Deutscher Wetterdienst
Wetter und Klima aus einer Hand

DWD

DKRZ

KIT Karlsruher Institut für Technologie

natESM

Federal Ministry of Research, Technology and Space

# ICON atmosphere-ocean simulations (a MPI-M perspective)

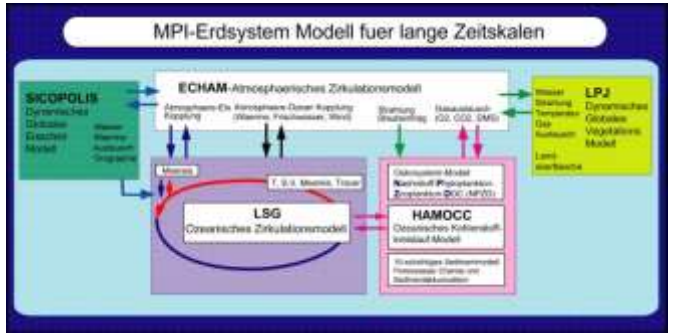
Johann Jungclaus, Max Planck Institute for Meteorology, Hamburg

# Outline

- Introduction
- The ICON framework and the ICON component models
- ICON “Ruby”: experiments on “climate” time scales
  - ICON-ESM V1.0: The first coupled ICON-based ESM
  - ICON-ESM XPP: toward seamless predictions from seasonal to decadal scales
- ICON “Sapphire”: experiments using storm and eddy-resolving model set-ups at km scale
- Conclusions

# …a little bit of history…

- Klaus Hasselmann, as founding director of MPI-M, brought together experts for atmospheric, land and ocean modeling in Hamburg
- …and established the German Climate Computing Center DKRZ: equipping German climate research with high-performance computers.
- In the mid-90s, MPI-M is one of the world's leading climate modelling centers
- MPI-M's coupled and Earth System models contributed to all rounds of CMIP
- MPI-ESM1.2 as in CMIP6 concludes the "era" of ECHAM-based ESMs in 2019



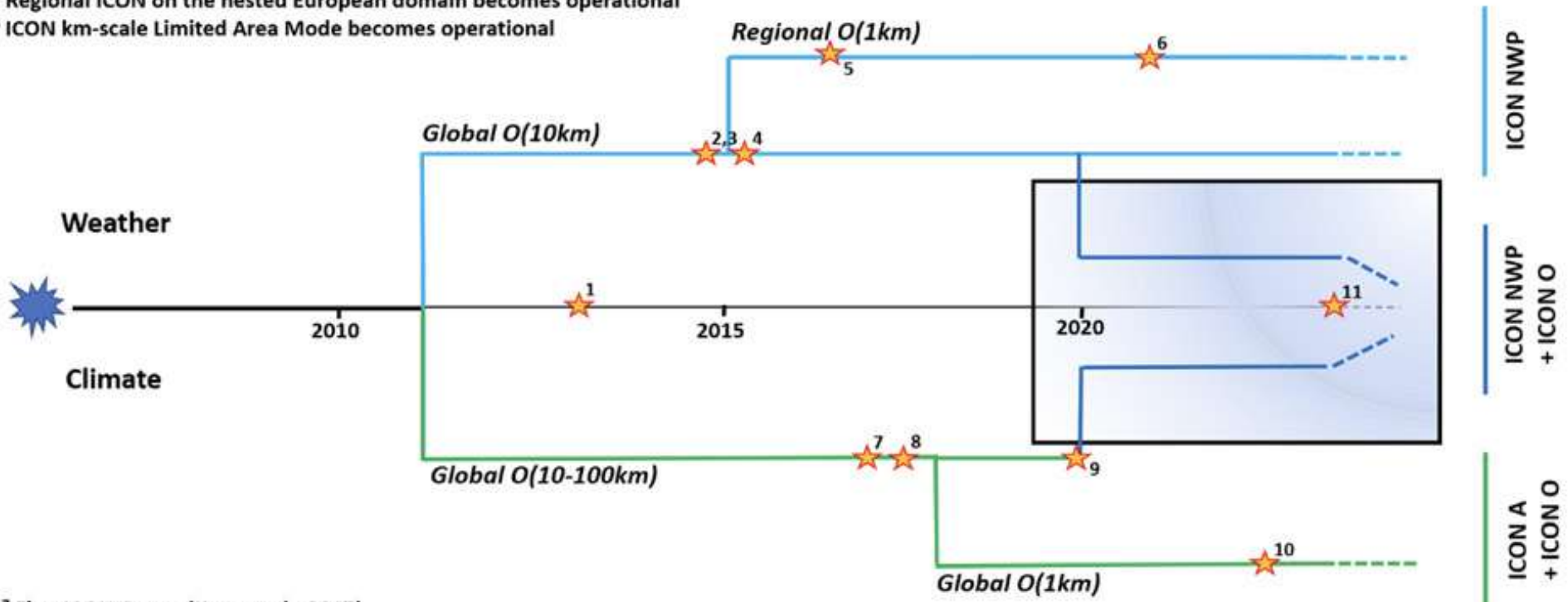

*ECHAM4/LSG*

*CDC 205, 1988*

# …and some ICON history…

(a)

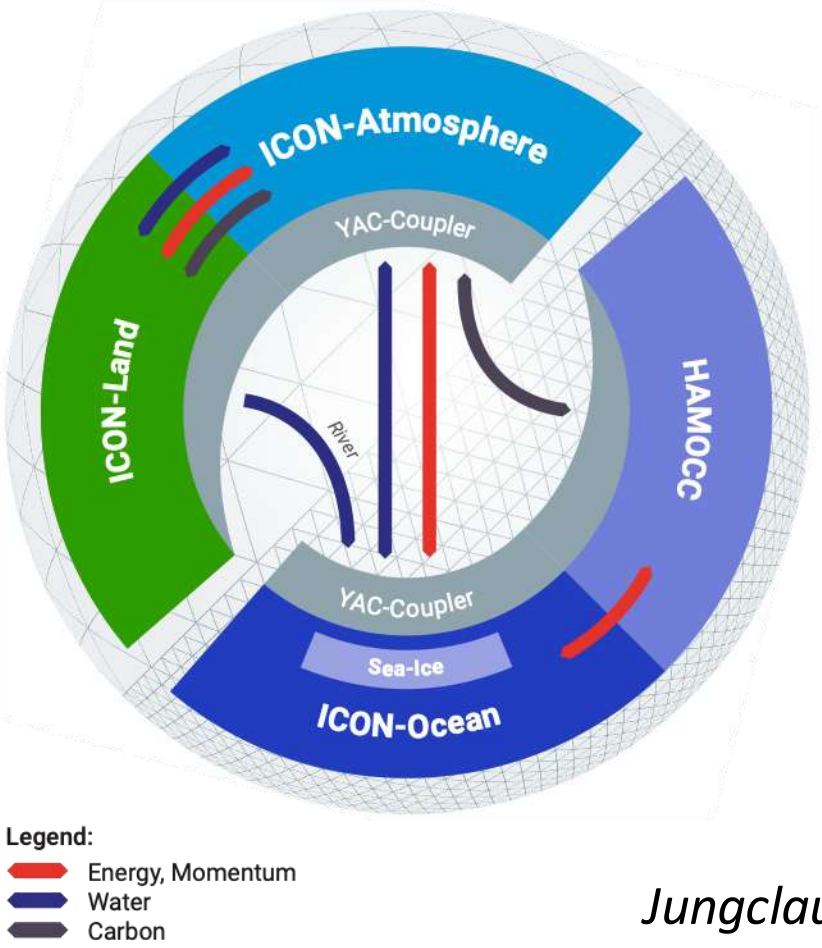
[1] First ICON hydrostatic atmospheric dynamical core on triangular grids (Wan et al., 2013)
[2] ICON modelling framework of DWD and MPI-M (Zängl et al., 2015)
[3] ICON-NWP becomes operational
[4] ICON-ART 1.0 (Rieger et al., 2015)
[5] Regional ICON on the nested European domain becomes operational
[6] ICON km-scale Limited Area Mode becomes operational




[7] First ICON Ocean (Korn et al., 2017)
[8] ICON-A, the atmosphere component of the ICON Earth system model (Giorgetta et al., 2018)
[9] First ICON coupled Earth system model – ICON-ESM (Jungclaus et al., 2022)
[10] First ICON Earth system at kilometer and subkilometer scales (Hohenegger et al., 2023)
[11] ICON Open Source Release in 2024

*Müller et al., BAMS, 2025*

# The coupled ICON ESM

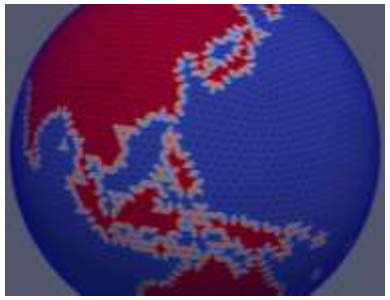


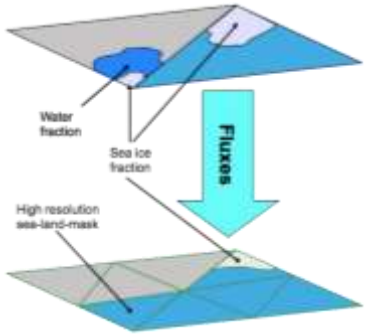

*Jungclaus et al., 2022*

**Processes, sub-models and interfaces:**

- Atmosphere (ICON-A):
  - Energy fluxes
  - Water cycle and water mass exchange
  - Energy momentum
- Ocean (ICON-O):
  - Sea surface temperature
  - Sea ice
  - Surface ocean velocity
- Land (JSBACH+HD):
  - Energy and energy momentum (between atmosphere and land)
  - Runoff to the ocean

# The YAC coupler






- collaboration between DKRZ and MPI-M
- universal coupler software
- imbedded MPI (Message Passing Interface)
- scalable parallel neighbourhood search and data exchange of 2d fields on the sphere

coupling on tiles:

- fractional SLM in the atmosphere
- physically consistent methods for partitioning of fluxes (tiles) and interpolation provided

*Hanke et al., 2016; Hanke and Redler, 2019*

# The ‘experiment-driven’ modelling strategy @ MPI-M

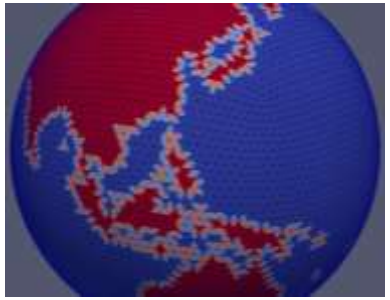
- The ICON modelling system provides MPI-M with a modern and unified modelling platform. ICON can be configured in various ways to model a broad range of spatio-temporal scales of the climate system.
- MPI-M employs ICON in the two overarching projects ‘Sapphire’ and ‘Ruby’. Sapphire and Ruby both are experiment-driven and comprise several specifically designed experiments.
- The term ‘experiment-driven’ reflects the focus on concrete scientific interest and the priority of basic research in contrast to model development as service to the community.

