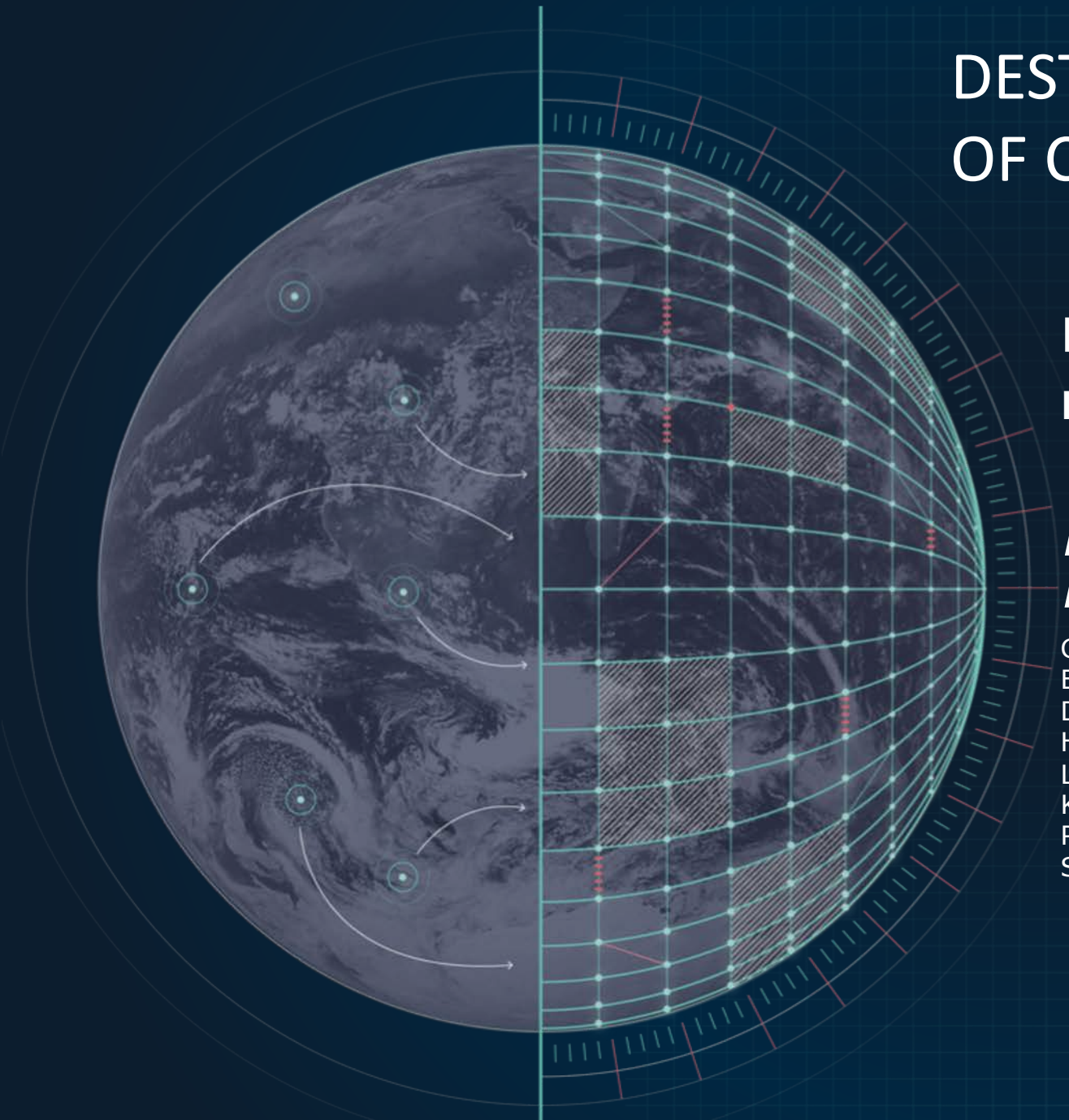


DESTINATION EARTH AND THE FUTURE OF CLIMATE INFORMATION

Peter Dueben

Head of Earth System Modelling @ ECMWF

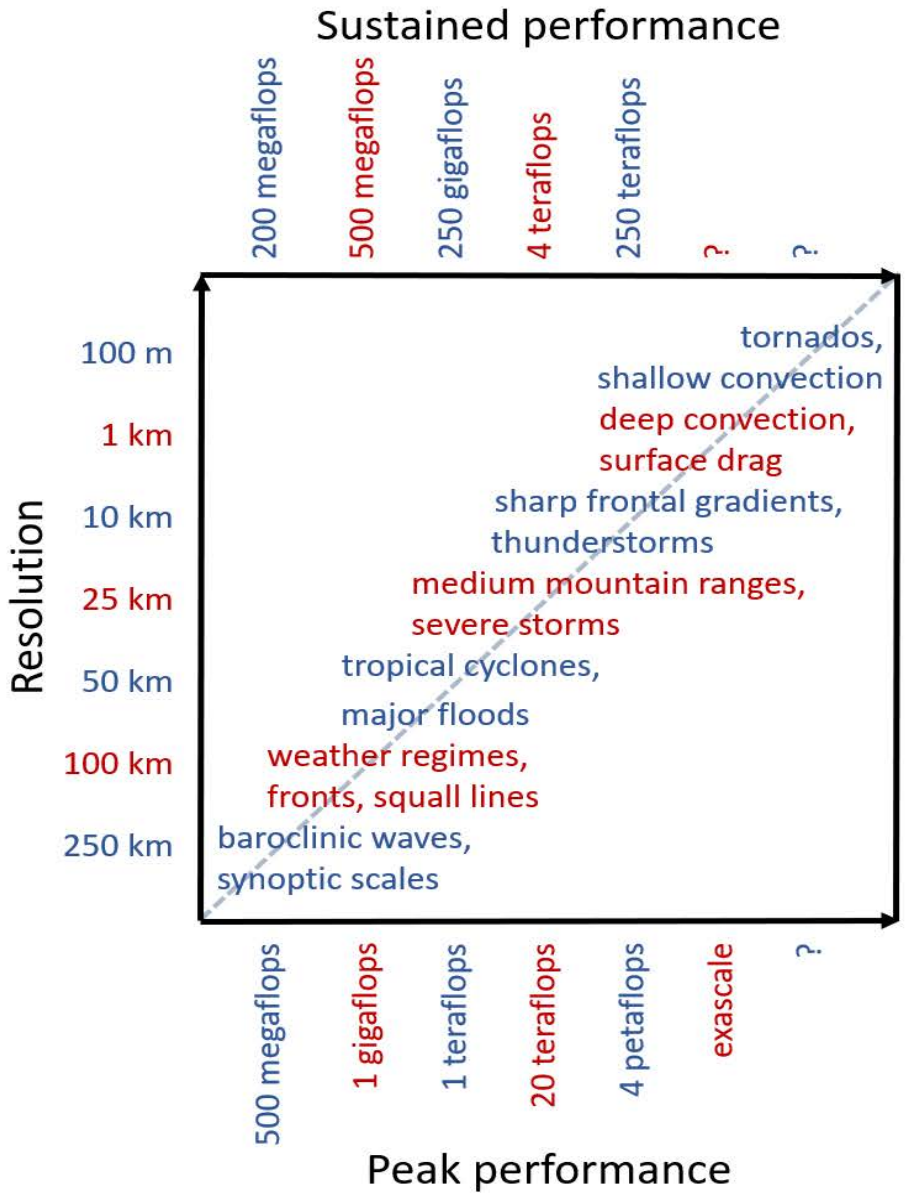
Presenting many slides from Irina Sandu, Nils Wedi, Peter Bauer et al.

Gabriele Arduini, Gianpaolo Balsamo, Peter Bechtold, Tobias Becker, Anton Beljaars, Jean Bidlot, Andy Brown, Jasper Denissen, Michail Diamantakis, Richard Forbes, Estibaliz Gascon, Ioan Hadade, Sam Hatfield, James Hawkes, Olivier Marsden, Josh Kousal, Simon Lang, Llorenç Lledó, Linus Magnusson, Michael Maier-Gerber, Sebastian Milinski, Kristian Mogensen, Florian Pappenberger, Xabier Pedruzo, Inna Polichtchouk, Tiago Quintino, Thomas Rackow, Josef Schroettle, Simon Smart,Annelize van Niekerk, Benoit Vanniere

Funded by the European Union

ECMWF

Km-scale models for better predictions

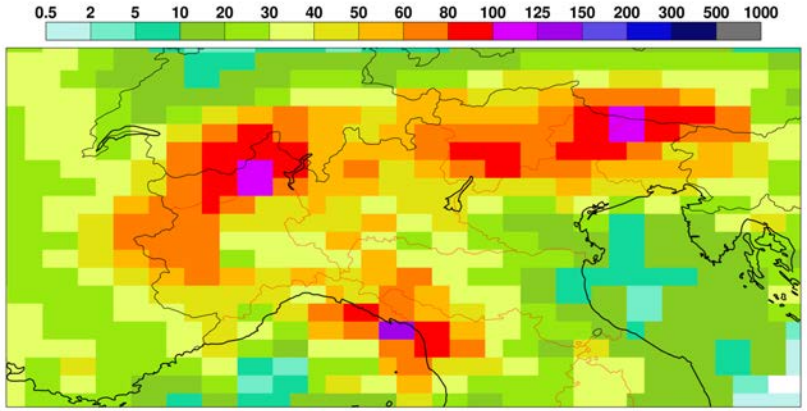


Adapted from Neumann, Dueben et al. Phil Trans A 2018

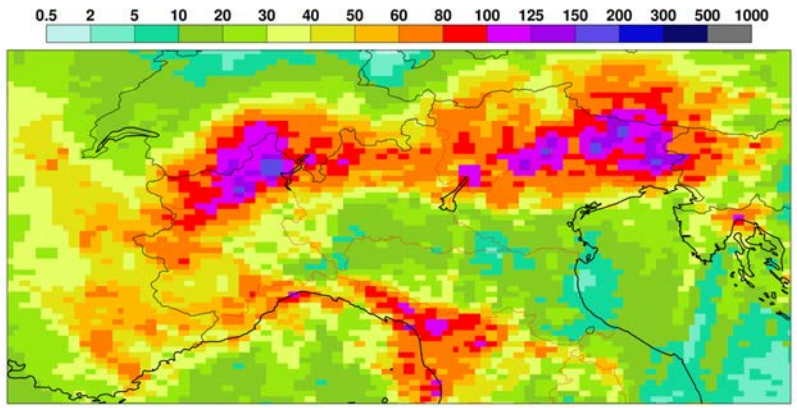
- More resolution – more skill
- Better representation of topography and gravity wave drag
- Explicit representation of convection (“storm-resolving” models)
- Eddy resolving oceans + tides
- Same resolution as satellite measurements

