Very high resolution coupled climate modelling with an unstructured ocean model

FESOM team at AWI, Climate Dynamics

Finite volumE Sea Ice Ocean Model configurations

AWI-CM2
FESOM2/ECHAM6

FESOM2/PISM
Ice sheet

FESOM2/OpenIFS
Very high resolution
Atmosphere coupling

FESIM+Icepack
Sea ice model

FESOM2
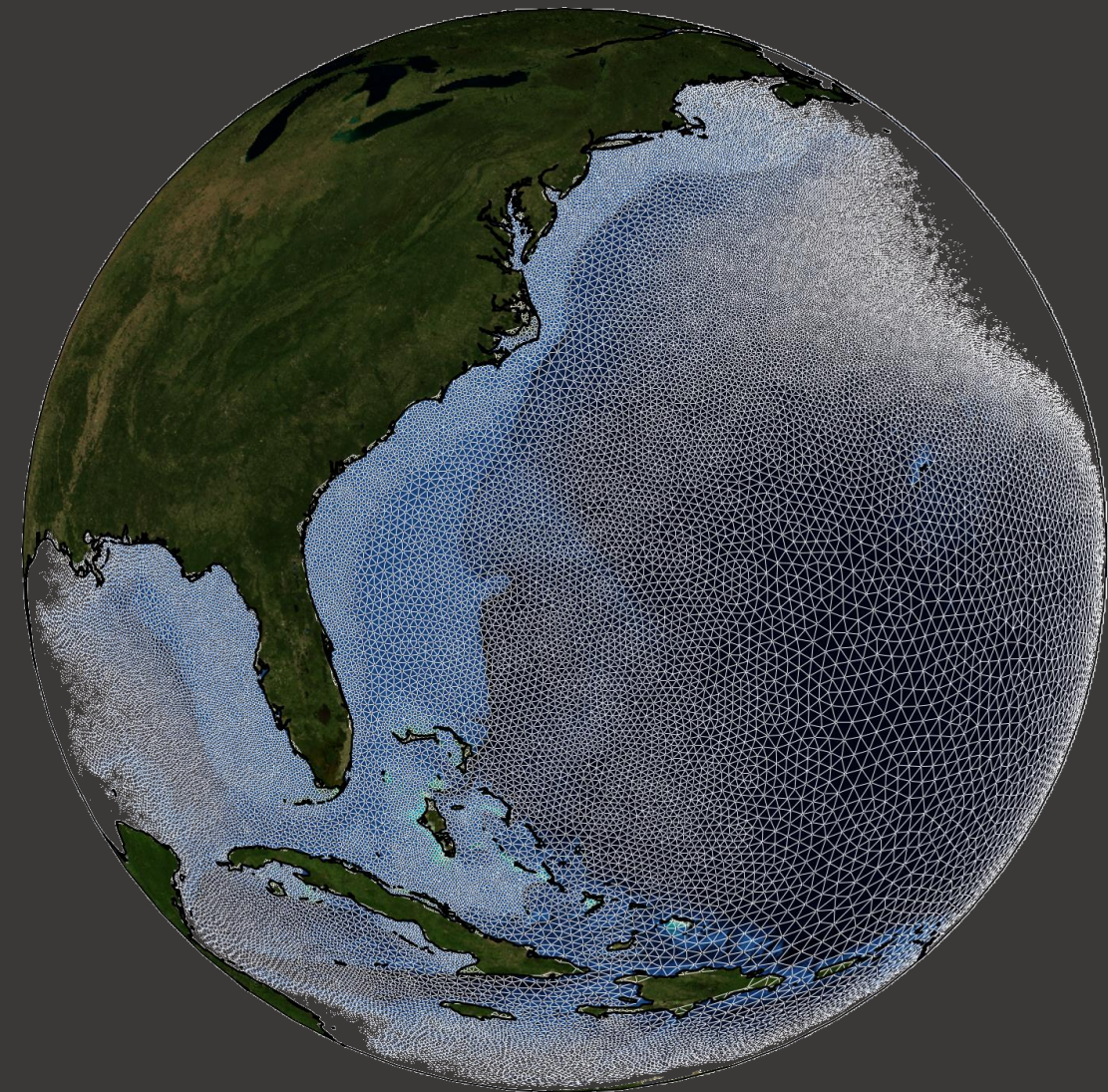
FESOM2/REcoM
Biogeochemistry

FESOM2/IFS
Numerical weather
prediction

FESOM2/PDAF
Coupled DA

FESOM-C
Coastal model

AWI-ESM2
FESOM2/REcoM/PISM/ECHAM6/JSBACH/VILMA

FESOM2

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FESOM2

- ✓ **ALE vertical coordinate**
  different vertical coordinates including z-level, z-star, z-tilde, sigma etc.
- ✓ **CVMIX library (Griffies et al., 2015)**