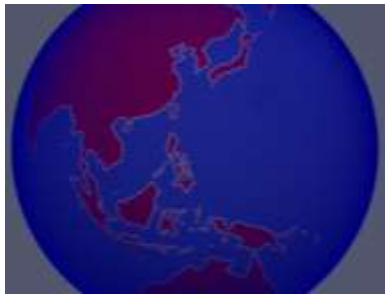
# “Ruby”

**Red:** Long wavelength, low frequencies

- at least century-long global integrations (demands on stability and quality of the solution)
- long time-scales (“low” resolution, Paleo applications)
- large ensemble simulations and CMIP6-like simulations at “medium” resolution
- Near-term predictions, initialised ensembles at “medium” resolution
- longer “frontier” simulations at “high” resolutions

# ICON-ESM 1.0 (“Ruby-0”)





**Atmosphere/Land:**

- 160km resolution (R2B4, 20,480 grid-points), time-step 10 minutes
- 47 levels up to 0.1 hPa, nonhydrostatic core, ECHAM physics
- Moist atmosphere initialization.

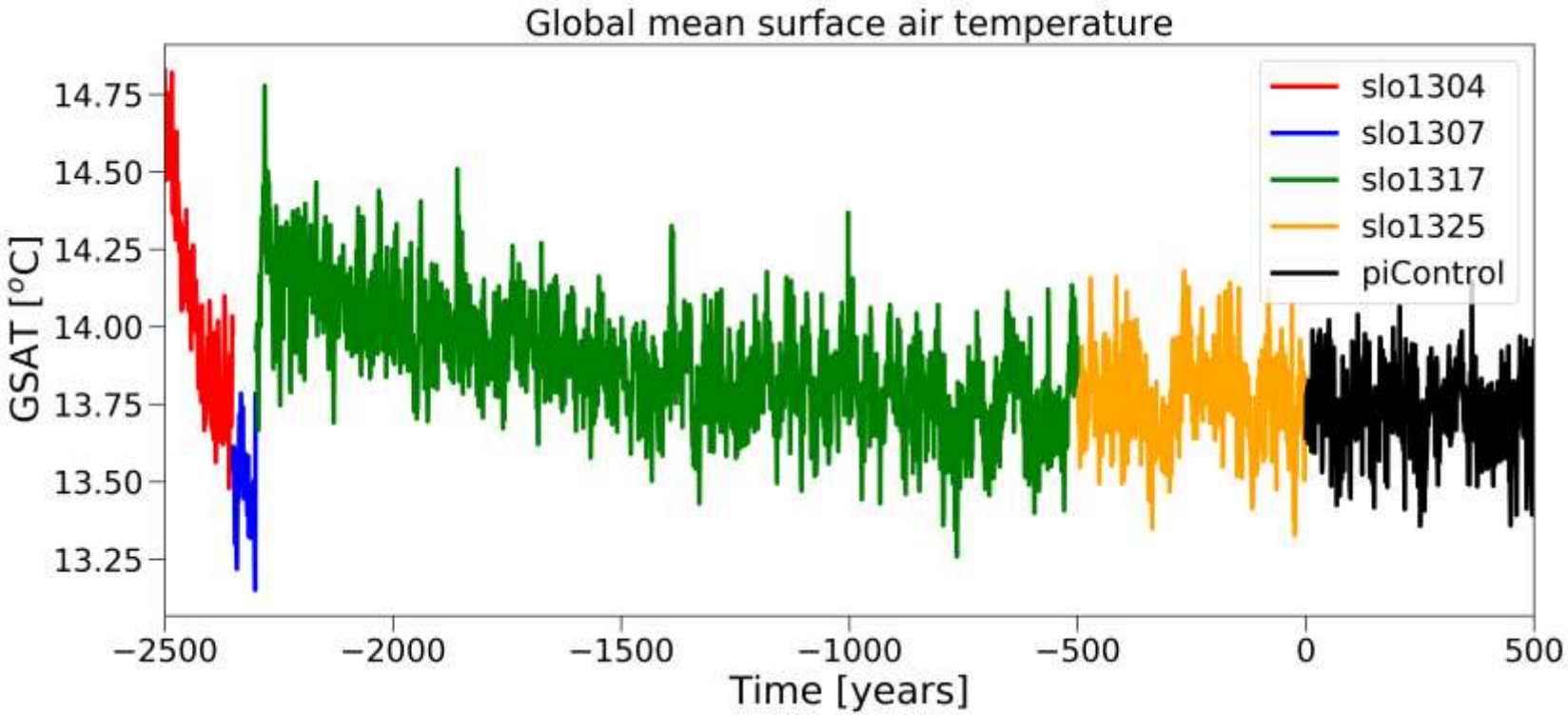
**Ocean/Sea-ice:**

- 40km resolution (R2B6, 230,000 wet points), time-step 30 minutes
- 64 vertical levels, 10-320m thickness,
- Thermodynamic sea-ice module with sea ice dynamics from FESIM
- Ocean biogeochemistry model HAMOCC included
- Sub-grid scale eddy parameterization (GM/Redi)

Throughput on DKRZ Mistral: up to 120 SYPD, 40 SYPD with HAMOCC

*Jungclaus et al., JAMES, 2022*

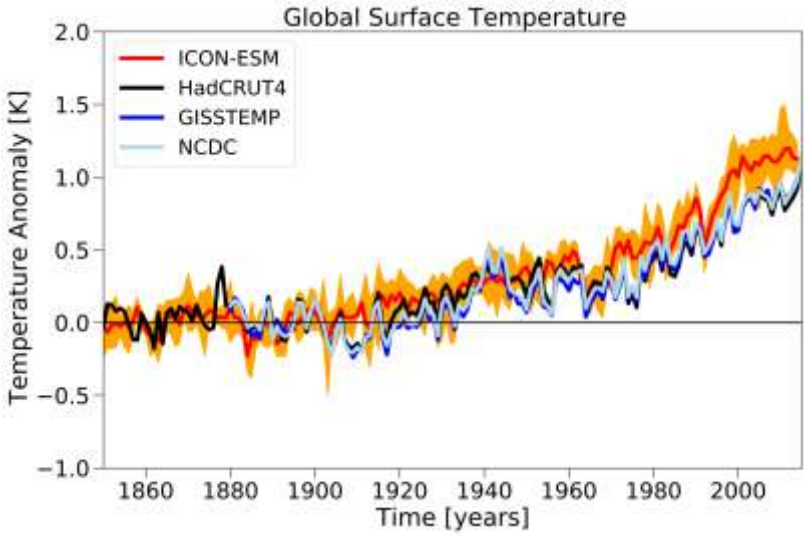
# ICON-ESM 1.0 (“Ruby-0”)

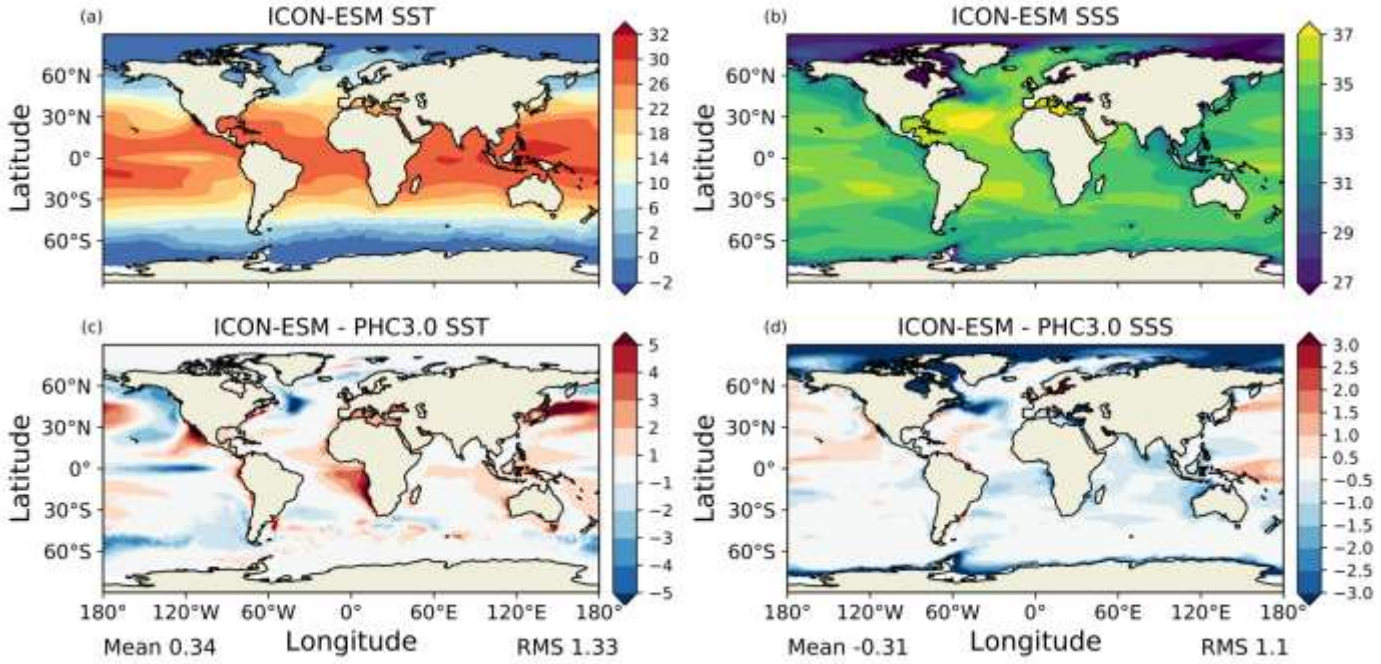



*Jungclaus et al., JAMES, 2022*

spin-up history reflects long adjustment times

# ICON-ESM 1.0 (“Ruby-0”)




CMIP6 historical runs show overall good agreement with observations, bias patterns similar to MPI-ESM. Slight overestimation of the late historical period, possibly related to aerosol effects