Continuous Extremes Digital Twin simulations: Storm Adrian (Oct 2018)

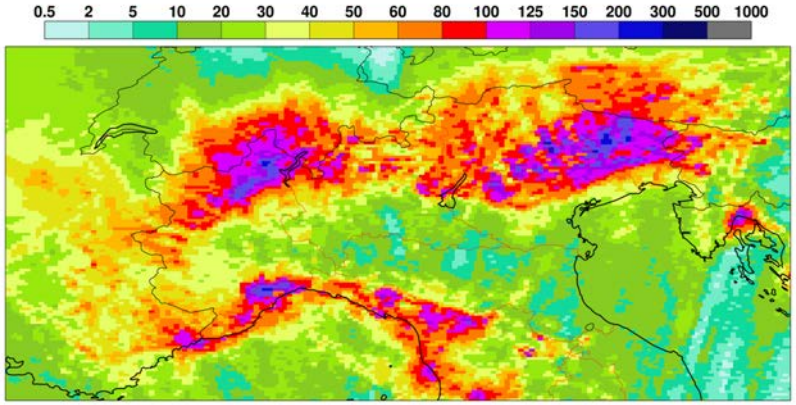
24h accumulated precipitation (T+54h - T+78h)



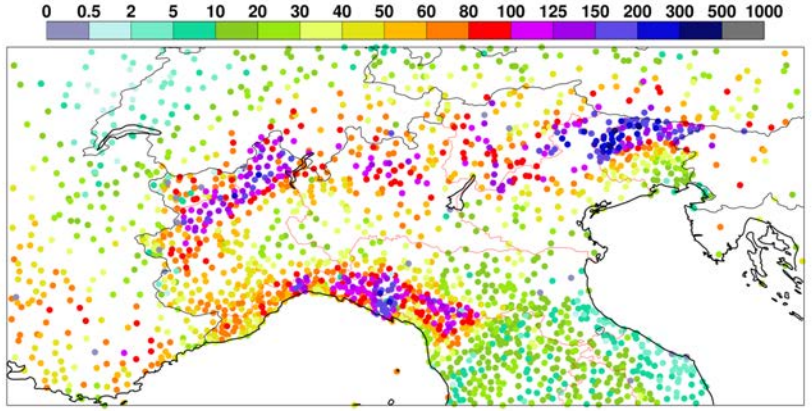
IFS 48r1 29 km



IFS 48r1 9 km



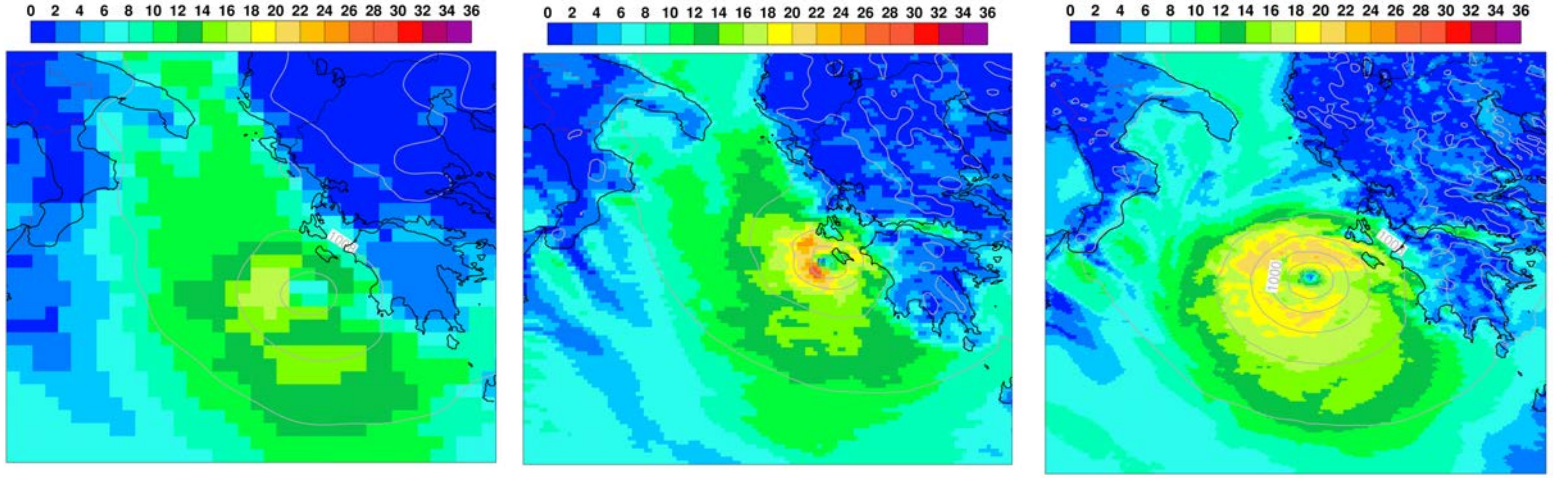
IFS 48r1 4.5 km



Observations

Simulations of Medicane Ianos (Sep 2020)

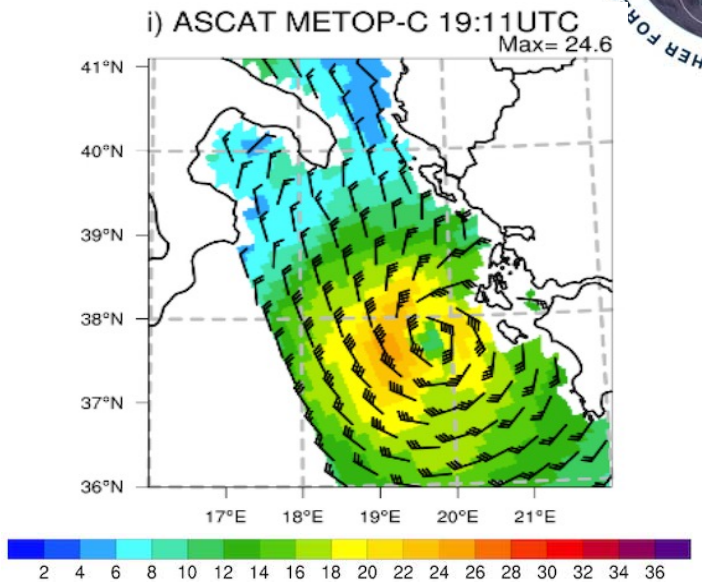
Surface wind speed (T+66h, m/s)



IFS 48r1 29 km

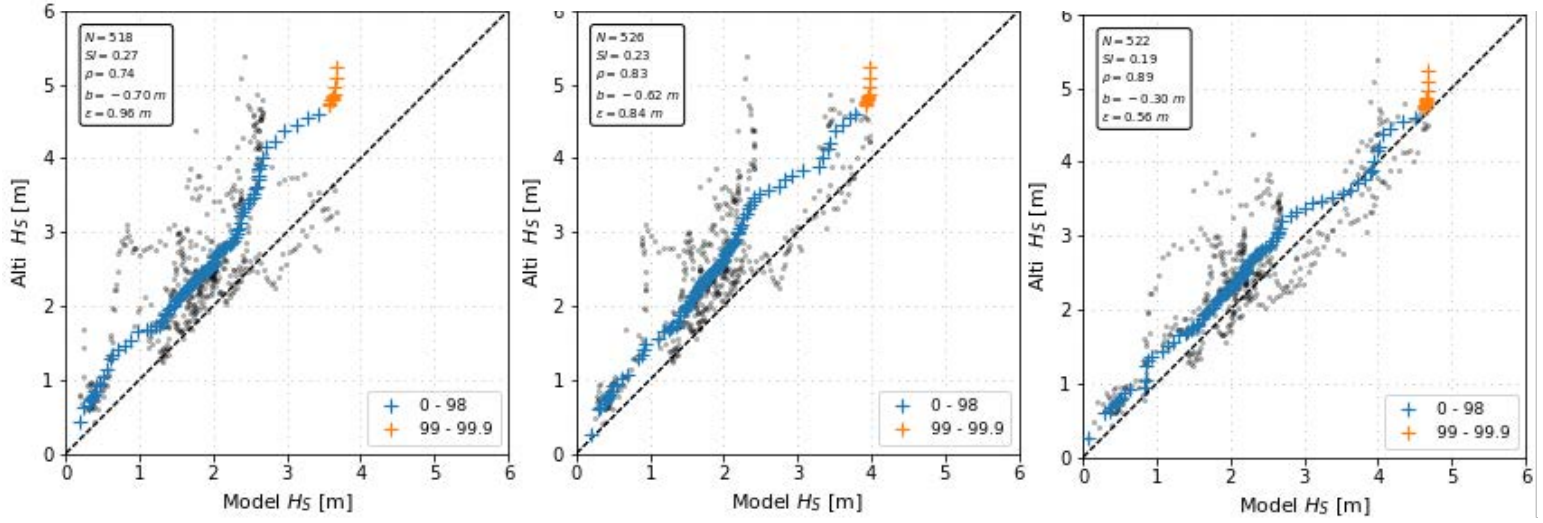
IFS 48r1 9 km

IFS 48r1 4.5 km



Observations

Waves (T+44h – T+84h) : Model vs. Observations (altimeter)