  multiple mixing schemes like PP, KPP, K-ε, IDEMIX
- ✓ **Parallel support for multiple forcing data and initial conditions:** JRA55, CORE II, ERA5, etc
- ✓ **I/O facility** (*asynchronous implementation from J. Hegewald*)
- ✓ **Ice shelf ocean cavity**
- ✓ **Coupling interfaces**
- ✓ **MPI+OpenMP hybrid parallelization**
- ✓ **Refactoring: modularization / dwarfs**
- ✓ **Own barotropic solver instead of PETSc & pARMS**
- ✓ **Sub-cycling instead of solver for the sea surface height**
- ✓ **FESOM can be used as a library**
- ✓ **Part of FESOM sea ice code (EVP dynamics) on GPU**

FESOM2

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In comparison to regular grid models

SYPD for 1/10° equivalent mesh.
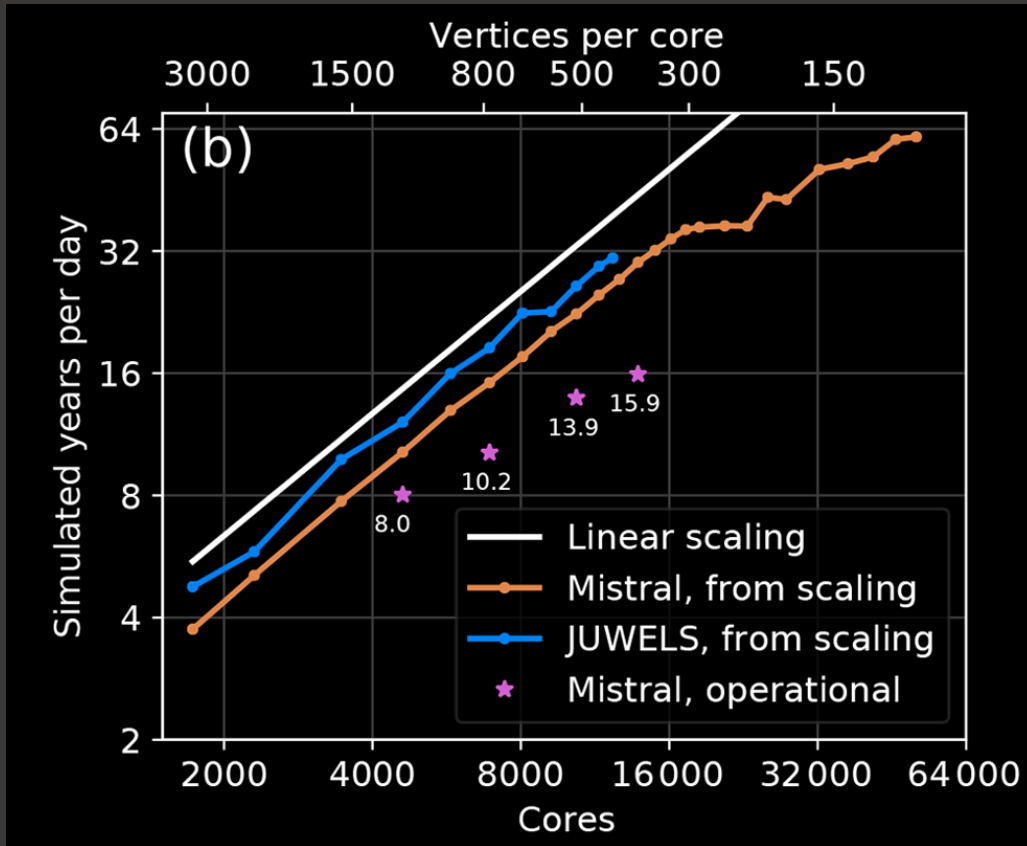
Koldunov et al., *GMD*, 2019