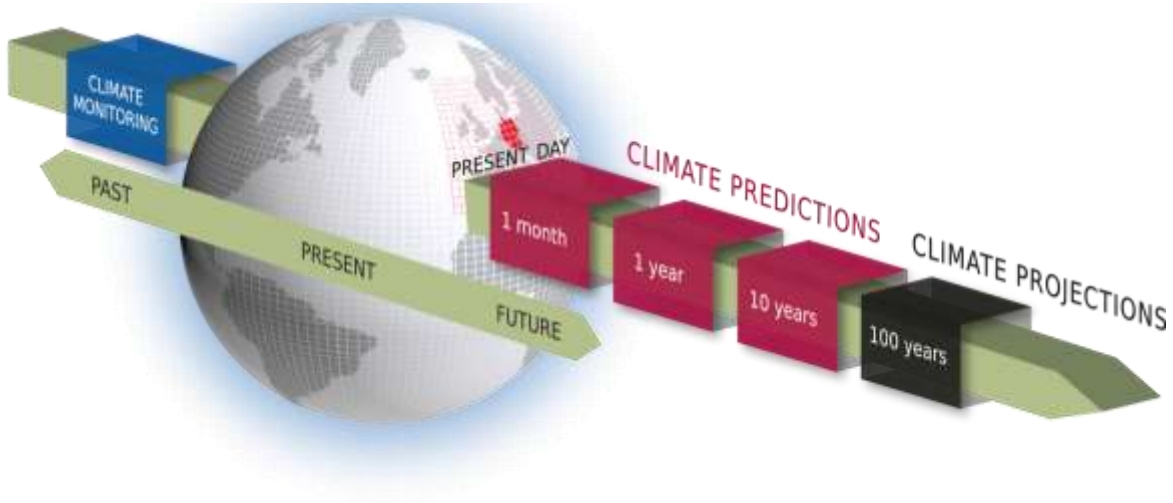
*Jungclaus et al., JAMES, 2022*

# “Seamless” towards ICON-XPP

ICON-Seamless =
Model and Data Assimilation for

- ✓ Numerical Weather Prediction (NWP)
- ✓ Climate Prediction (Seasonal, Decadal)
- ✓ Climate Projections

- One consistent model including Atmosphere (ICON-NWP), Ocean (ICON-O), Land (ICON-Land), ICON-ART
- Configurations for different application scenarios well balanced and compatible



# ICON-ESM XPP "Target"

**Atmosphere/Land:**

- 80km resolution (R2B5, time-step 450 s)
- 130 levels up to 0.1 hPa, nonhydrostatic core, **NWP** physics
- external HD model (Hagemann et al., 2023)

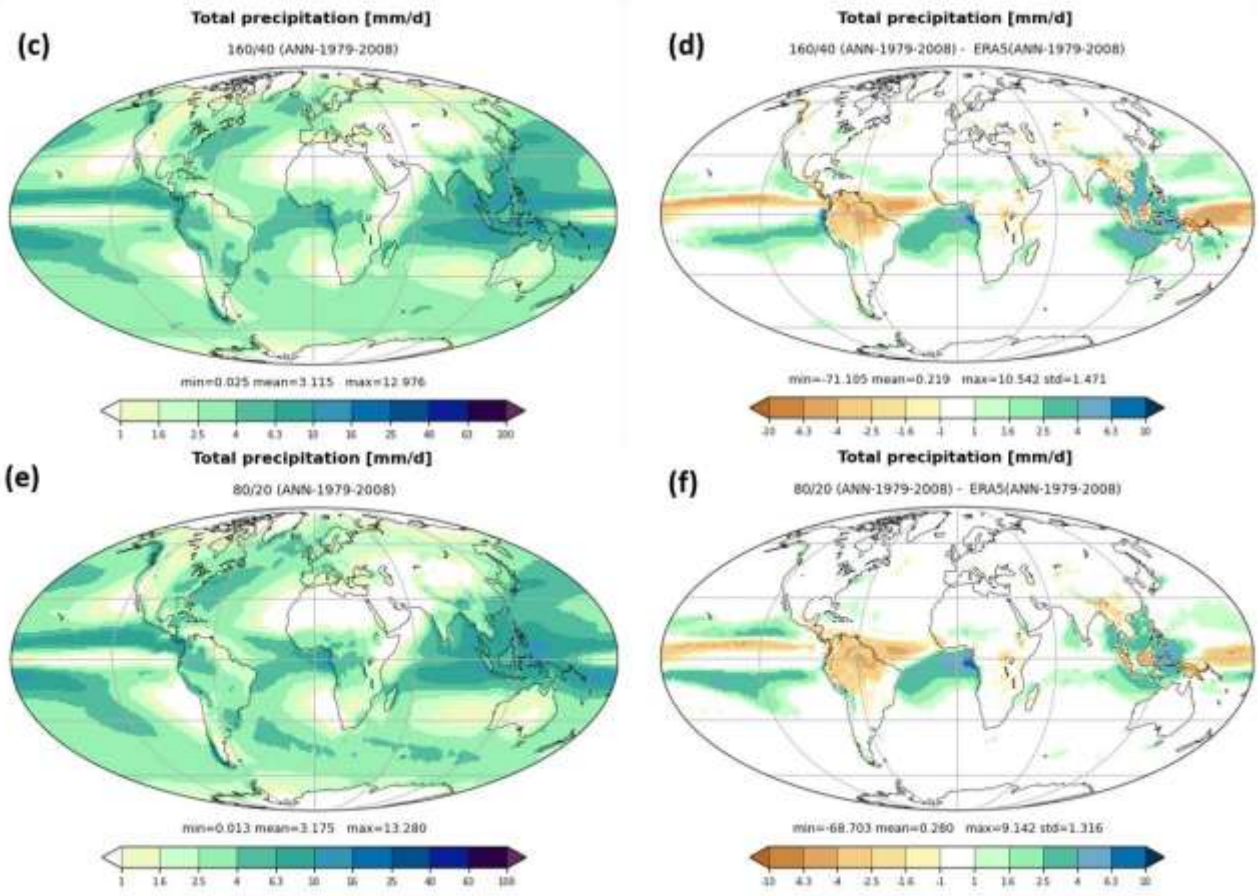
**Ocean/Sea-ice:**

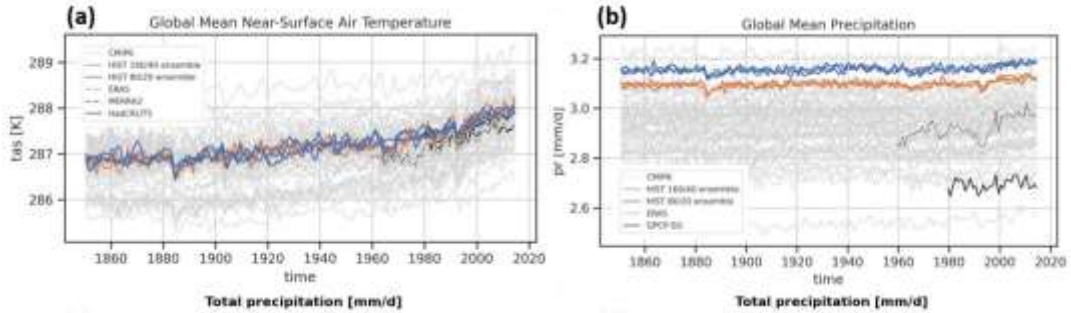
- 20km resolution (R2B7, time-step 20 minutes)
- 72 vertical levels, 2-320m thickness, z*coordinate
- Thermodynamic sea-ice module with sea ice dynamics from FESIM
- Ocean biogeochemistry model HAMOCC included
- Sub-grid scale eddy parameterization (GM/Redi)