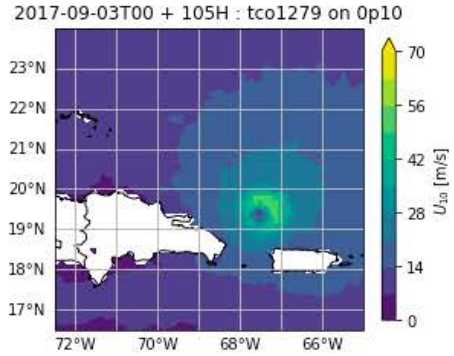


Wind and wave extremes in Tropical Cyclone Irma

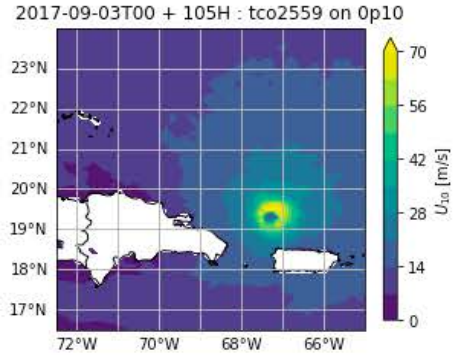
U.S. DEPARTMENT OF ENERGY INCITE LEADERSHIP COMPUTING

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

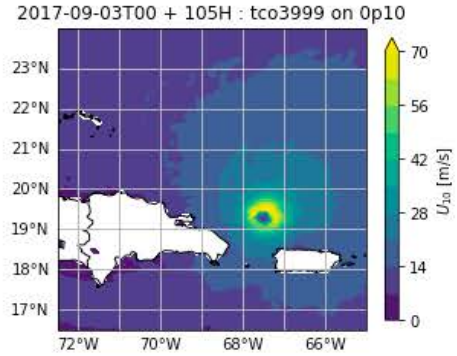
IFS 9 km



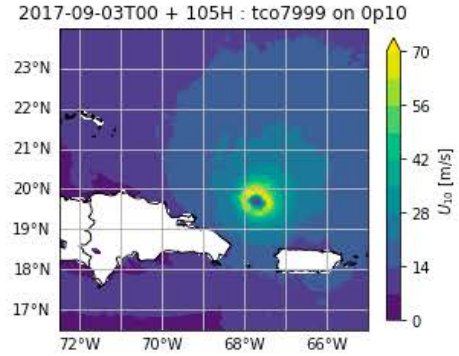
IFS 4.5 km



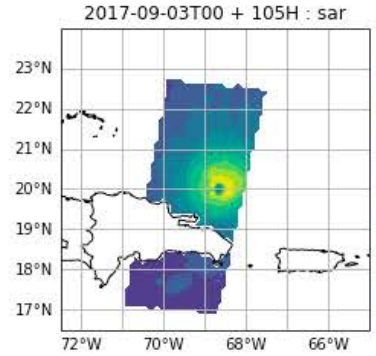
IFS 3 km



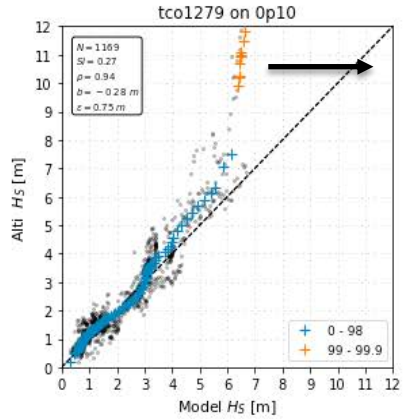
IFS 1.5 km

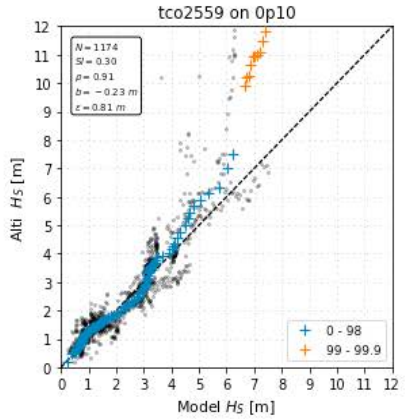


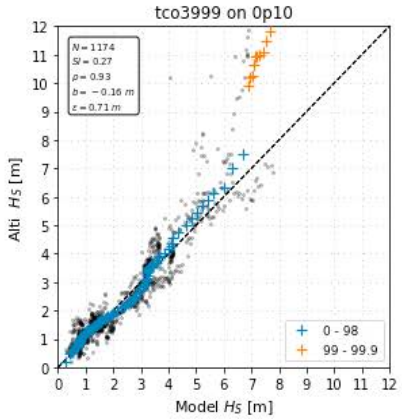
SAR

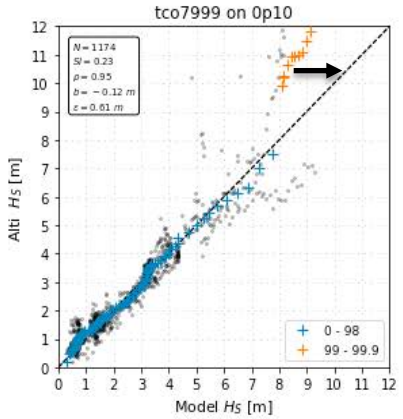


WAVES, H_s (vs. altimeter)









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So let's push km-scale models to operations!?

Climate is changing,
→ we need better models now

Compute power?
9 km → 1 km → Factor 9^3 = 729 compute power

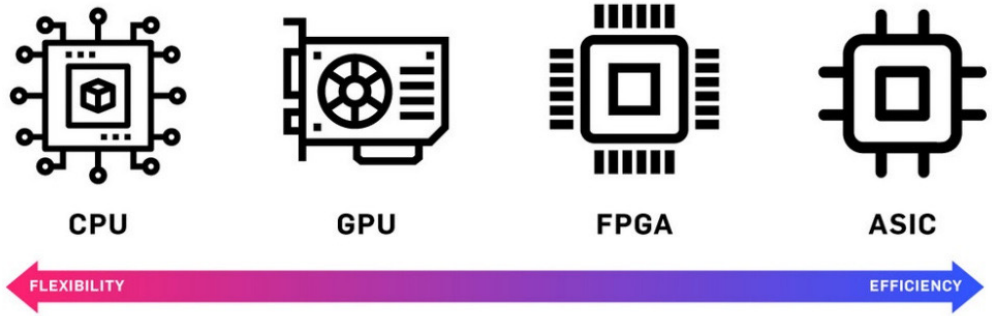
Moore's law is the observation that the number of transistors in an integrated circuit doubles about every two years.
→ 2^9 = 512 → Let's wait for 18 years?

Data and storage?
9km: 6,599,680 points x 137 levels x10 variables
→ 9 billion points → > 0.5 TB

1.5km: 256,800,000 points x 137 levels x 10 variables
→ 352 billion points → > 20 TB

Uff…

ECMWF



Source: venturebeat.com

- Individual processors will not be faster
  → Parallelisation / power consumption
- Hardware will be more heterogeneous
  → CPUs / GPUs / FPGAs / ASICs
- Machine learning has strong impact on hardware development
  → High floprate at low precision

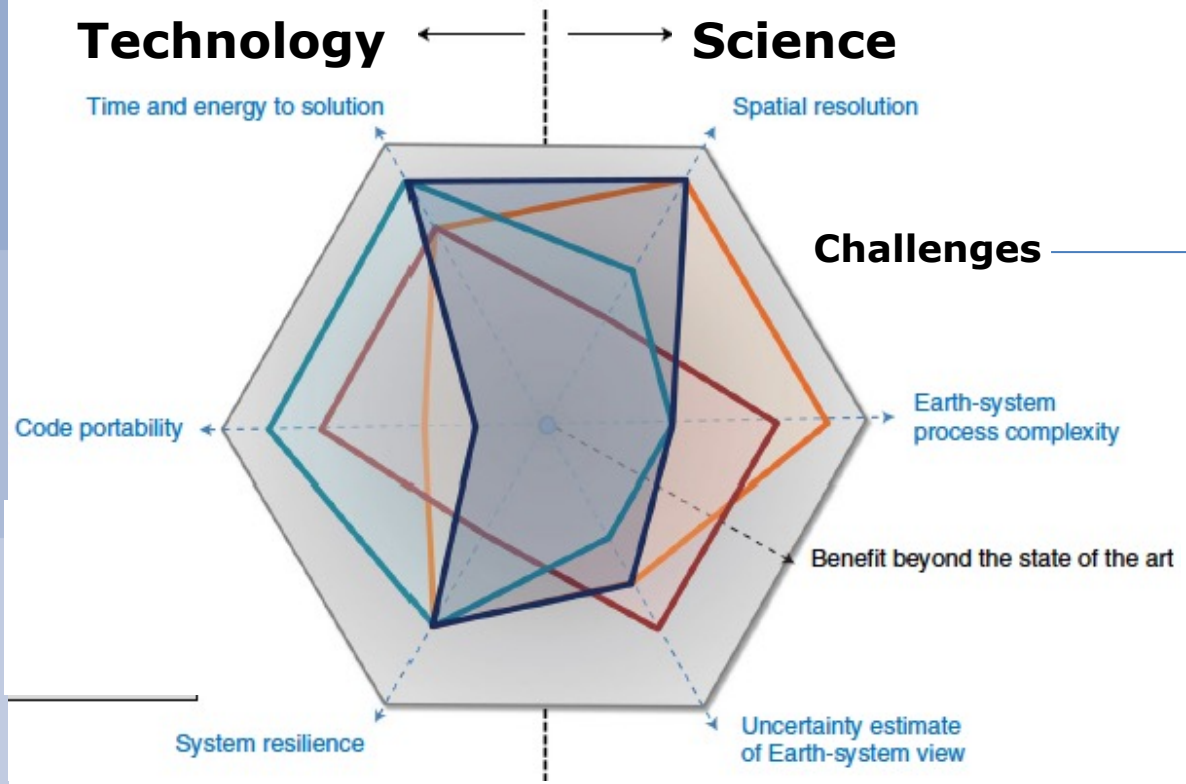
Are you ready for a revolution?

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.



