MAX-PLANCK-INSTITUT
FÜR METEOROLOGIE

ICON – TOWARDS (VERTICALLY) INTEGRATED EARTH SYSTEM MODEL FOR NUMERICAL WEATHER FORECAST, CLIMATE PREDICTIONS AND PROJECTIONS

WA Müller, R Potthast (DWD), B Früh (DWD), P Korn

2nd June 2025, Seamless GCM, Bristol

VERTICAL INTEGRATION

- **ICON (Icosahedral Nonhydrostatic)**
- **All components with same grid type and common data structures**

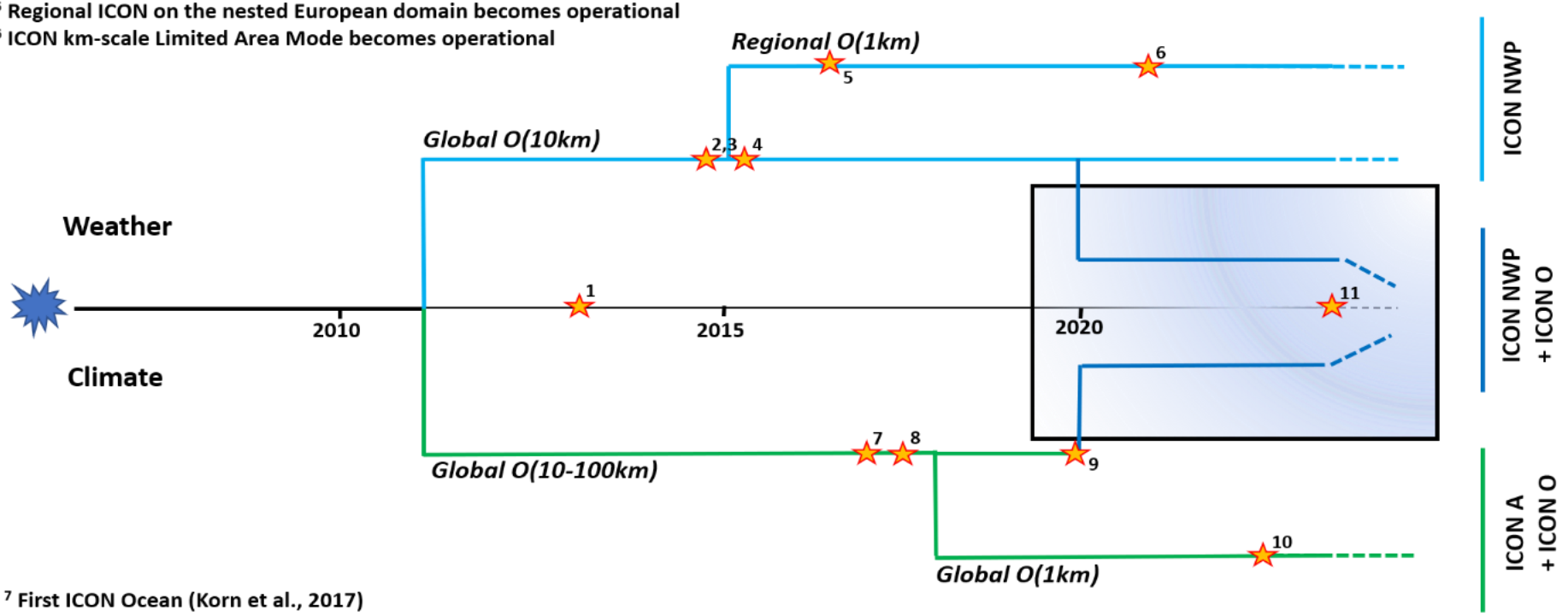
  ↘ *Key differential operators on the ICON grid are identically used between model component, and algorithms such as tracer transport are shared*

  ↘ *Common grid is advantageous in closing budgets and reducing interpolation errors across interfaces of model components*
- **Value chain extension by integration of weather and climate production stages (1+1=3)**
- Example: atmosphere grid and ocean local grid refinement

Credits: Y. Schrader (MPG)