Throughput on DKRZ Levante: 45 SYPD on 100 nodes

*Müller et al., GMDD, 2025*

# ICON-ESM XPP “Target”

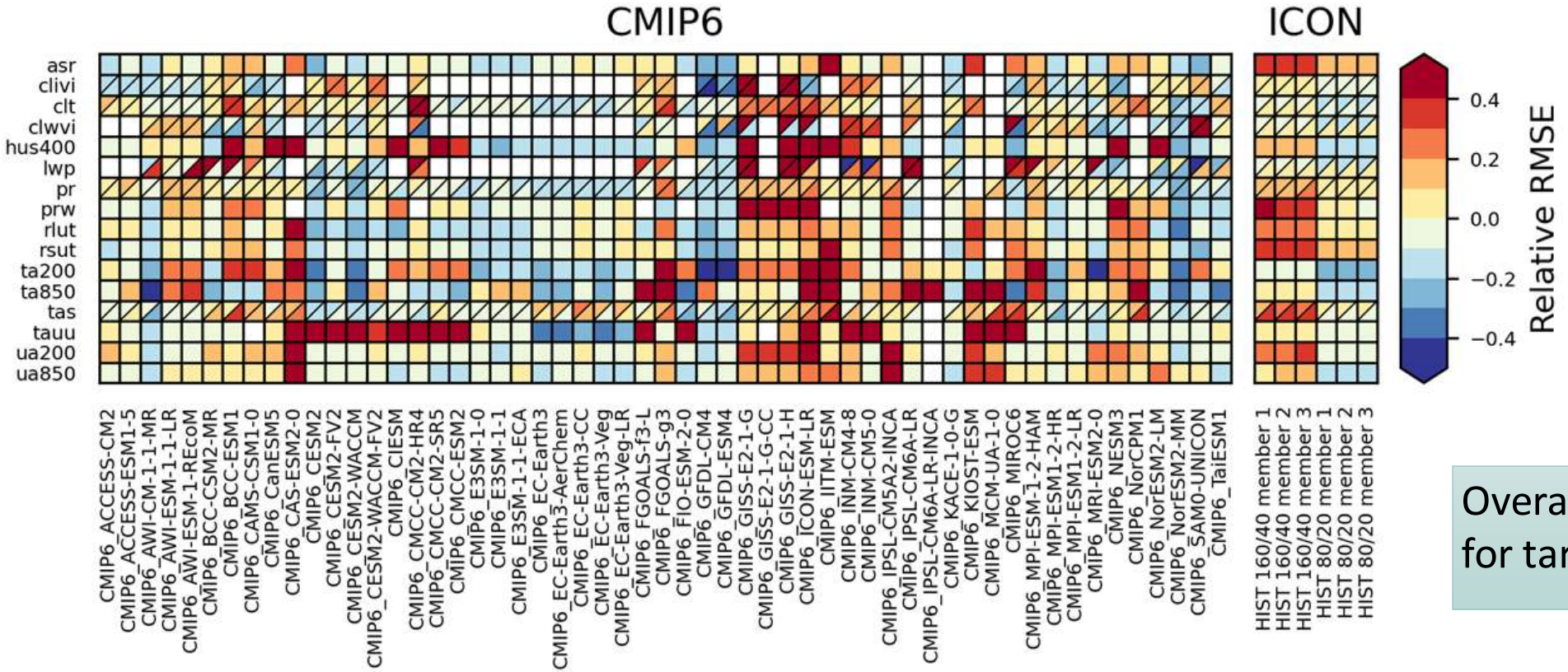



Ongoing efforts to tune ICON-XPP for bias reduction as basis for a version suitable for CMIP7

*Müller et al., GMDD, 2025*

# ICON-ESM XPP “Target”




Overall metrics score quite good for target version

*Müller et al., GMDD, 2025*

# Plans for CMIP7

- BMBF project “CAP7” led by DWD. Project partners Uni Hamburg, MPI-M, MPI-BGC, DKRZ, DLR, AWI
- Goal: conduct “core” CMIP7 experiments (DECK, Scenarios) on FastTrack (all)
- Develop ICON-XPP as full ESM with interactive carbon cycle for emission-driven CMIP7 experiments (MPI-BGC, Uni HH)
- Explore new parameterisations for specific model resolutions (ICON-O: MPI-M)
- Explore AI - based methods for parameter tuning in ICON-A (DLR)
- Data curation  and CMIP adaptation (DKRZ)

Status: Tuning phase to be finalised in October 2025. Production starts in 2026

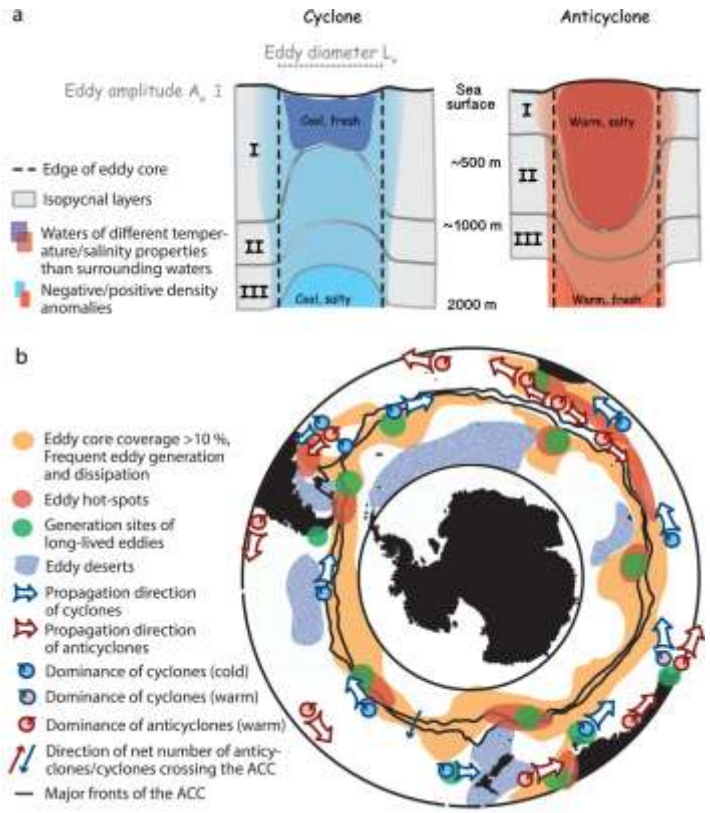
# “Sapphire”

Blue: Short wavelengths, high frequencies, very high resolution

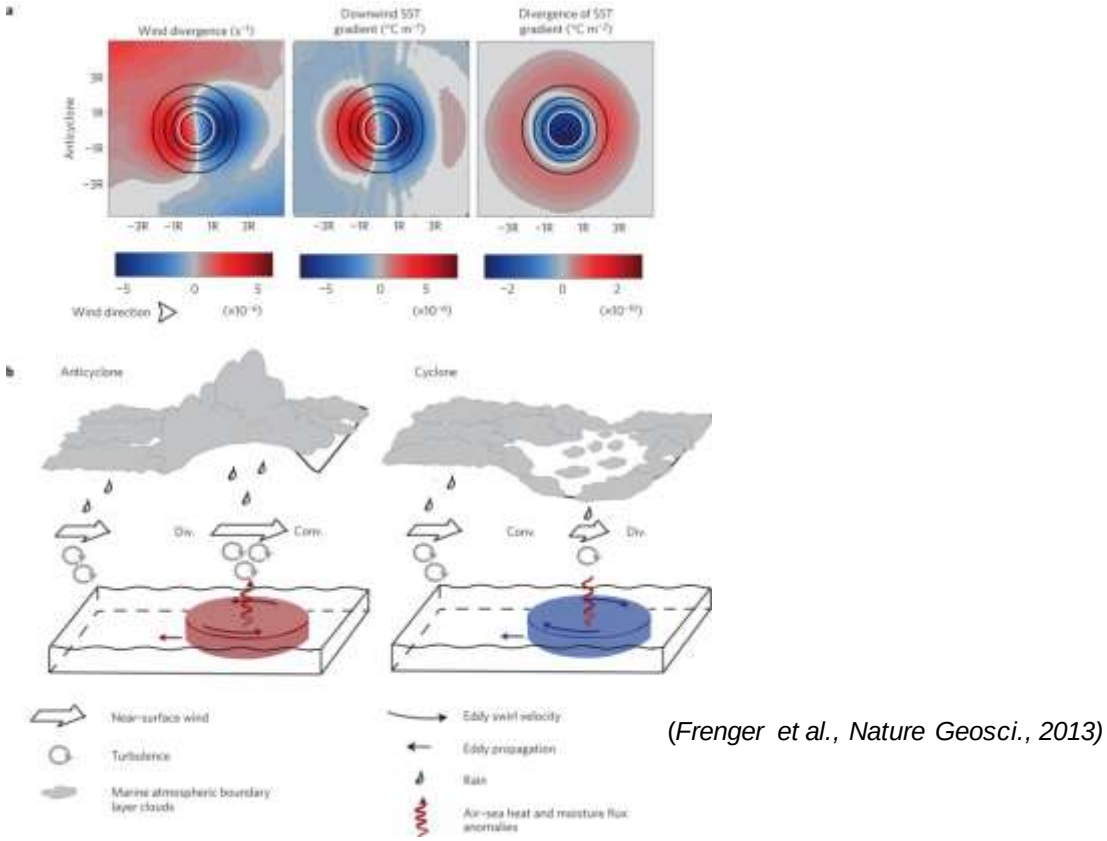
Sapphire develops:

- ICON versions where, in contrast to CMIP-type General Circulation Models, the major modes of energy transport are resolved explicitly.
- global storm resolving atmosphere and eddy-resolving ocean models at km scale
- “ICON-A” atmosphere, independent of NWP, many parameterisations switched off or re-designed for purpose
- (nested) limited area models at km-scales for the atmosphere
- focusing grids for ICON-O, zooming into the sub-mesoscale

# Why storm and eddy-resolving models?



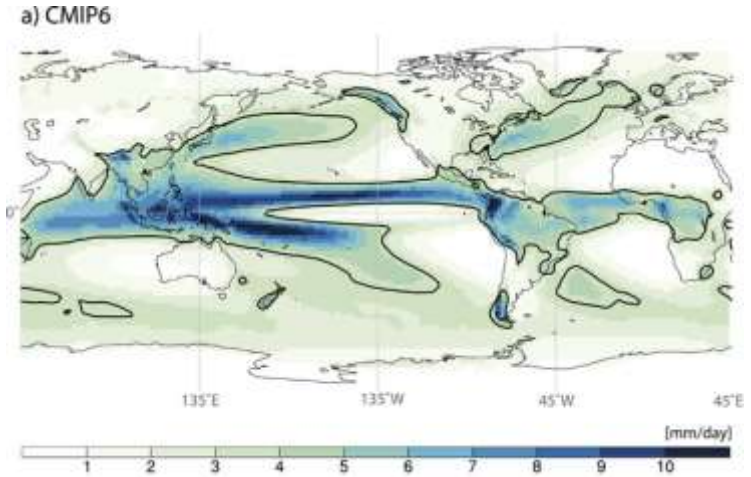

(Frenger et al., JGR-O, 2015)

