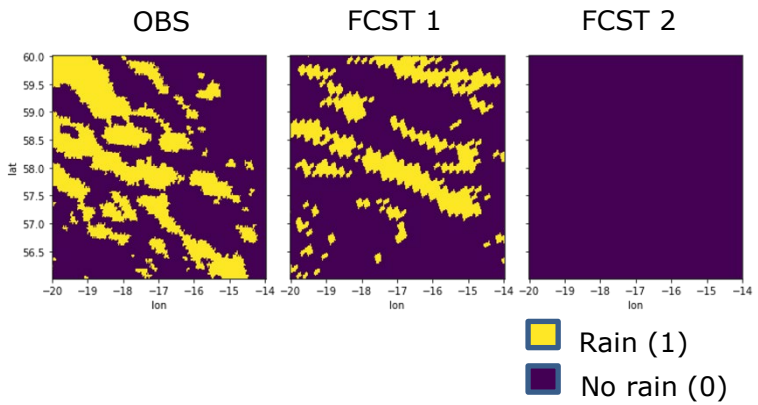


Increase in RMSE
Decrease in RMSE

Scorecard FC Winter 2021-2022
4.5km – 9km



Using relevant metrics for “grainy fields” : FSS



Double penalty effect: RMSE worse in FCST1 wrt FCST2

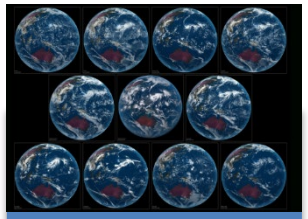
FSS compares precipitation distribution above a “scale k”. FCST1 scores increase over larger domains.

	RMSE	FSS k=1	FSS k=11	FSS k=61
FCST 1	0.61	0.32	0.52	0.86
FCST 2	0.56	0	0	0

ECMWF

Challenges in key science elements of the Digital Twins

- **Science-computing codesign**
- **Performance portability**
- **Data-centric workflows**
- **HPC & cloud**
- **ML/AI**

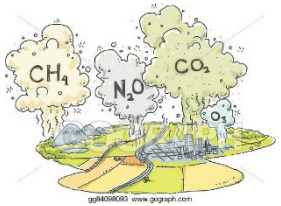


Earth System Modelling development

Beyond prototype SR-ESMs & pretty pictures

Users

Atm composition



integration & codesign with impact modelling

Hydrology

Assimilation at scales closer to obs. Validity of the TL approx.?

Data assimilation

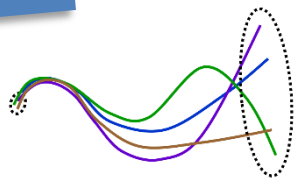
Observation information extraction

IoT

Under exploited and HR observations

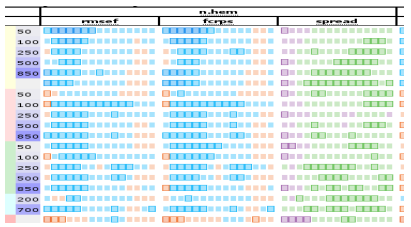
Uncertainty

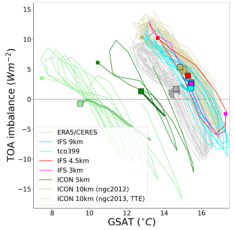
New approaches to account for uncertainty