INTEGRATED CONFIGURATIONS FOR WEATHER AND CLIMATE

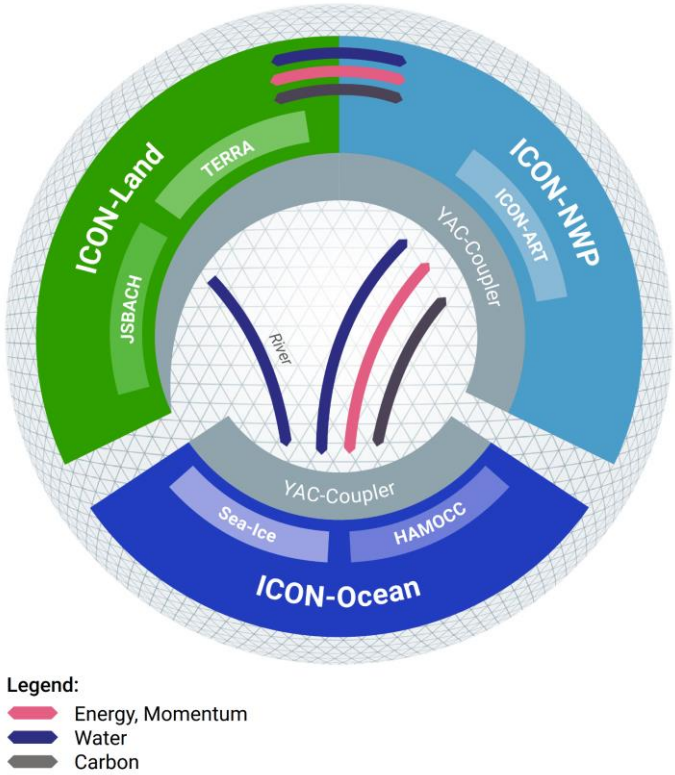
[1] First ICON hydrostatic atmospheric dynamical core on triangular grids (Wan et al., 2013)
[2] ICON modelling framework of DWD and MPI-M (Zängl et al., 2015)
[3] ICON-NWP becomes operational
[4] ICON-ART 1.0 (Rieger et al., 2015)
[5] Regional ICON on the nested European domain becomes operational
[6]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

INTEGRATED CONFIGURATIONS FOR WEATHER AND CLIMATE

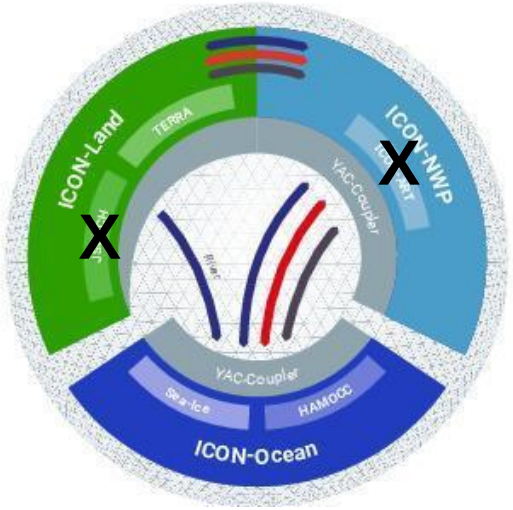
- **New modeling initiative between climate modeling institutes and the Deutscher Wetterdienst started 2020**
- **New configurations coupling ICON NWP with ICON Ocean**
  - ↘ *Combining parametrizations of NWP and climate*
  - ↘ *Incorporating new components (aerosol and tracer – ART, ocean-biochemistry – HAMOCC)*
- **Combination of DA methods from NWP and climate predictions**
  - ↘ *Ensemble variational data assimilation scheme (EnVAR) with a localized ensemble transform Kalman Filter (LETKF)*
  - ↘ *Ensemble Kalman Filter (EnKF) for ocean observations*
- **Modularization of land surface component**
  - ↘ *Status: still using TERRA (weather) or JSBACH (climate)*
  - ↘ *Goal is the process decomposition in ICON Land framework*



Müller et al. (2025) BAMS

A COUPLED PROTOYPE FOR NWP

- **A coupled ESM for NWP**
  - ↘ *ICON NWP with TERRA coupled to ICON Ocean*
  - ↘ *No Aerosol Tracer Model*
  - ↘ *Employs weakly coupled DA, multi-stage of seasonal (1980-2021) and NWP daily (2022) DA cycles, and NWP daily higher-resolved (>2023)*



Deutscher Wetterdienst
Wetter und Klima aus einer Hand
DWD

Zentrum für Geoinformationswesen der Bundeswehr

- **Mid-term to complement NWP portfolio**

atmosphere

- 3DVAR 3 hourly
- 3h assimilation window
- conventional and satellite data

- No IAU → **IAU**
- 80km (R2B5) 90 lev → **13km 120 lev**
- Start: operational DWD coarsened