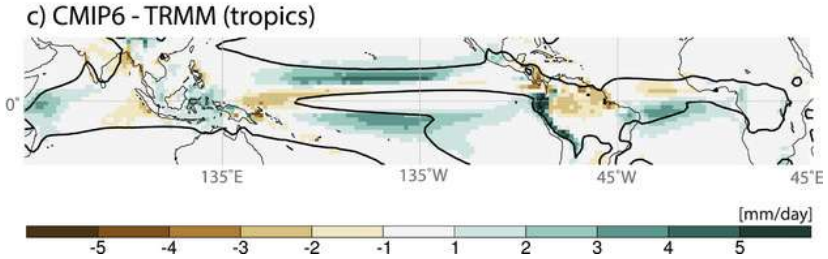


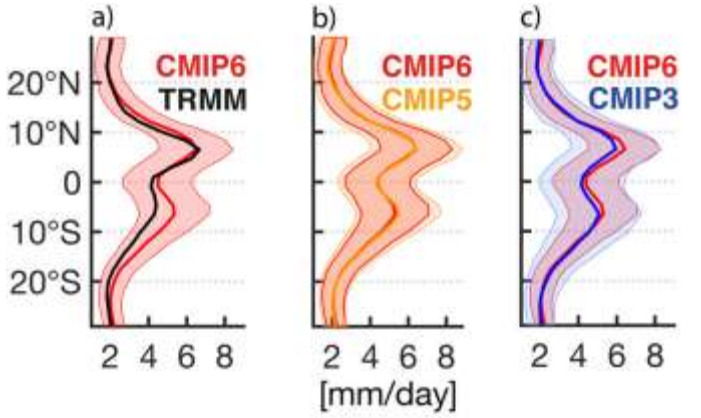

(Frenger et al., Nature Geosci., 2013)

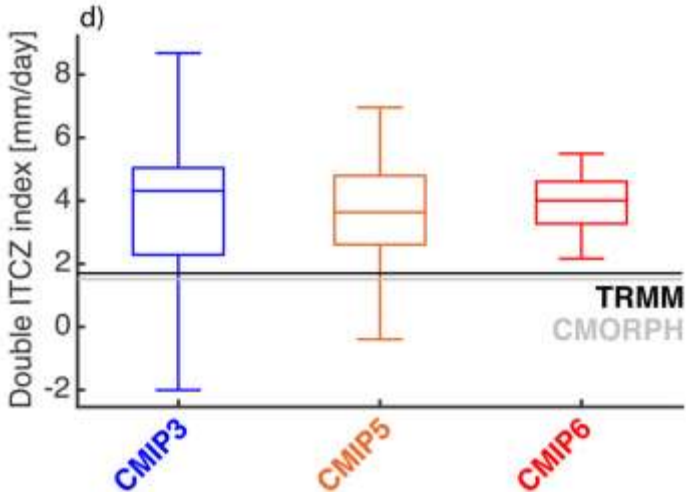
The presence of (sub) mesoscale features alter transport processes (e.g. meridional heat transports) and introduce new complexity in air-sea coupling

# Why storm and eddy-resolving models?




*(Fiedler et al., MWR, 2020)*

Limited progress in model accuracy as long as we stay in the “parameterized” world?

# The H2020 nextGEMS project

Legacy | Development (*O1*) | Application (*O2 & O3*)

## Project Clusters:

NextGEMS builds on a rich legacy:

**Tech:** ESiWACE2, ESCAPE-2, ENIAC, DYAMOND

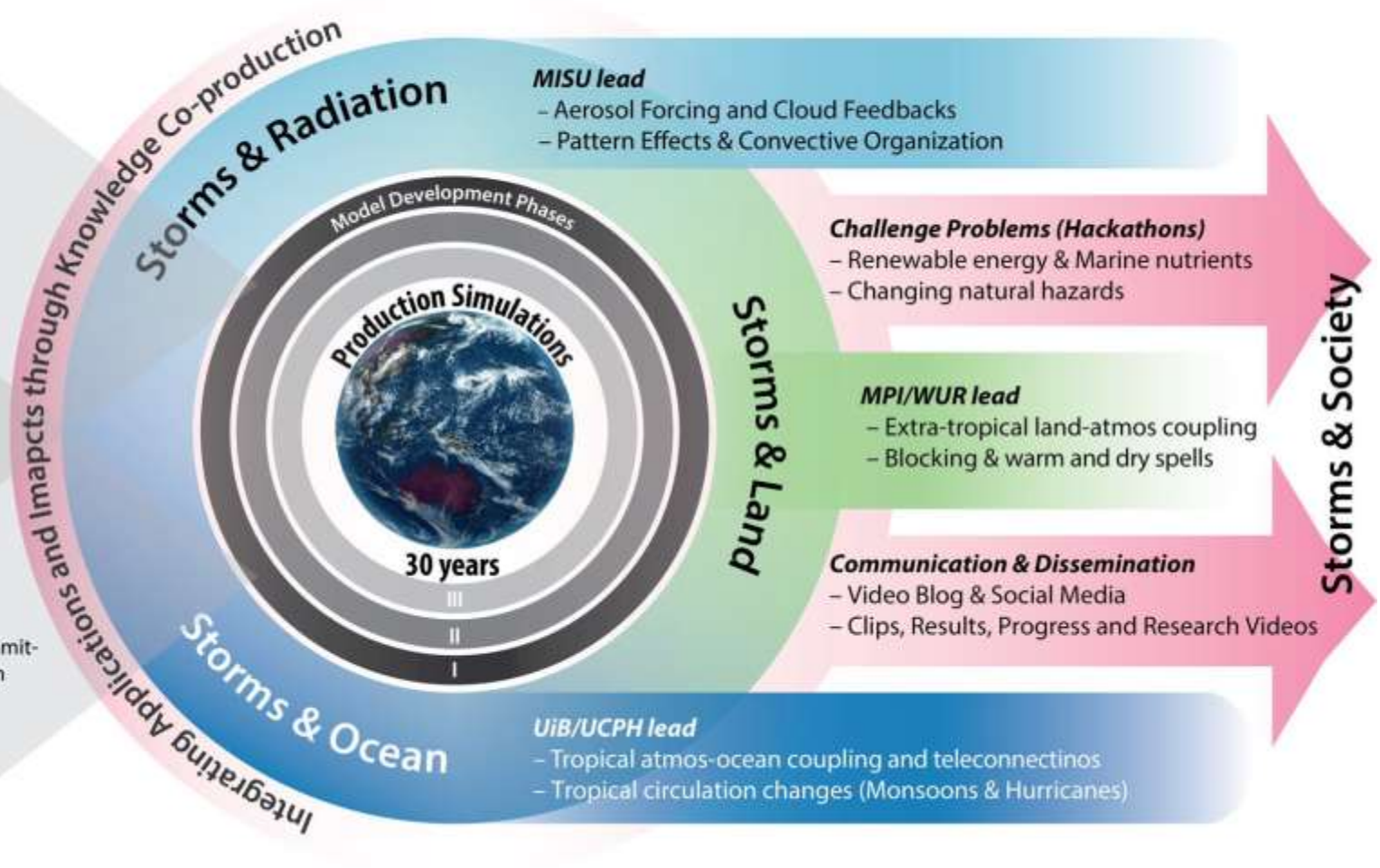
**Apps:** CONSTRAIN PREFACE, PRIMAVERA

**Obs:** EUREC⁴A, BOW-TIE/TOOC & FESSTVaL

## People:

NextGEMS expands the modelling enterprise by integrating groups from outside the traditional modelling centers.

NextGEMS benefits from strong institutional commitments (MPI-M, ECMWF, AWI and BSC) and PIs with a track-record of leadership.



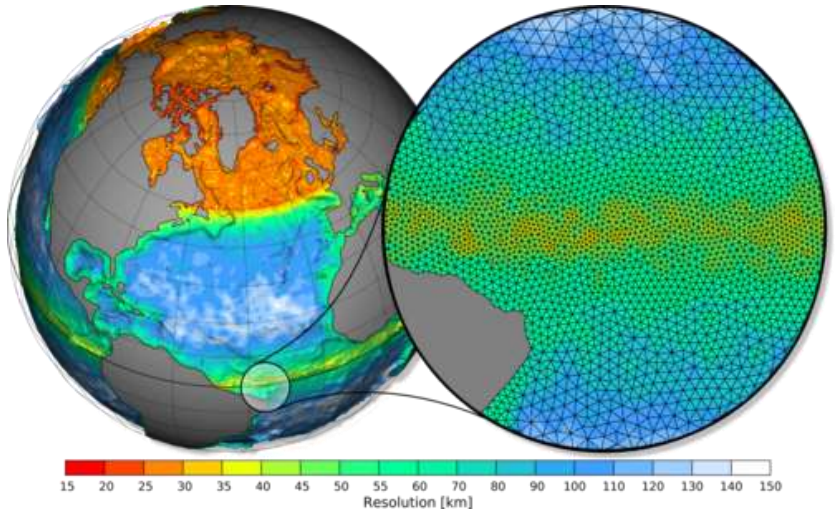
# nextGEMS models

- based on recently developed Earth System Models that are suitable for ultra-high resolution

**ICON**

*Hohenegger et al., 2023*

**IFS/FESOM**




*Rackow et al., 2024*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# Why now?