Solutions

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

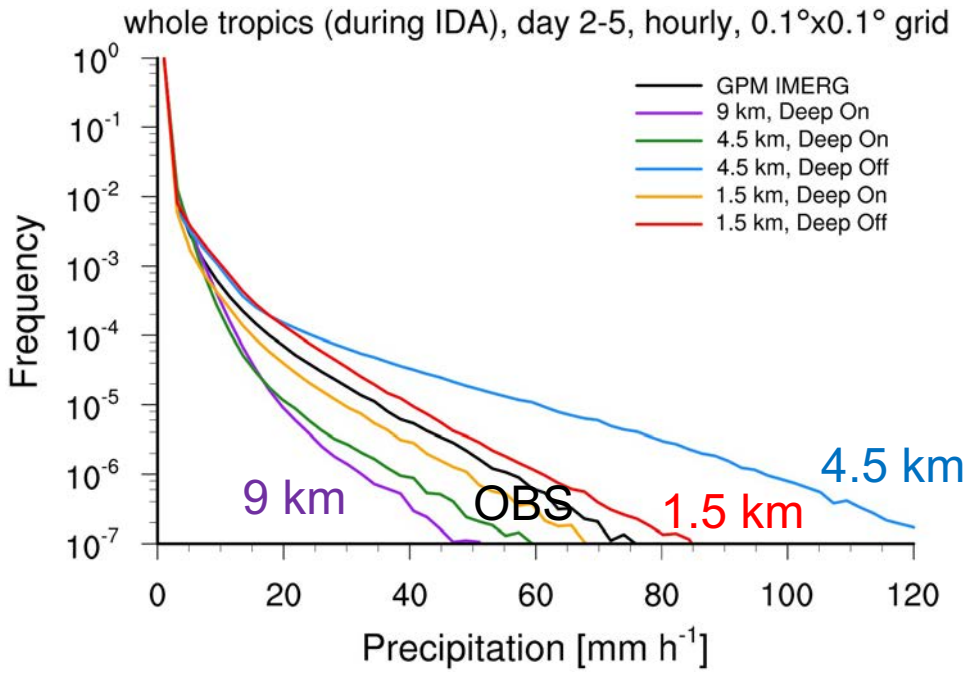
EuroHPC Joint Undertaking

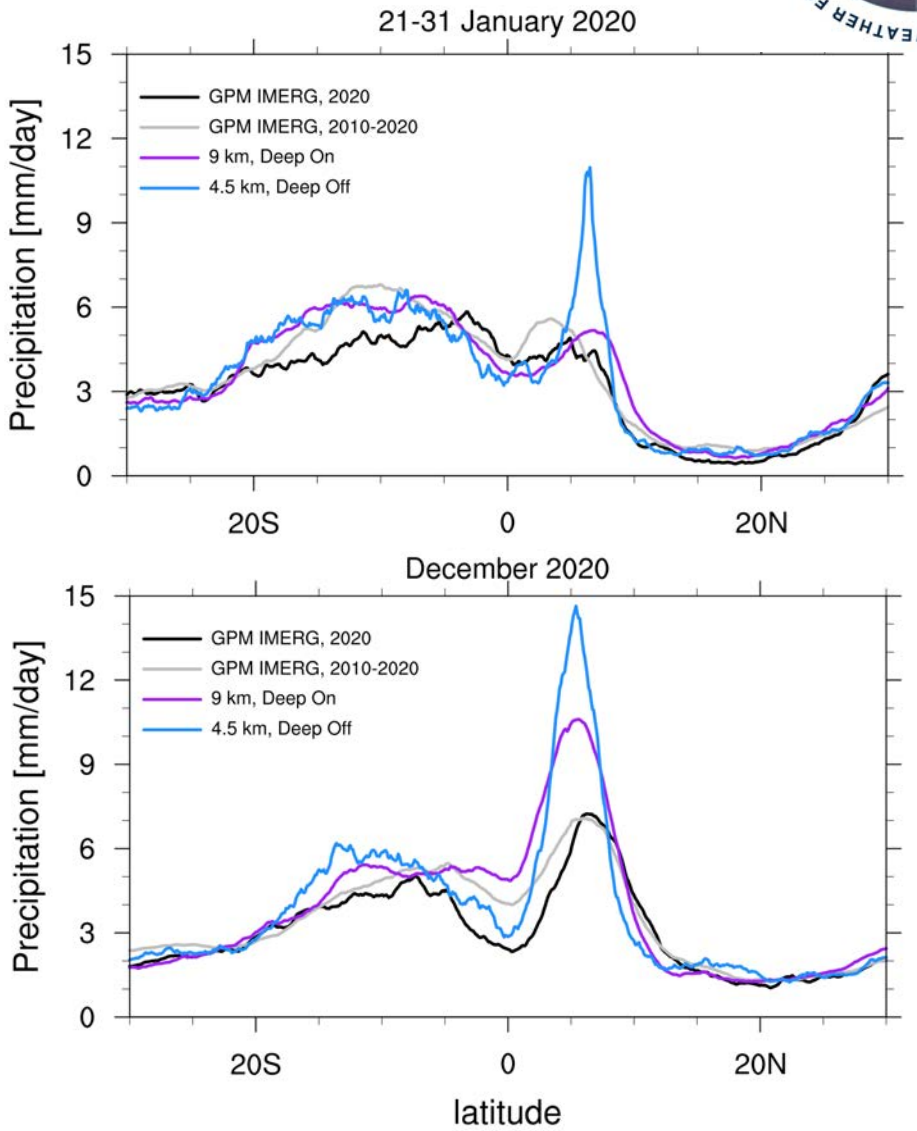
… make sure that technology is not running away from us!

So let's push km-scale models to operations!? – Not out of the box

Scientific developments will be needed to make the most of km-scale models!

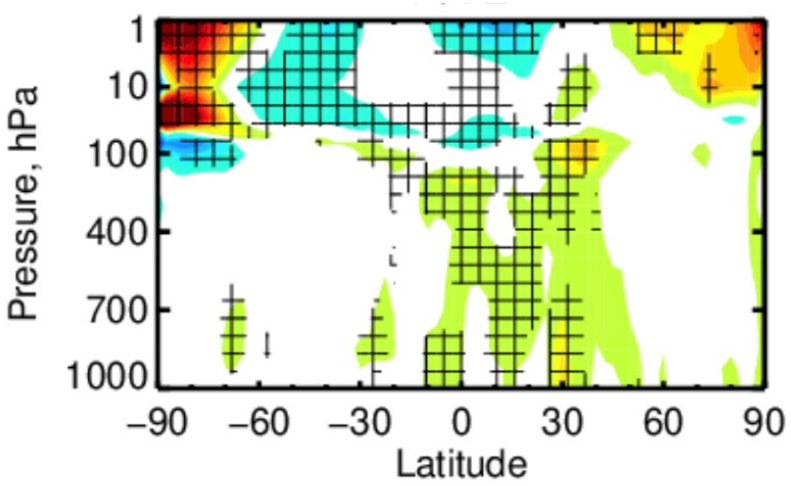
Precipitation (extremes, MCS, etc)





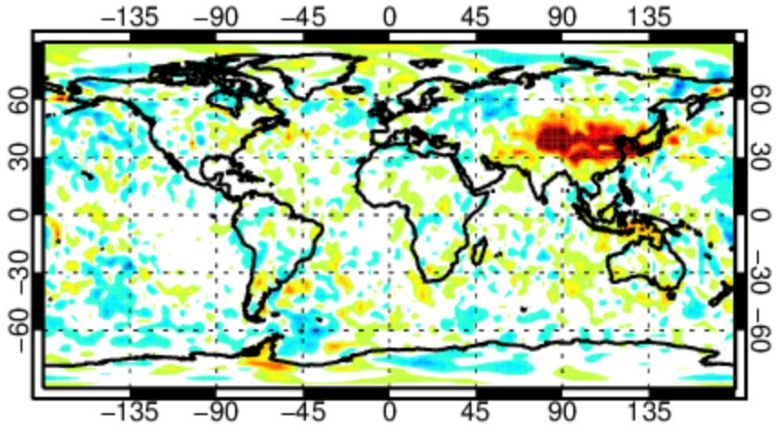
So let's push km-scale models to operations!? – Not out of the box

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

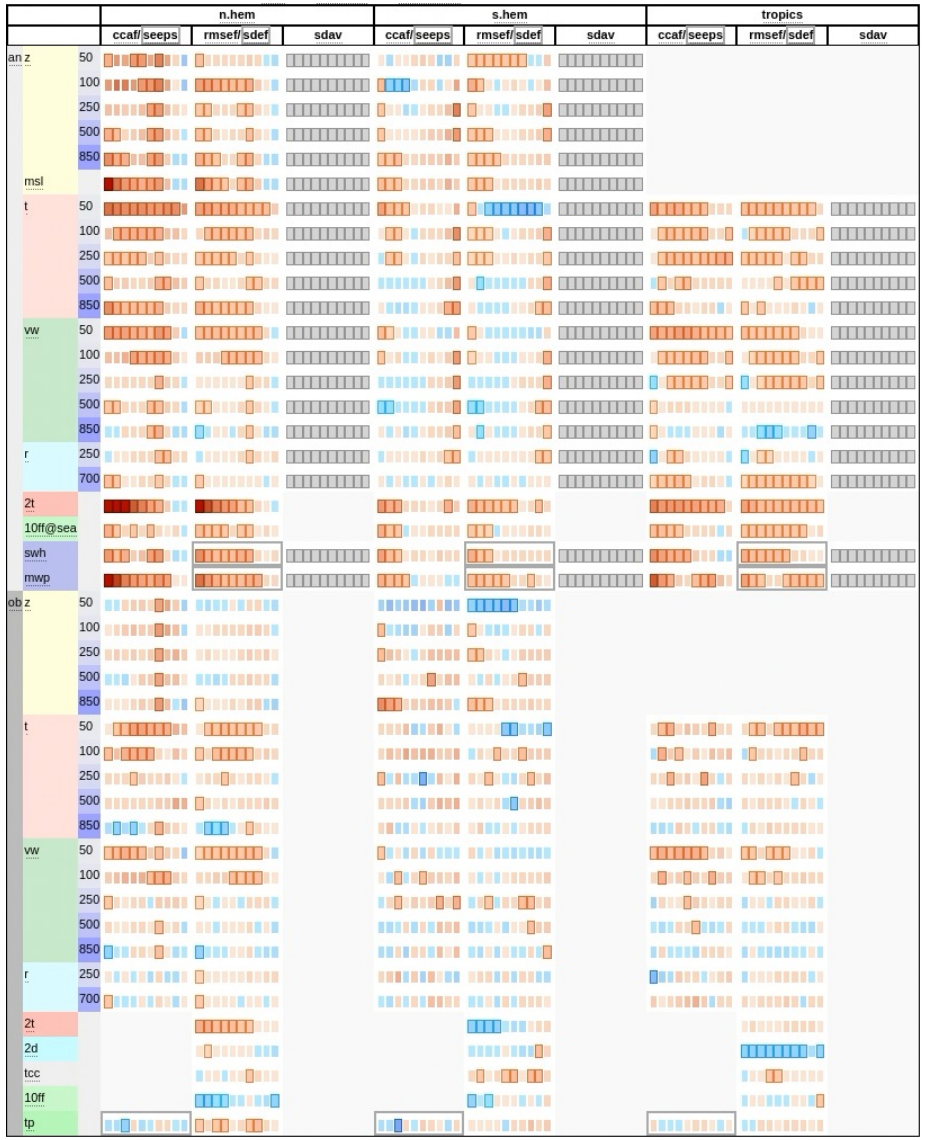


Increase in RMSE - Decrease in RMSE

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



Scorecard FC Winter 2021-2022
4.5km – 9km



EU's Destination Earth (DestinE) initiative

Towards a Digital Twin Earth

simulations

(ECMWF IFS 1.4 km)