FESOM is part of CORE (now OMIP-1) and OMIP-2

Table D3. Root mean square bias and mean bias of the 30-year mean (1980–2009) sea surface temperature (°C) and salinity (psu) relative to observations (PCMDI-SST and WOA13v2, respectively) and root mean square bias of the 17-year mean (1993–2009) SSH (cm) relative to observations (CMEMS) for individual models. The smallest root mean square bias values for models in each simulation are emphasized with bold numbers.
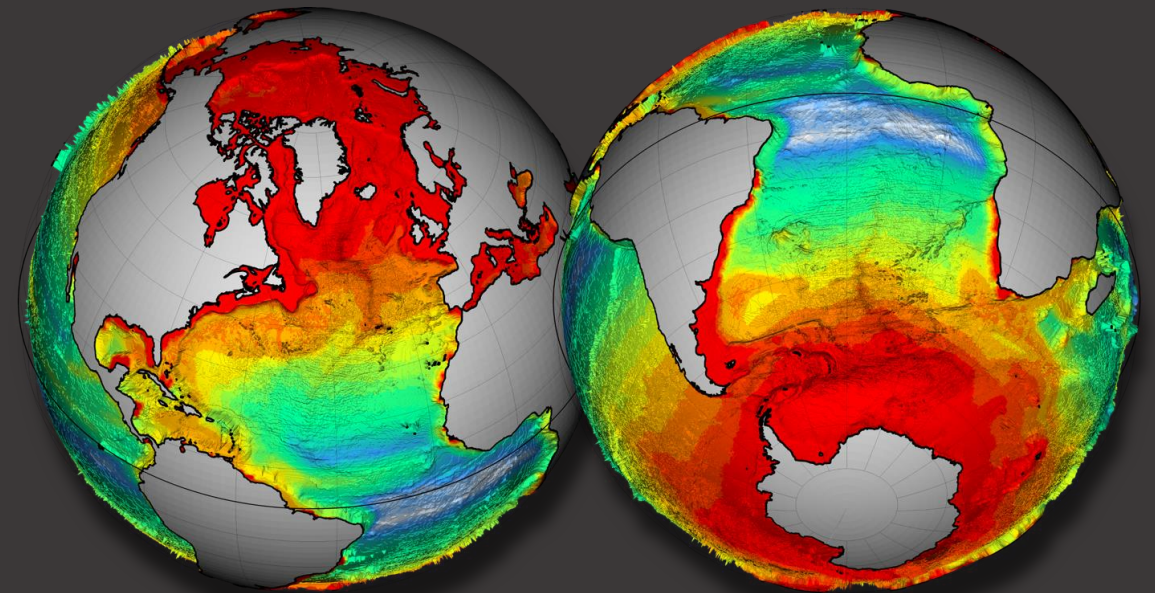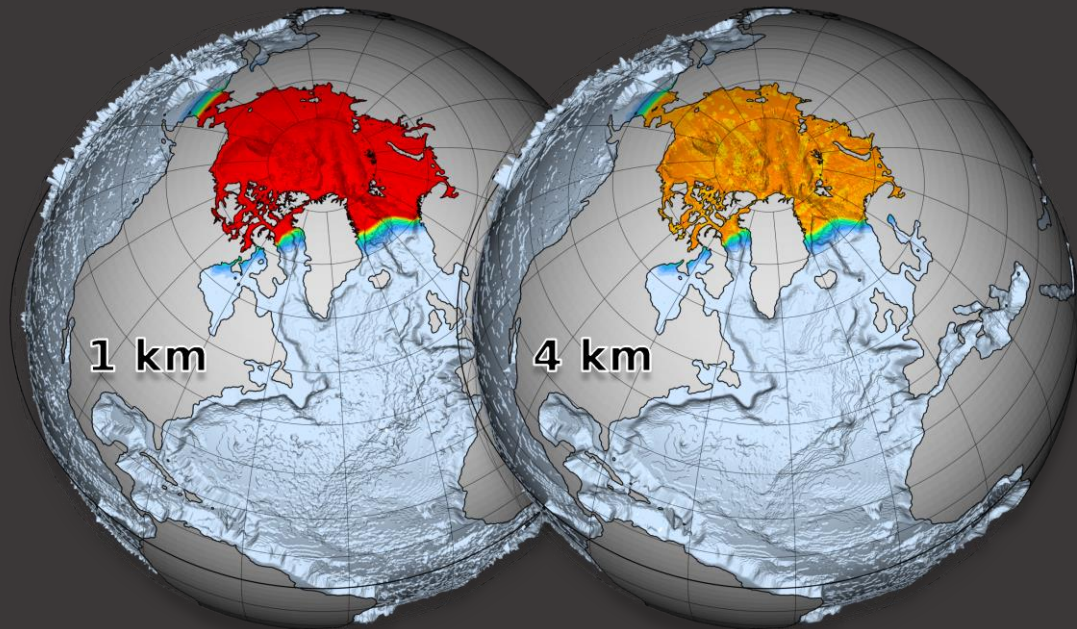
Model name	SST bias RMSE (°C)		SST bias mean (°C)		SSS bias RMSE (psu)		SSS bias) mean (psu)		SSH bias RMSE (cm)	
	OMIP-1	OMIP-2	OMIP-1	OMIP-2	OMIP-1	OMIP-2	OMIP-1	OMIP-2	OMIP-1	OMIP-2
AWI-FESOM	0.671	0.675	−0.171	−0.205	**0.355**	**0.314**	−0.091	−0.099	10.66	10.75