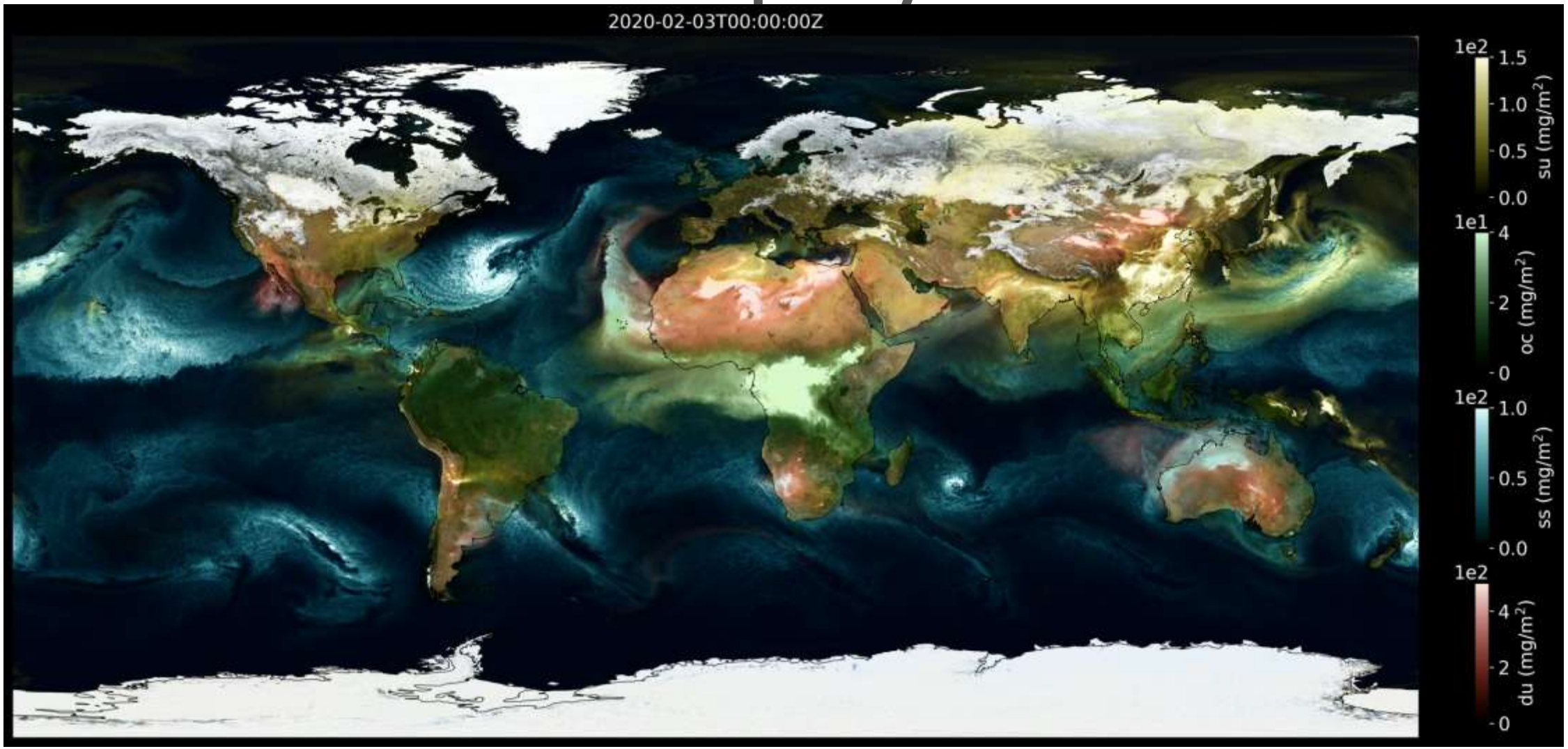
- For climate-relevant simulation, a throughput of min. 100 SDPD* is needed
- DKRZ Levante: 14 PetaFLOPS (4x Mistral), Global rank 83)
- (LUMI: > 300 PetaFLOPS, Rank 1 in Europe, rank 3 global (spring 2023)
- More to come: MareNostrum, JUPYTER,….

| Grid spacing | Machine | Nodes | SDPD |
|---|---|---|---|
| 5 km | Mistral | 420 (300 A, 120 O) | 17 |
| " | Levante | 600, 24A:8O | 126 |
| " | Levante | 420, 24A:8O | 96 |
| " | Levante | 400, 24A:8O | 90 |
| " | Levante | 200, 24A:8O | 48 |
| " | Levante | 100, 24A:8O | 24 |
| 2.5 km | Levante | 600, 24A:8O | 20 |
| 1.25 km (A) | Levante | 908 | 4 |
| 1.25 km (O) | Levante | 1024 | 97 |