observations

ECMWF

EuroHPC Joint Undertaking

Funded by the European Union

EU’s Destination Earth (DestinE) initiative

Towards a Digital Twin Earth

Entrusted entities

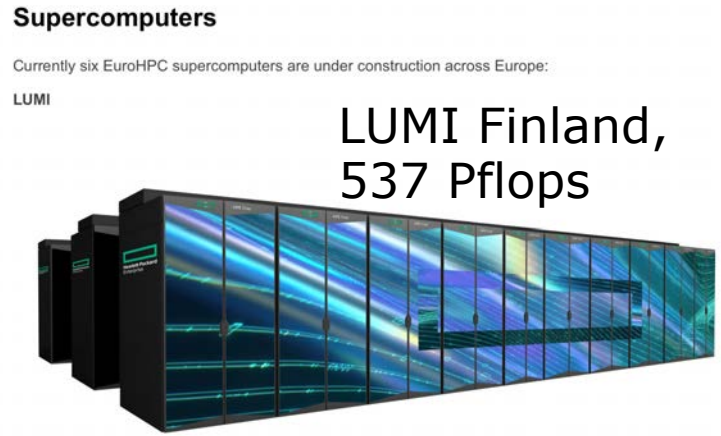
ECMWF esa EUMETSAT

Key elements

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

Funded by the European Union

EuroHPC: €8 billion programme towards exascale



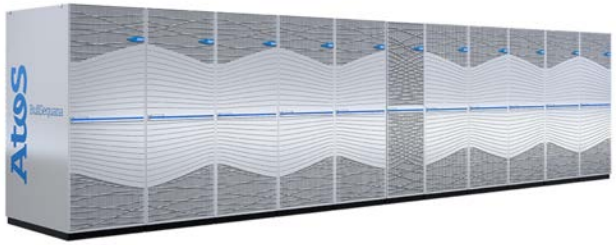
LUMI Finland,
537 Pflops

*from Sept 2022

- 3 large (O(100PFlops)) supercomputers in Finland, Italy, Spain
- 5 smaller ones (size of Archer in UK) in Luxembourg, Slovenia, Portugal, Czech Republic, Bulgaria
- 1-2 high-end supercomputers (~1000 Pflops) by 2024

*from March 2023

Leonardo Italy:
256 PFlops



MareNostrum 5
~300 Pflops
*from July 2023

ECMWF

A maximum of **10% of the Union's access time is dedicated to strategic initiatives**

ECMWF's role in EU's DestinE initiative

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 (a few days ahead)**

Climate Change Adaptation **Digital Twin**:

- capabilities and services in support of climate change **adaptation policies and mitigation scenario** testing **(multi-decadal)**

ECMWF

EuroHPC Joint Undertaking

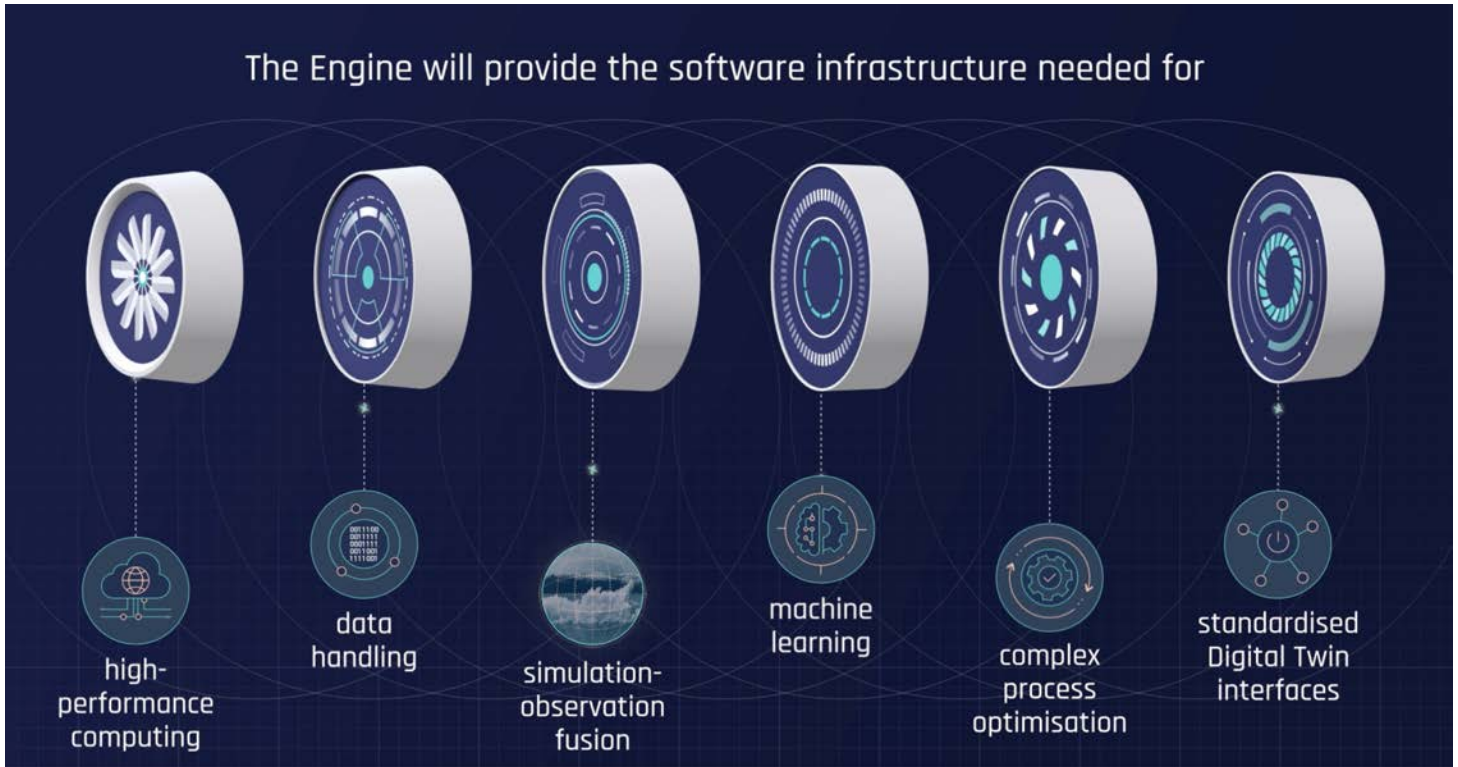
Funded by the European Union

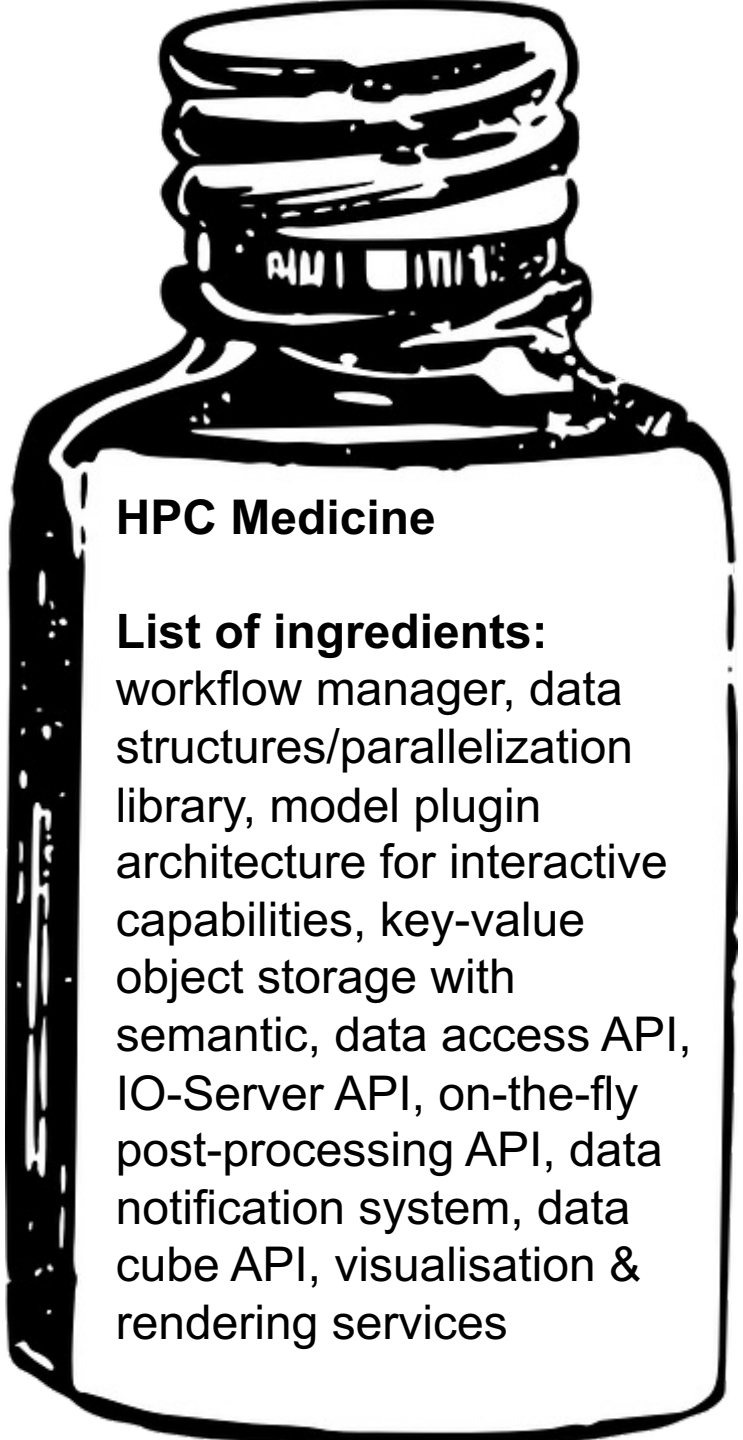
DestinE' Digital Twin Engine

Framework for Digital Twin Workflows

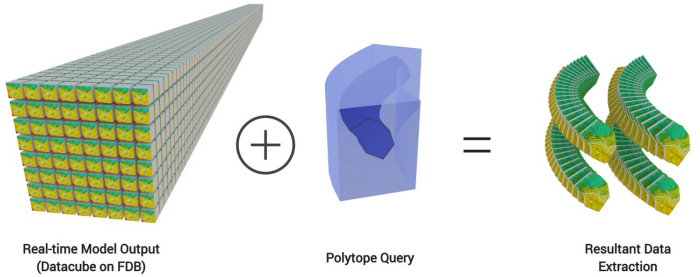
- High Performance Computing adaptation / Digital Twin optimisation
- IO and data workflows
- Software management, controlling workflows, cloud environments
- Visualization