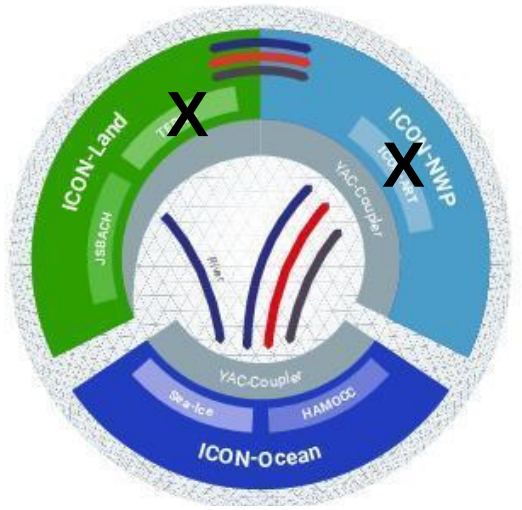
ocean

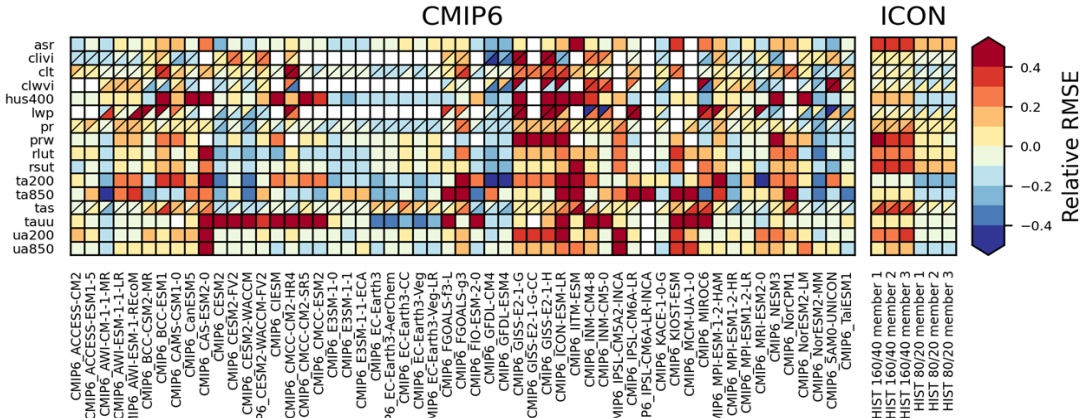
- 3DVAR daily (00 UTC)
- 24h assimilation window
- ARGO CTD, SMOS SSS, FGAT OSTIA SST
  - **OSTIA sea ice fraction**
- No IAU
- 40km (R2B6) → **20km (R2B7) + 72 levels**
- Start: climate forecast → **multi-stage spin-up***

Credits: Nora Schenk (DWD)

A COUPLED PROTOYPE FOR CLIMATE

- **ICON XPP (XPP = eXtended Predictions and Projections)**
  - ↘ *ICON NWP with JSBACH both coupled to ICON Ocean*
  - ↘ *Earth System model incl ocean-biogeochemistry, land carbon cycle etc*
  - ↘ *No interactive aerosol tracer model yet*
- **ICON XPP version 1.0 released**
  - ↘ *80km (ATM)/ 20km (OCE) ~40 SYPD -> suitable to tun long integration and large ensembles*
  - ↘ *DECK evaluation fits with standards of CMIP6-categories of GCMs, incl. their long-standing biases*
  - ↘ *Overly good performance of atmospheric dynamics (e.g. NH jet stream, polar vortex)*