*SDPD = Simulation Days per Day on the computer

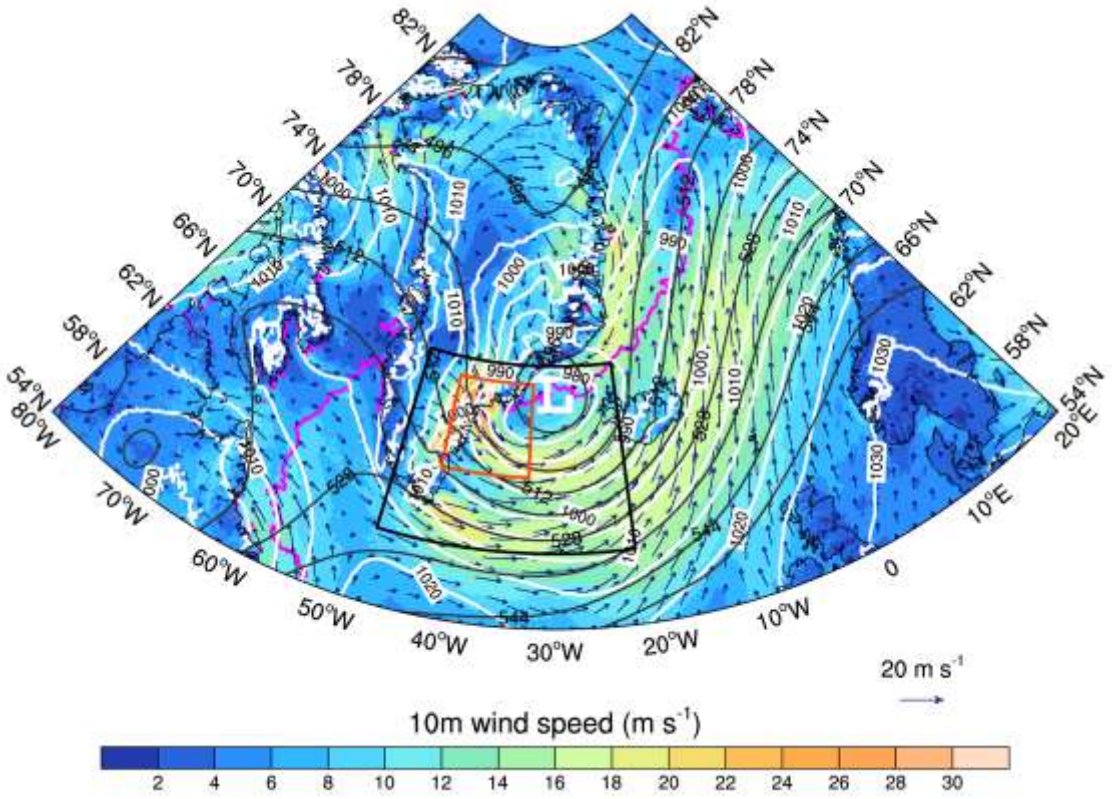
*Hohenegger et al., 2023*

# nextGEMS results: new complexity

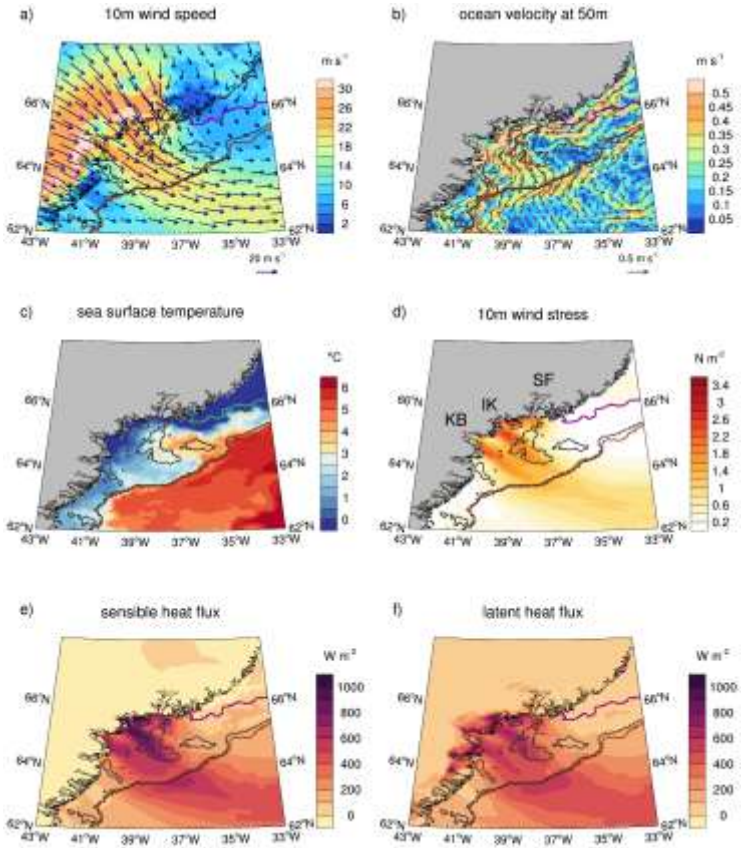



*courtesy P. Weiss, Oxford*

# nextGEMS results: improved process understanding



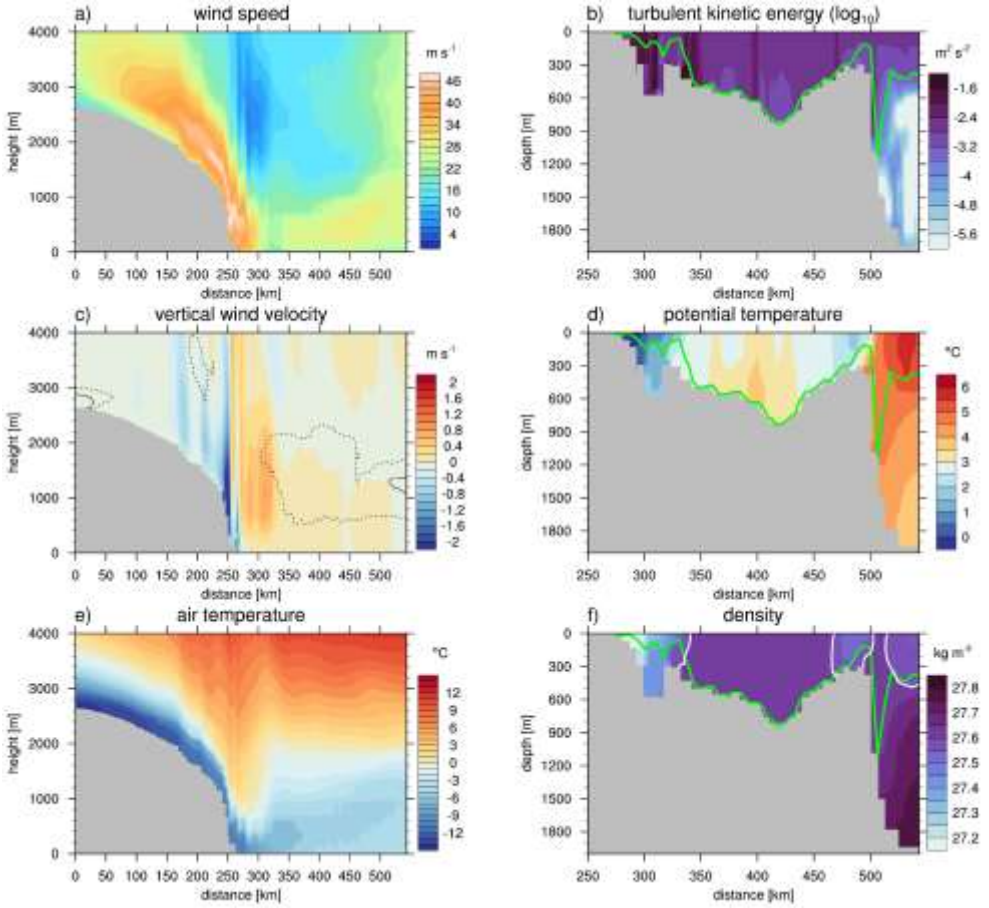

Synoptic conditions during the formation of a katabatic storm on 29 February 2020 in the ICON-Sapphire simulation.



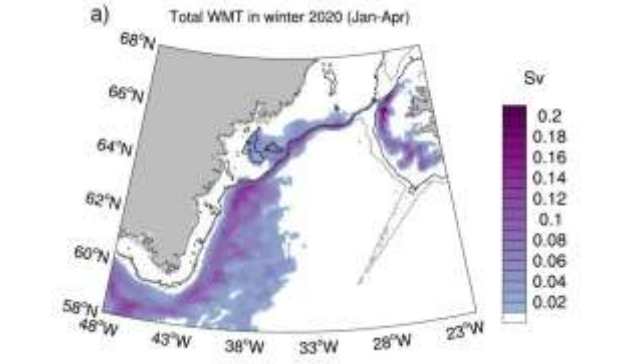

*Gutjahr et al., 2022*

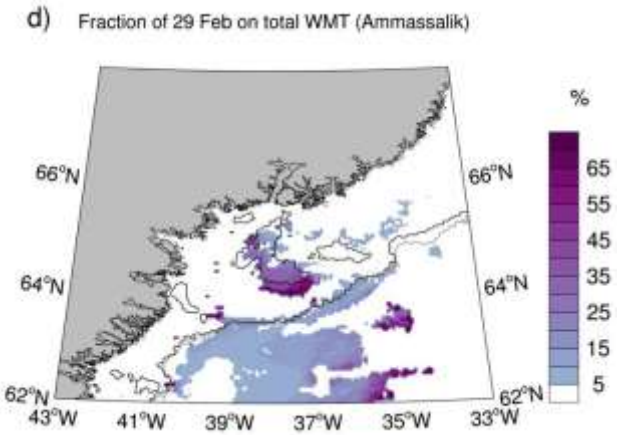
Air-sea interactions (daily means) in the Ammassalik area (southeast Greenland) and over the Irminger shelf.

# nextGEMS results: improved process understanding




Vertical transects (daily means) along Ikertivaq valley (atmosphere, a,c,e) and SermilikTrough (ocean, c,d,f)



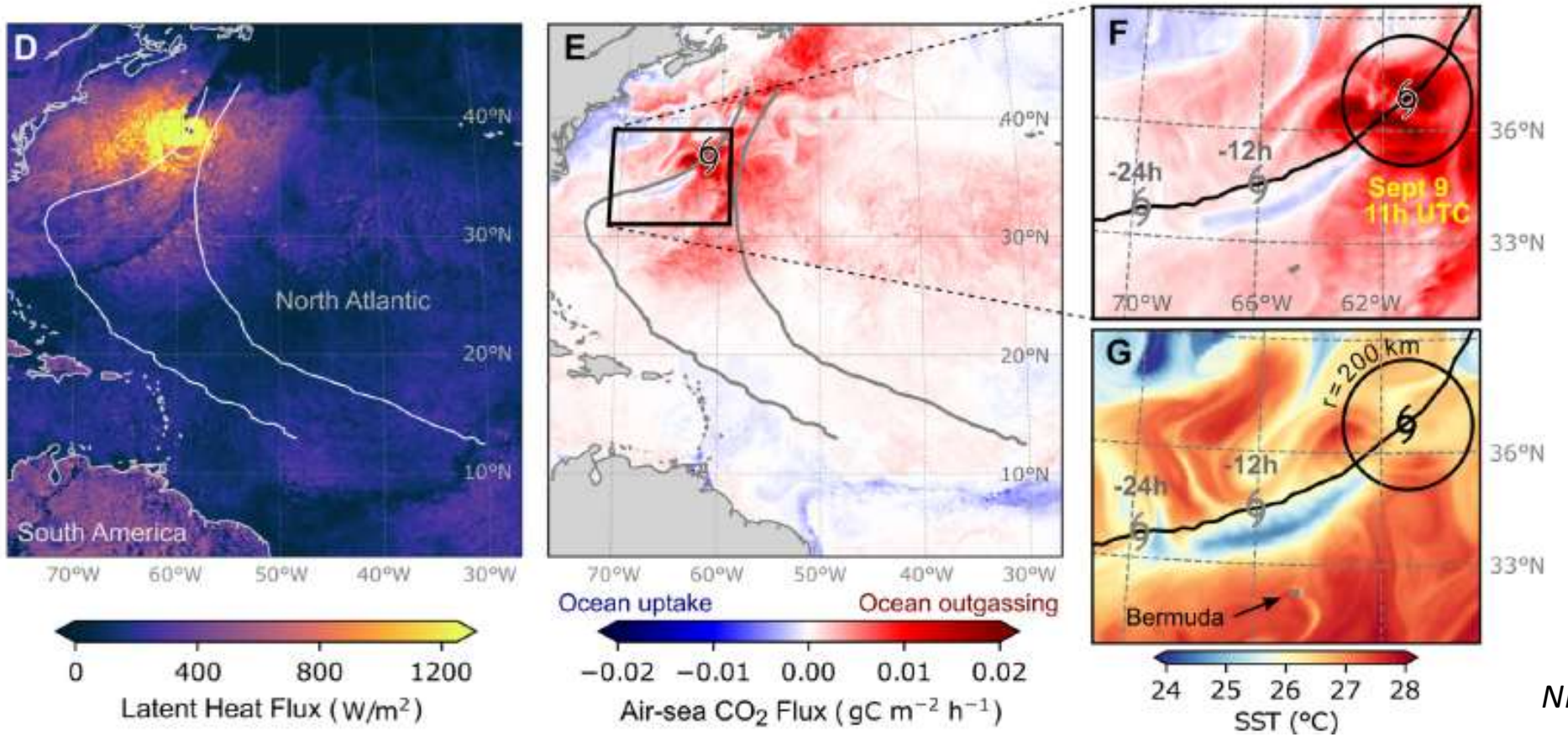

Water mass transformation in the Irminger sea (upper) and fractional contribution of the katabatibc storm event

a few days of katabatibc winds contribute a large part of the entire winter's water mass formation

feeds into AMOC

*Gutjahr et al., 2022*

# new complexity: ocean biogeochemistry



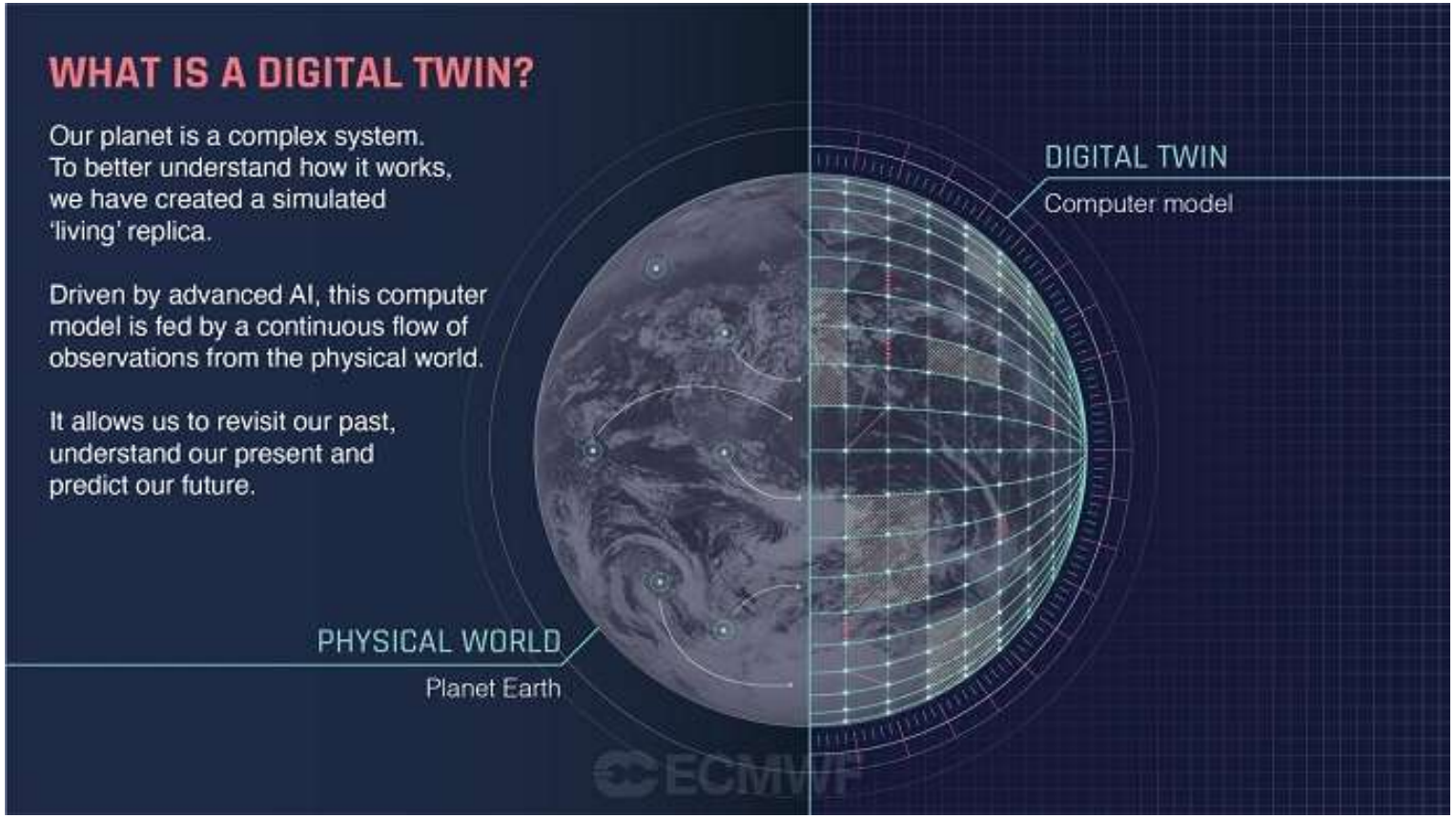

*Nielsen et al., subm.*

ICON 5km-coupled simulation with interactive ocean biogeochemistry (HAMOCC)