A Game Engine type framework but for Earth Systems…





DestinE's Digital Twins: functionalities



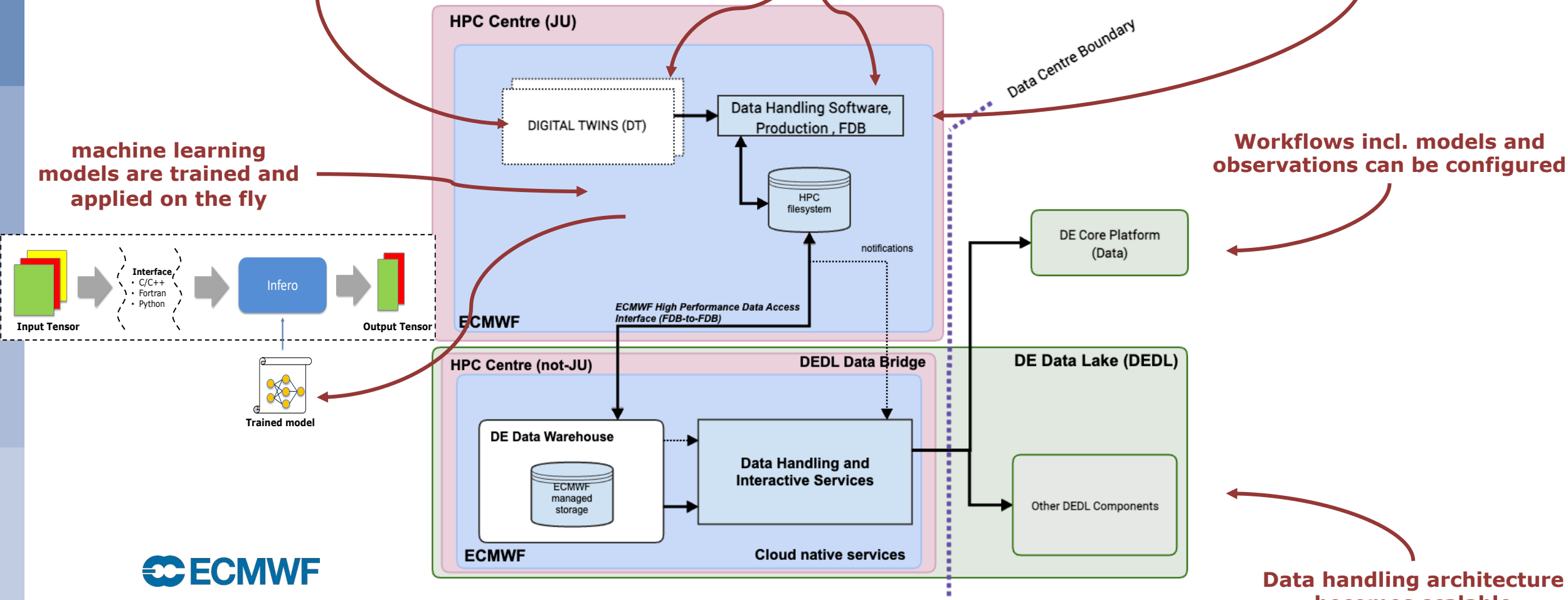
data is streamed at full 4D-resolution and coupled with applications (water, food, energy) on the fly

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

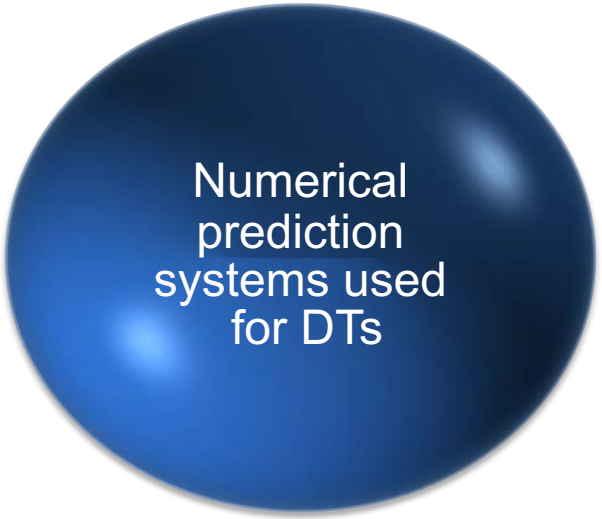
Workflows incl. models and observations can be configured



Data handling architecture becomes scalable

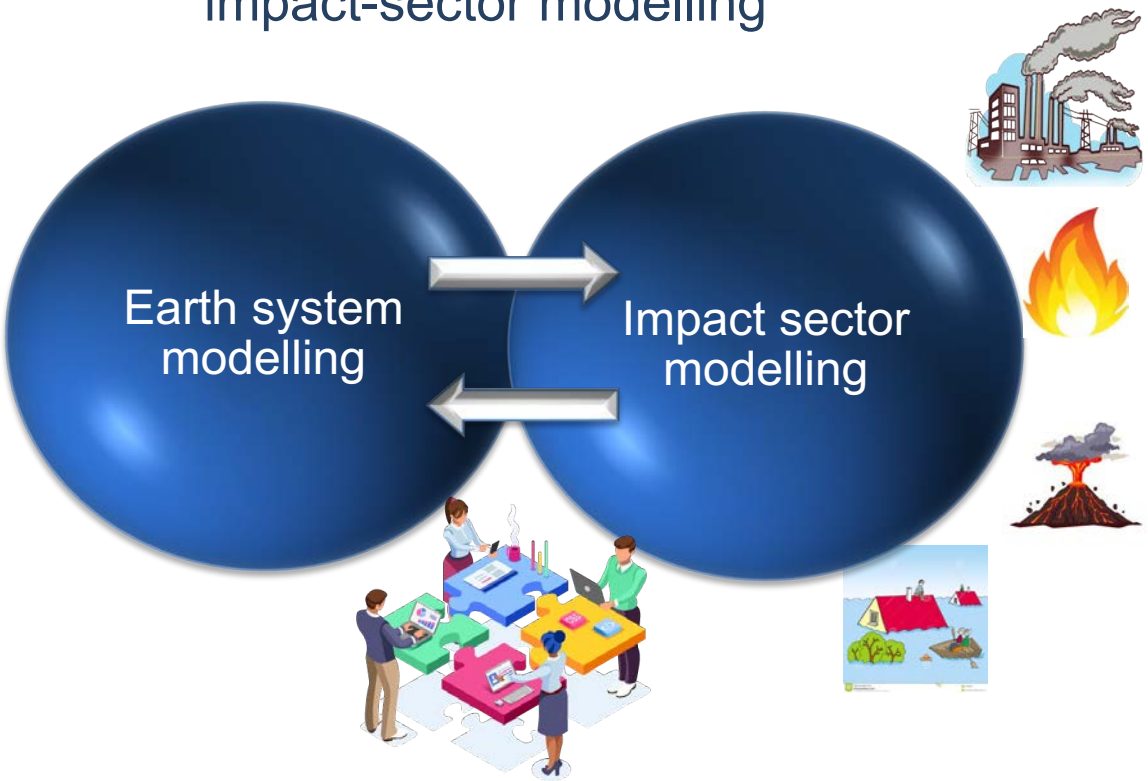
That's quite an investment – how do we make the most of it?

Stronger convergence of weather & climate prediction systems



Shared infrastructure, Use of observations, km-scale resolution

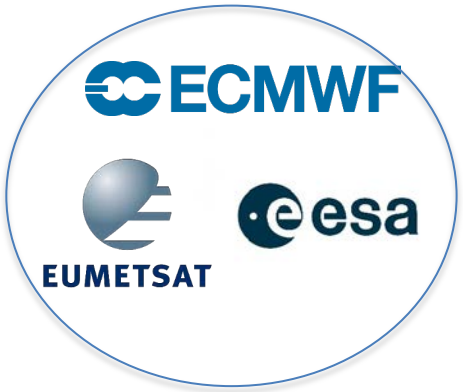
Integrated Earth-system & impact-sector modelling



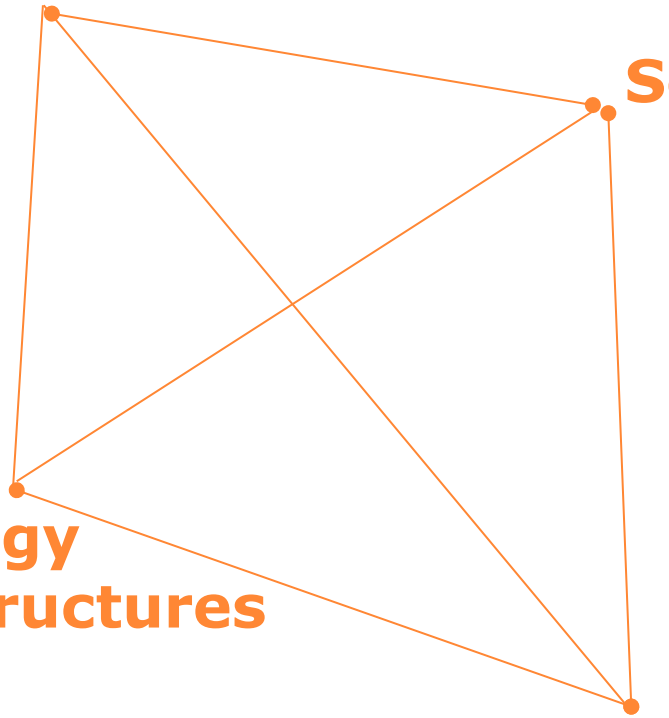
Codesign with users

ECMWF

A service-science-technology synergy



DestinE



Services

Technology
& infrastructures

Earth-system
& impact science

European Environment Agency

WMO

WCRP

Destination Earth | European Centre for Medium-Range Weather Forecasts

Copernicus
Europe's eyes on Earth

EUROPEAN OPEN SCIENCE CLOUD

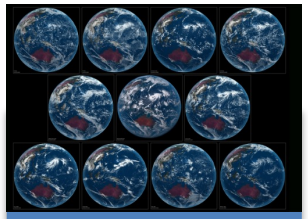
EuroHPC
Joint Undertaking

SIMPL

ECMWF

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

Challenges in key science elements of the Digital Twins

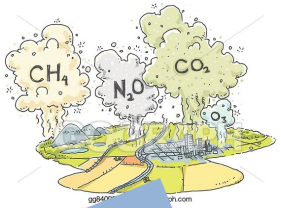


Earth System Modelling development

Beyond prototype km-scale ESMs & pretty pictures

Users

Atm composition



integration & codesign with impact modelling

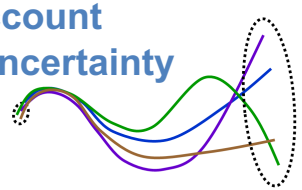
Hydrology

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

Data assimilation

Uncertainty

New approaches to account for uncertainty



DT

Observation information extraction

IoT

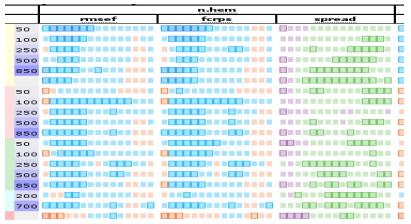
Under exploited and HR observations

ML/AI approaches

Emulation
Data compression
Uncertainty quantification
....