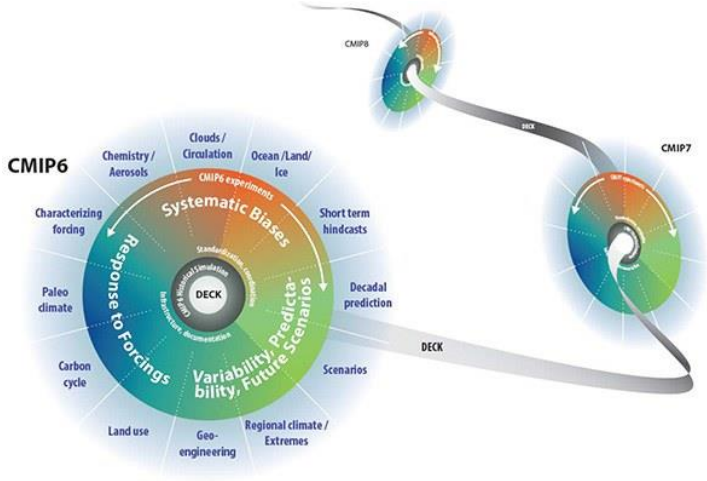


Müller et al. (submitted) GMD

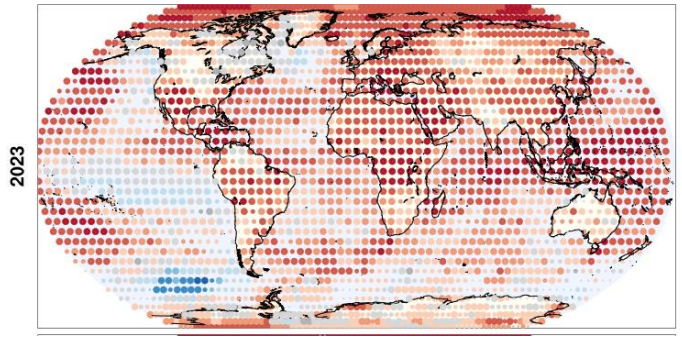
ICON XPP – NEXT GENERATION ESM FOR CLIMATE PREDICTIONS AND PROJECTIONS

- **ICON XPP baseline model for CMIP7**
  - ↘ *National program CAP7 started 02/25*
  - ↘ *Deliver DECK experiments, concentration-driven scenarios.*

  Eventually also emission- and data-driven scenarios



- **ICON XPP baseline model for climate predictions**
  - ↘ *National program ComingDecade started 11/23*
  - ↘ *Replace predecessor model for operational seasonal to decadal predictions*



© DWD

ICON XPP – BASELINE FOR CLIMATE RESEARCH

- **DRAGON** - Development of gRey-zone Atmosphere and eddy-resolvinG Ocean eNsembles

  ↘ *Setup of a NWP-analog resolution 13km (ATM)/5km (OCE) for running multiple-decades and ensembles*

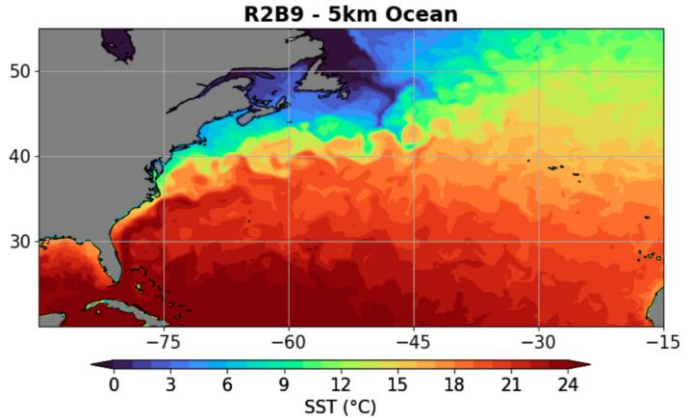
  ↘ *Technical progress: porting ICON XPP on GPUs*

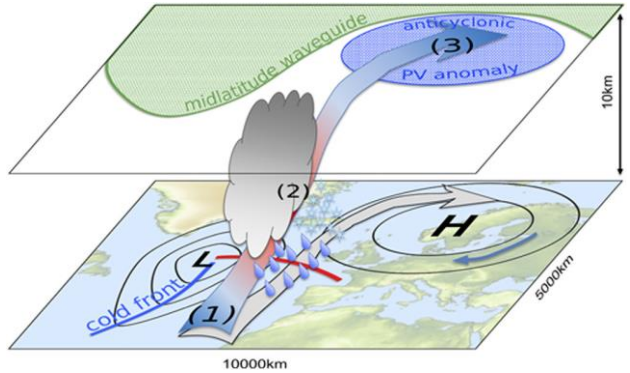
  Scientific questions

  ↘ *Southern Ocean climate and global response*

  ↘ *Role of ocean meso-scale eddies for weather*

Hans-Ertel-Zentrum
für Wetterforschung





What is the impact of meso-scale ocean fronts on e.g., storm track development, warm-cold conveyor belts ?