- TCs and storms alter stratification and air-sea exchanges
- Important ingredient for $CO_2$-uptake

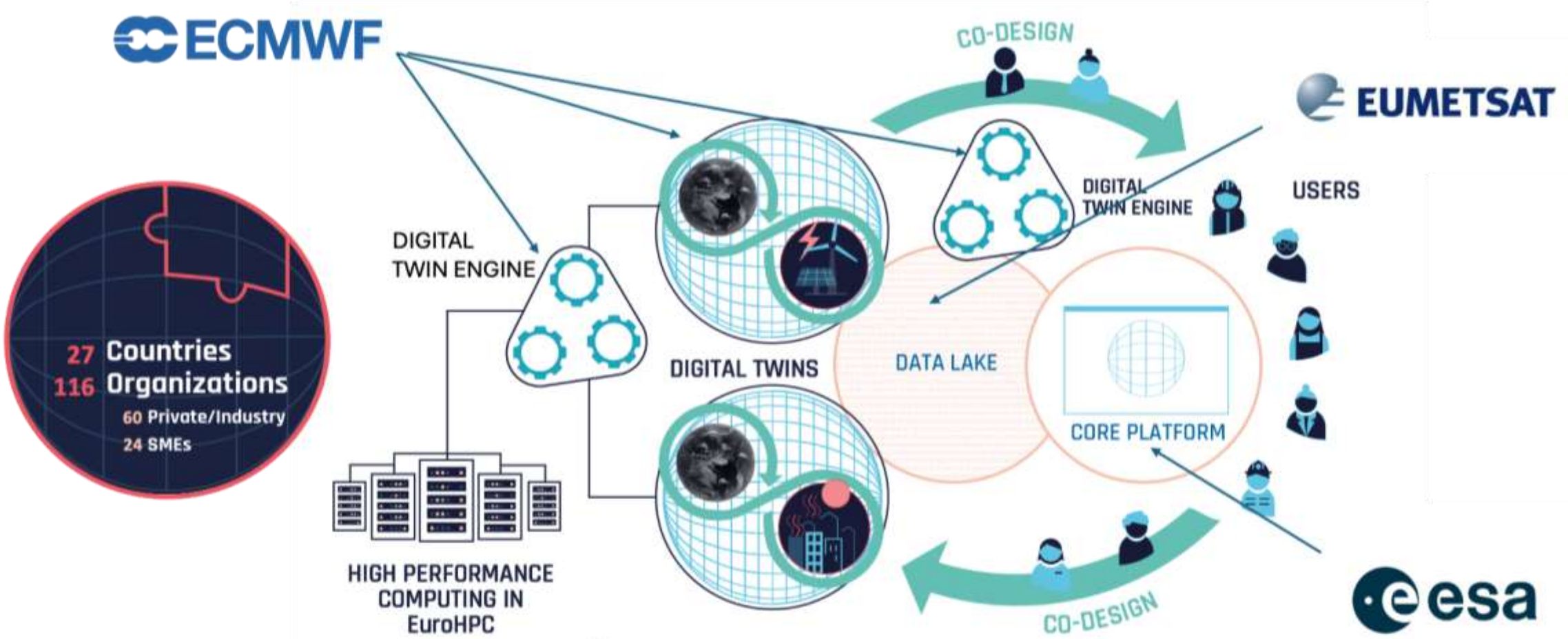

(courtesy Sebastian Milinski, ECMWF)

# nextGEMS as “stepping stone”

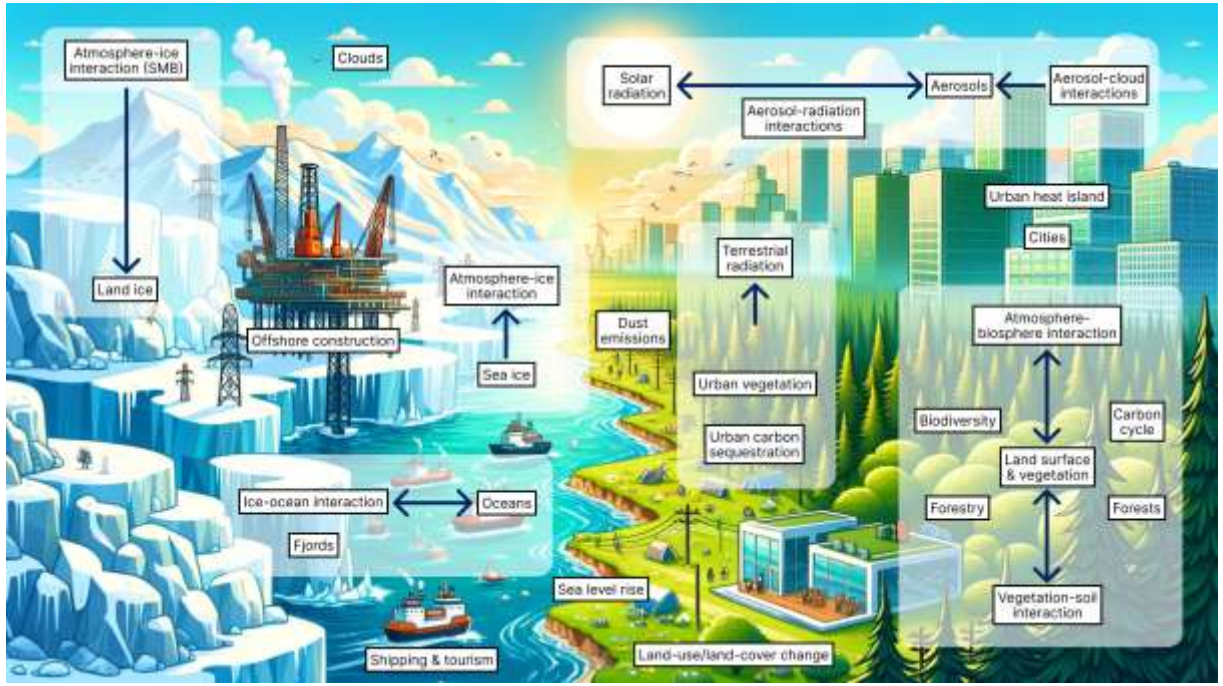



- NextGEMS is embedded in the „Destination Earth“-initiative of the EU commission
- IfS/FESOM and ICON serve as prototype for “Digital Twins”
- Upcoming initiative “Earth Virtualization Engine” (EVE)

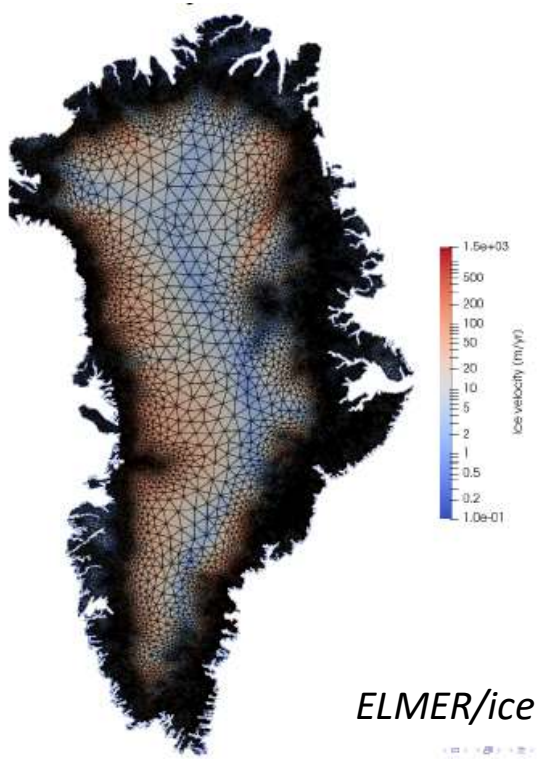
# DestinationEarth



# Next steps: Including ice sheets in high-resolution ICON simulations: The EU TerraDT project




*TerraDT*




*ELMER/ice*

The EU DestinationEarth project TerraDT aims at advancing climate modelling with a modular digital twin of the cryosphere and land systems.

# Summary

**ICON @ CMIP-style resolution**

- The first version of ICON-ESM was documented in a set of CMIP6 DECK experiments
- ICON-XPP at “target” resolution with promising performance for CMIP7 and near-term predictions
- BMBF “CAP7” project as carrier for ICON-ESM with interactive carbon cycle and improved land model

**ICON “Sapphire”**

- First coupled global storm and eddy resolving experiments have been produced as part of the H2020 projects NextGEMS and EERIE, DestinE, and national projects (e.g. “WarmWorld”)
- model output available through catalogue systems
- new insights on ocean-atmosphere and land-atmosphere interactions
- connection of small-scale and regional processes to the global scale

# Questions?