R2O

Verification



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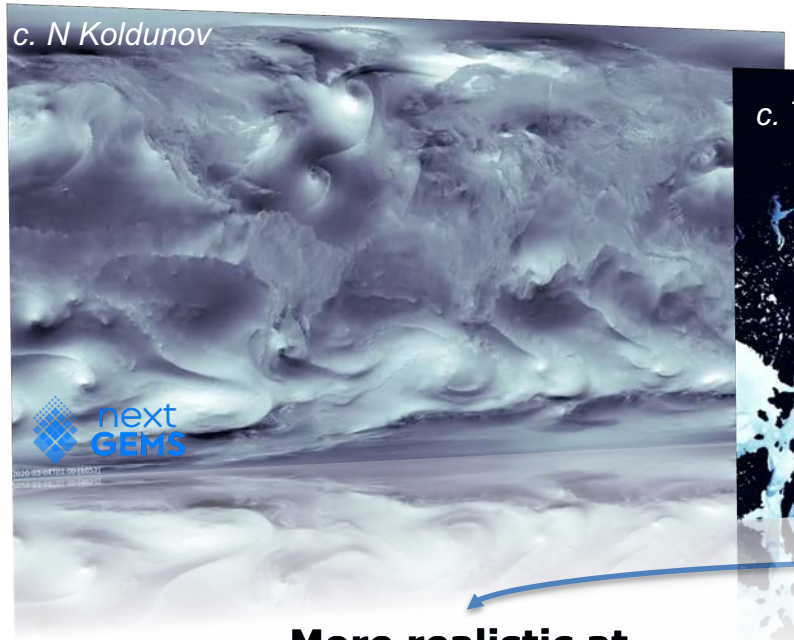
DestinE's Digital Twins: Quality + Impacts + Interaction

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

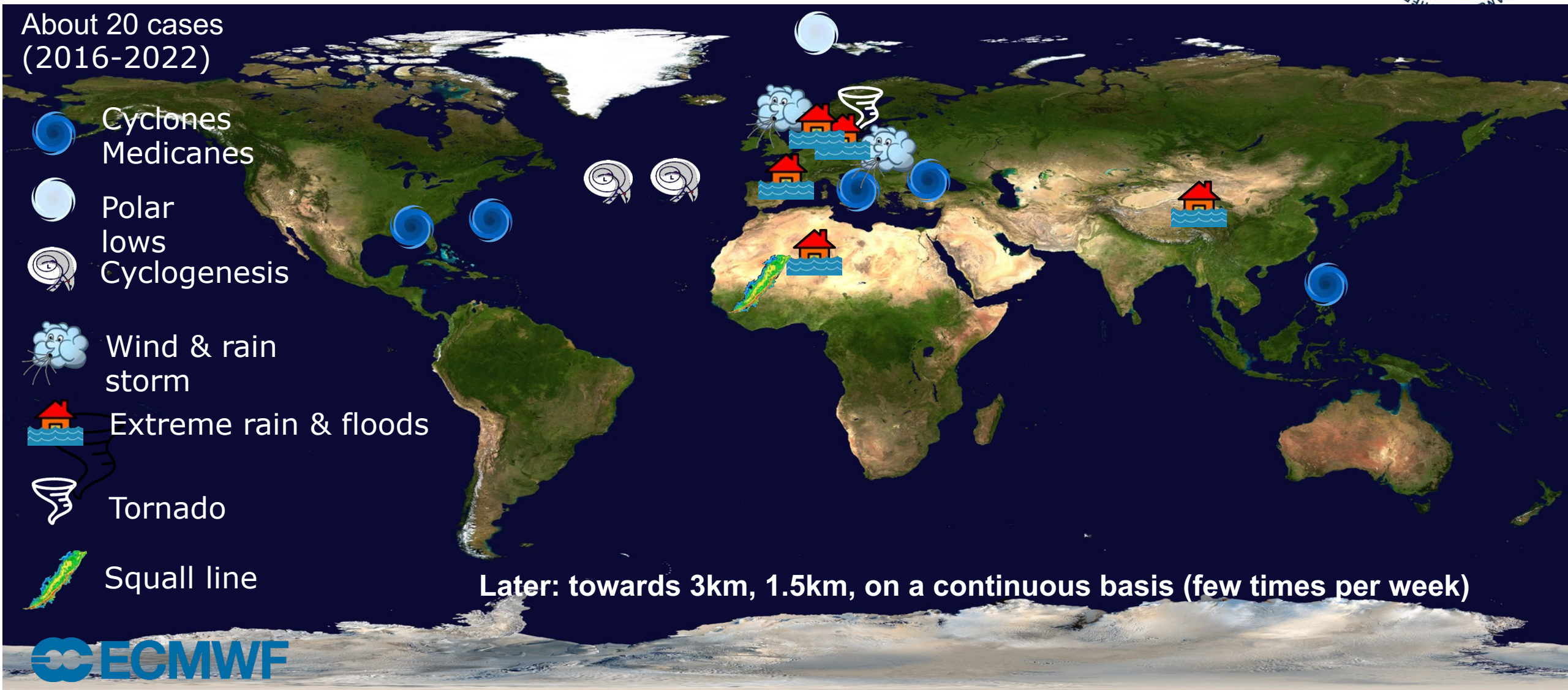
Include impacts where they matter

Trial different adaptation and mitigation scenarios

ECMWF

Continuous Extremes Digital Twins – initial extreme events cases

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

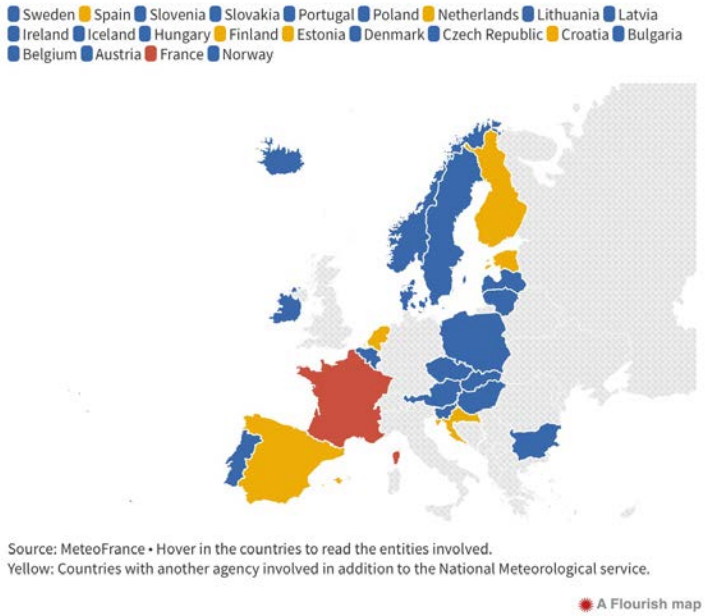


ECMWF

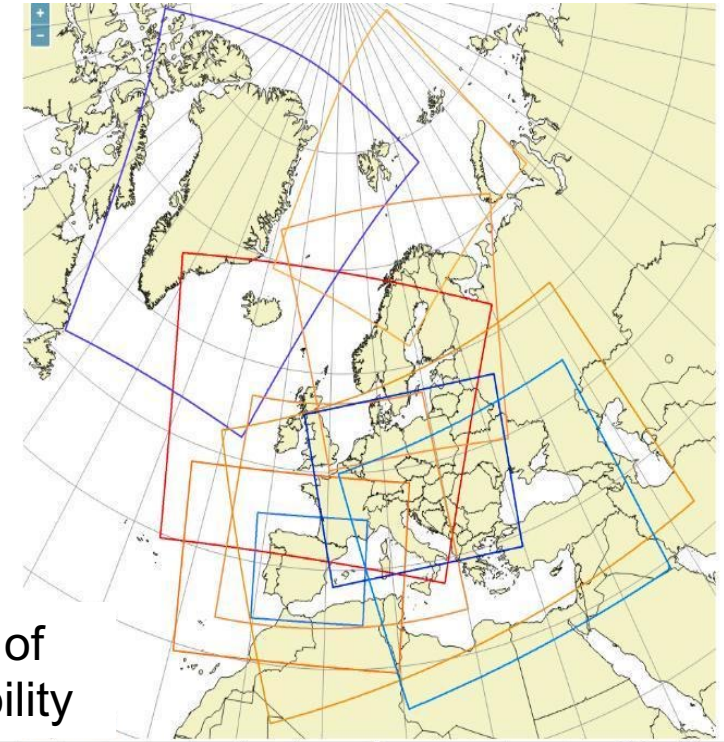
On-demand Extremes Digital Twin (procured)

Meteo-France led consortium to develop 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

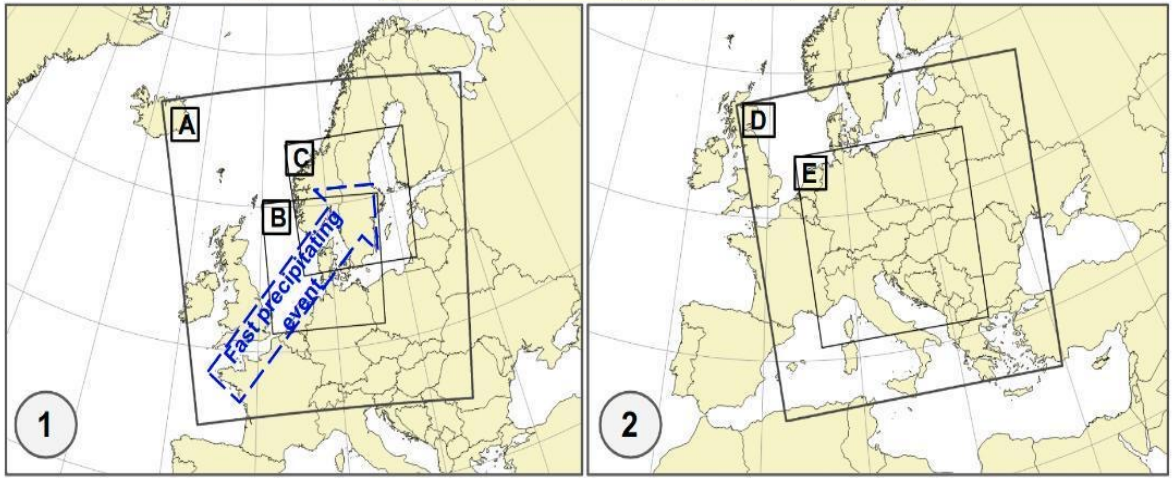
Participant countries and agencies from the ACCORD consortium