R2O

Verification



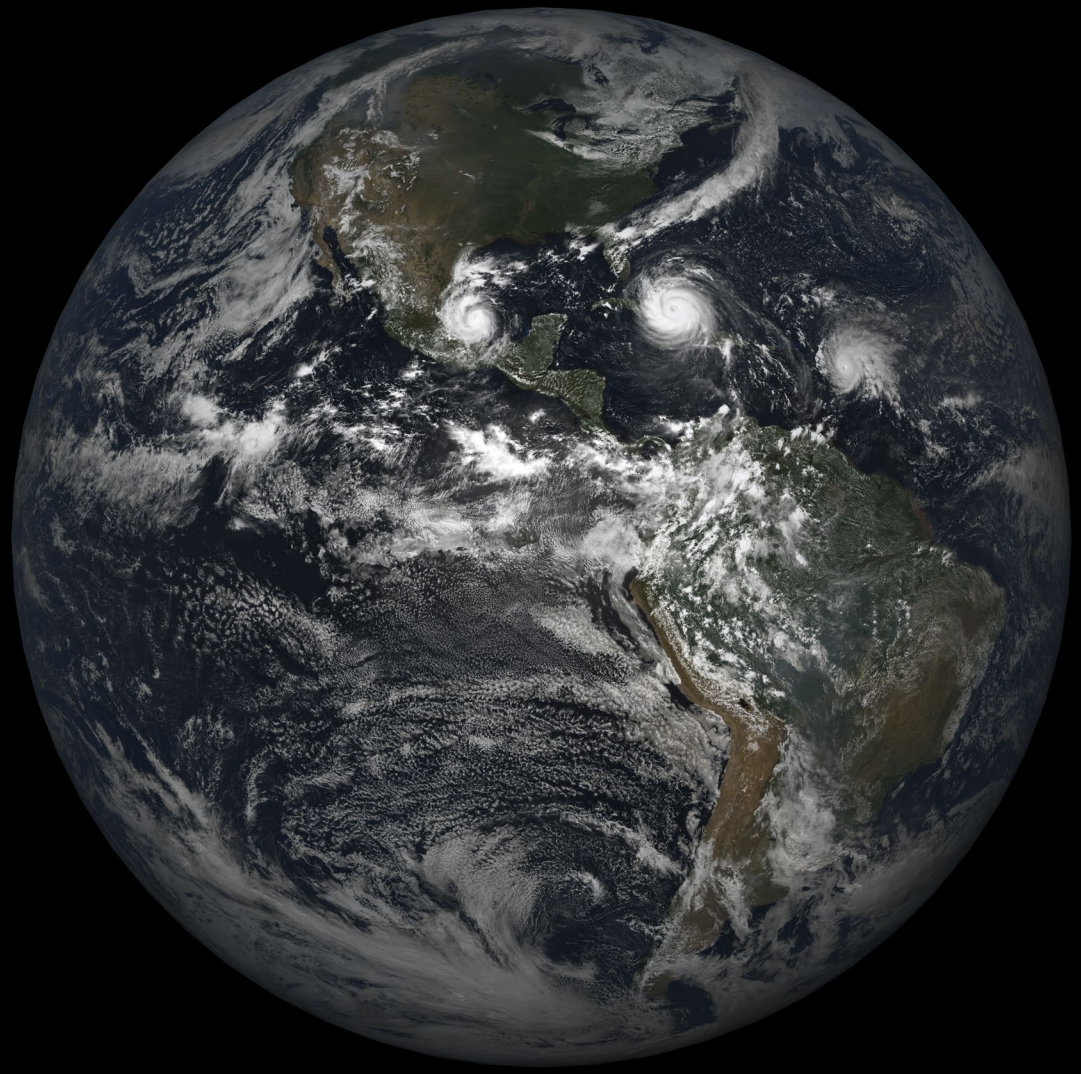


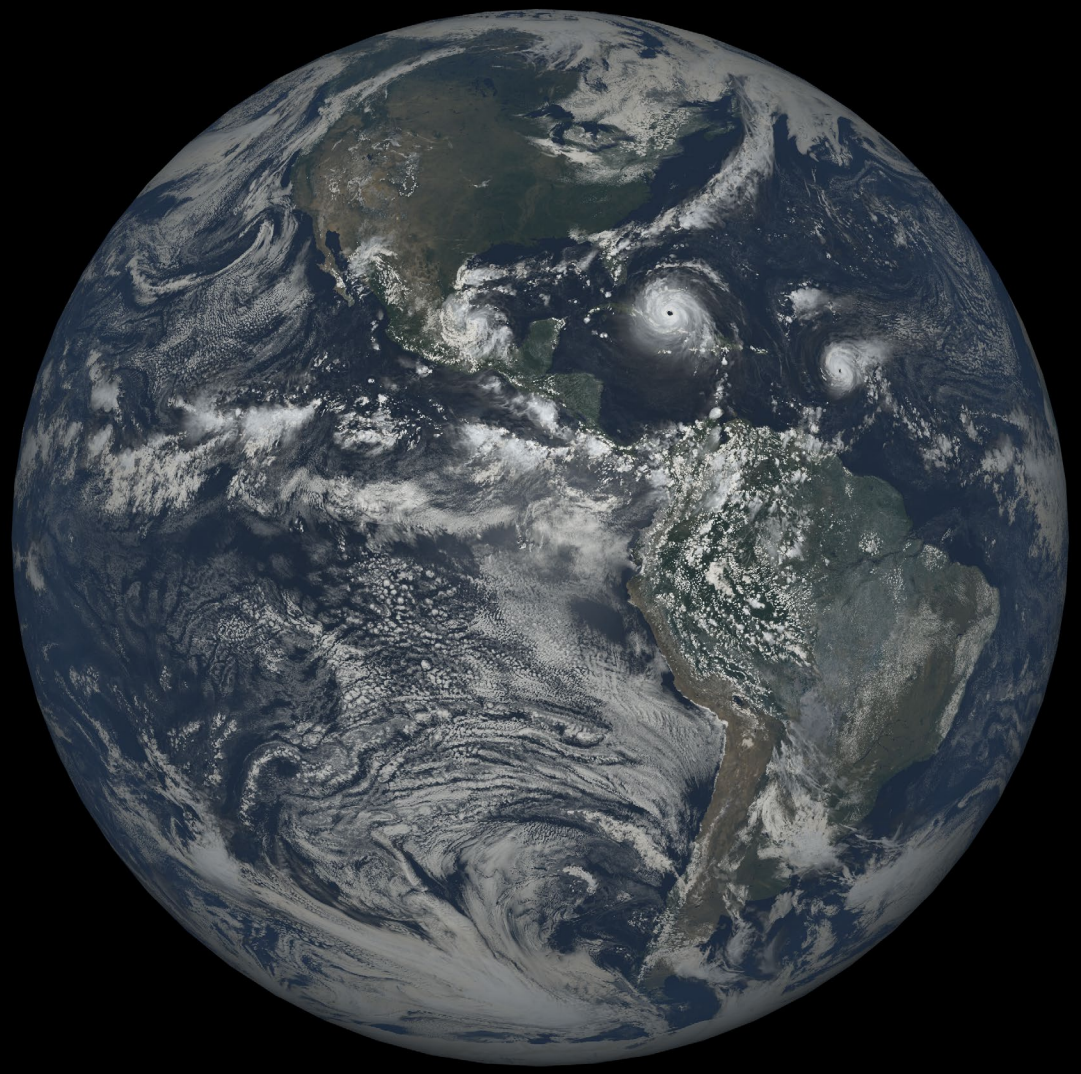
ECMWF

Towards Digital Twins of the Earth-system

GOES16_ABI CH2_3_1 composite 20170908 1800 UTC

IFS FC+18h at 2.5 km





Philippe Lopez

RTTOV-MFASIS: simulated imagery in the visible.