COMBINED WEATHER-CLIMATE MODEL DEVELOPMENT PROJECTS

- **Southern Ocean Clouds and Climate (M Ahlgrimm, M Köhler, WA Müller)**

  ↘ *Fundamental surface climate bias in the SO, e.g.T2m*

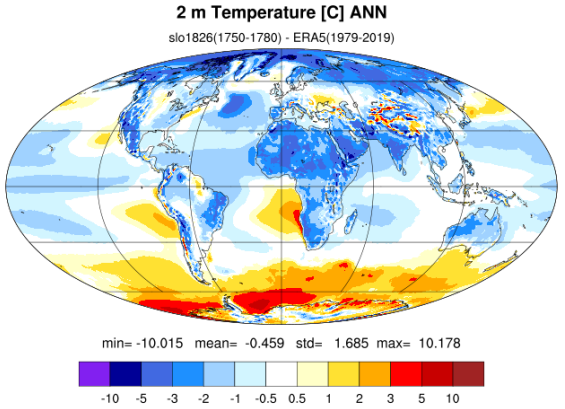
  ↘ *Associated with SW radiation bias and related surface fluxes, and deep mixed layer >4000m resulting warming and freshening of deep ocean, and unrealistic deep-layer carbon exchange*

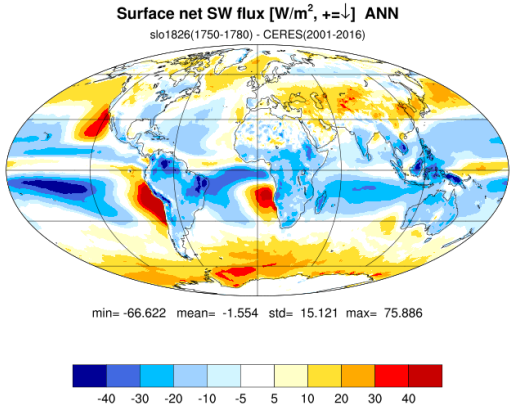
  ↘ *AMIP experiments reveal role of cloud properties at relatively short timescale*

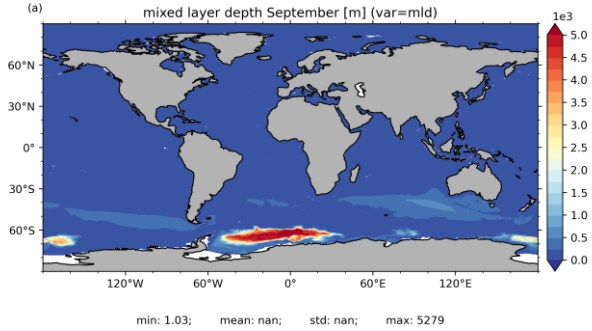
  -> combined exercise studying the effects of clouds and ocean mixing parameterization

- **Tropical Precipitation (K Castro Morales et al.)**

  ↘ *Dry bias over trop. land, wet bias over trop. ocean*







LESSONS LEARNT

- **Seamless with ICON**
  - ↘ *Two prototypes developed for weather and climate, starting the seamless modelling process*
    - *A fully coupled NWP configuration (incl DA in the atmosphere and ocean)*
    - *An Earth System model configuration based on the NWP components that meets the CMIP criteria*
  - ↘ *Recognition of 1+1=3, weather-in-climate and vice versa*
- **Technically challenging**
  - ↘ *Seamless components*
    - *different land surface components and their implementation in the turbulence/diffusion schemes*
  - ↘ *Meet the communities requirements (e.g. NWP scores, COSMO code developments)*
  - ↘ *Code development for NWP and climate is carried out in a common repository monitored by DWD*
- **Keeping up the momentum**
  - ↘ *Break out silo-thinking, naturally driven by deliverables (e.g. daily forecast, or climate applications)*
  - ↘ *Establish weather-climate interaction projects/program*

Multi-stage spin-up

Seasonal DA cycle

- Atmospheric nudging against ERA5
- monthly ocean DA (EN4 dataset)
- 80km/40km

NWP DA cycle

- atmospheric nudging against ERA5
- daily ocean DA
- 80km/40km

NWP DA cycle – higher resolution

- atmospheric nudging against ICON-DREAM
- daily ocean DA
- 13km/20km

1980 → 01/2022 → 01/2023 → 04/2025