Today's prediction systems



Examples of configurability

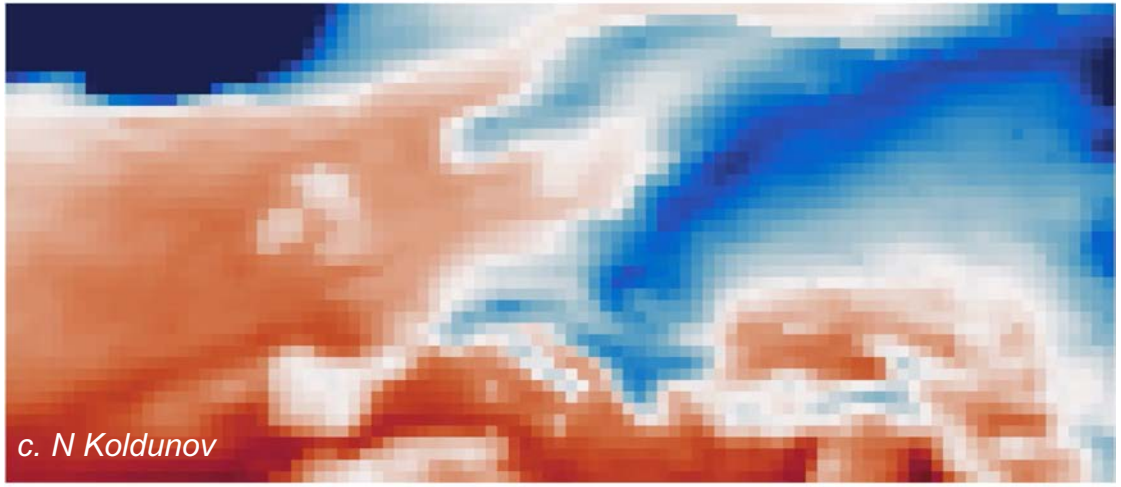


Climate Digital Twin (procured)

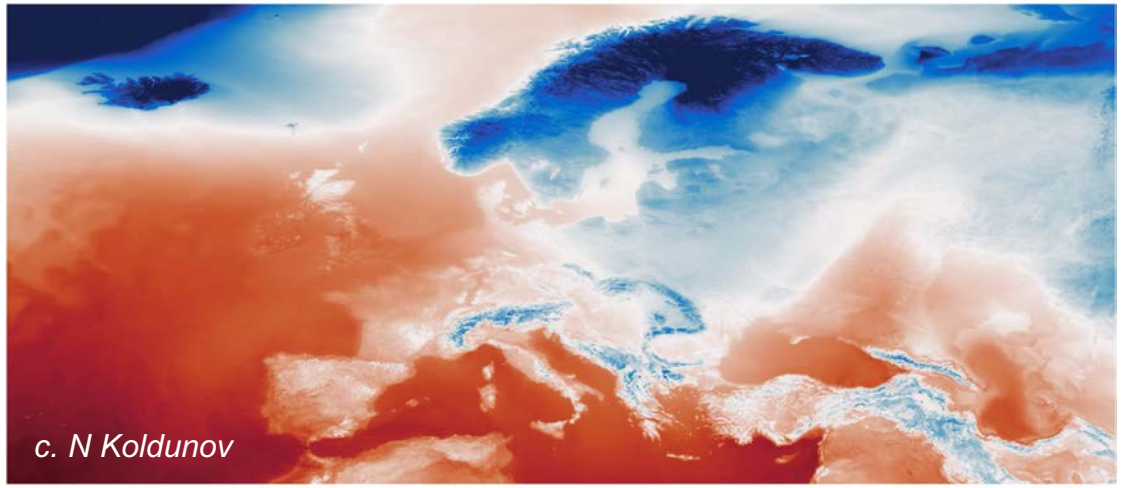
CSC led consortium to build multi-decadal, global, storm/eddy-resolving numerical Earth-system simulation capability with the timely delivery of climate information for policy adaptation; observation based assessment framework; use cases for impact-sectors such as water, energy, food or health

Two storm-and-eddy-resolving Earth system models:
- ECMWF's IFS coupled to NEMO or FESOM
- ICON

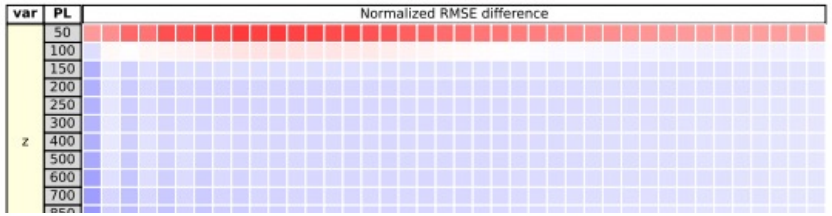
Today's global climate models

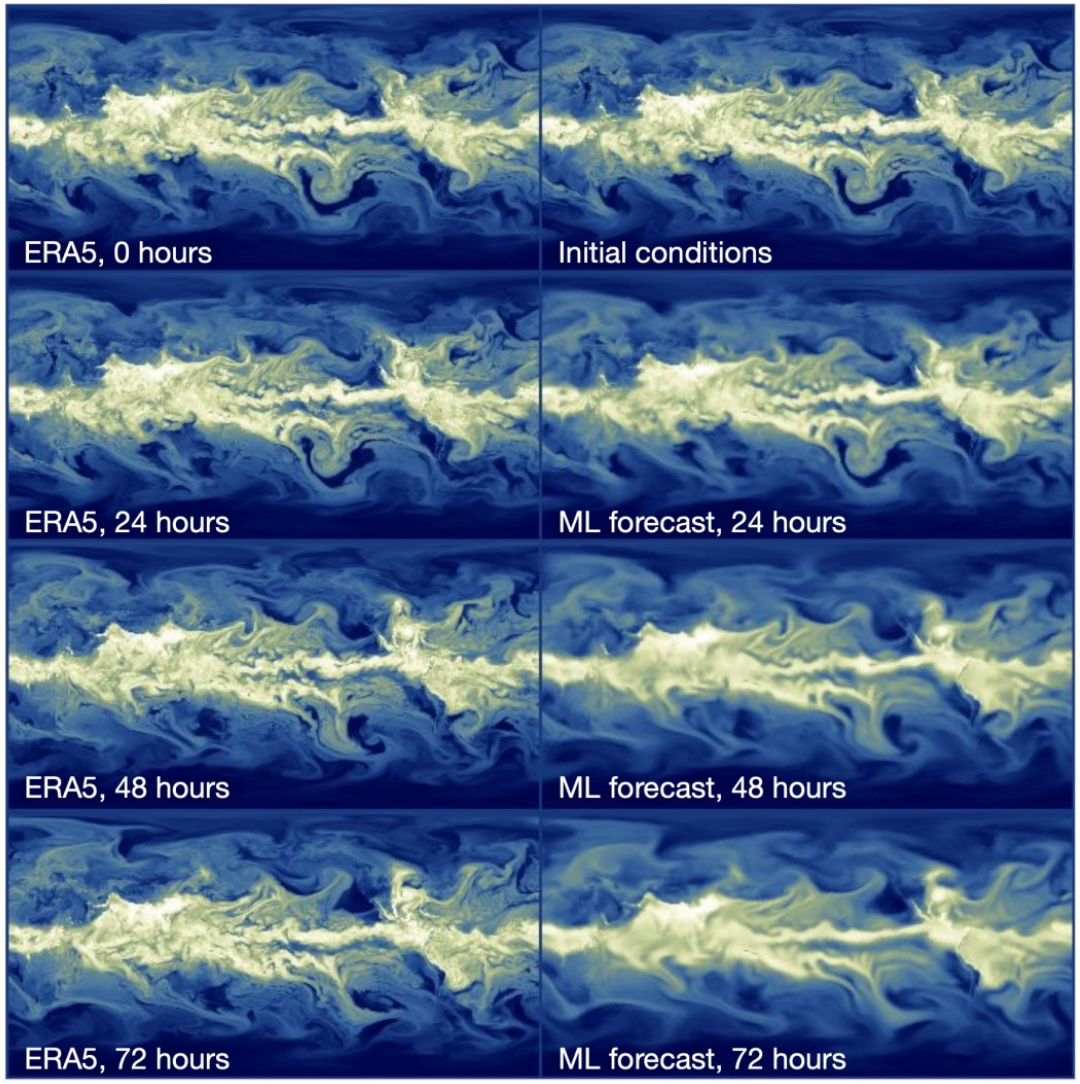


Storm & eddy resolving simulations



Will machine learned take over? – What's the point of DestinE?





GraphCast from Google/Deepmind is beating conventional weather forecast model in deterministic scores.

But how do these models actually work?

They are trained for a small Root Mean Square Error.
→ They smear out for large lead times.

They get the best results when using very large timesteps (6h vs. 600s) and a couple of the previous timesteps as input.
→ Implicit? Explicit?

They do not model the physical equations,
they learn to please the scores.

Can they extrapolate? Learn uncertainty? Learn from observations? Fill the state vector? Learn all important processes?

Images from Keisler (2022)

Will machine learned take over? – What's the point of DestinE?

You need the best data possible to train.

What could be better than a digital twin?
→ DestinE and Copernicus will be the place to go in the future.
See Hans' talk!

And machine learning can help to design and realise digital twins as well.

You want to learn more about machine learning? – Join our MOOC

You can join our ECMWF Massive Open Online Course (MOOC) on Machine Learning in Weather & Climate:
https://lms.ecmwf.int/pages/index.html

We have 4 open machine learning positions at ECMWF at the moment!
https://jobs.ecmwf.int/displayjob.aspx?jobid=134