CAS-LICOM3	0.597	0.581	0.042	0.033	0.458	0.471	0.078	0.083	12.61	12.03
CESM-POP	0.577	0.581	0.073	0.029	0.494	0.386	0.054	0.221	11.74	11.53
CMCC-NEMO	0.578	0.523	0.053	0.024	0.597	0.593	0.106	0.081	9.20	10.02
EC-Earth3-NEMO	0.617	0.568	0.170	0.141	0.560	0.564	−0.036	−0.035	9.16	8.74
FSU-HYCOM	0.717	0.690	0.192	0.125	0.555	0.602	0.306	0.306	11.67	12.74
GFDL-MOM	**0.493**	**0.467**	0.042	0.027	0.481	0.408	0.215	0.205	**8.04**	**8.42**
Kiel-NEMO	0.955	0.874	0.105	0.042	1.333	1.117	0.033	−0.008	10.09	9.83
MIROC-COCO4.9	0.593	0.578	−0.065	−0.084	0.558	0.516	0.149	0.127	15.49	18.48
MRI.COM	0.585	0.568	0.096	0.102	0.457	0.428	0.241	0.276	11.25	11.82
NorESM-BLOM	0.579	0.572	0.082	0.034	0.519	0.568	0.167	0.188	10.72	11.38
MMM	0.491	0.462	0.062	0.030	0.348	0.314	0.106	0.119	8.52	8.67

Tsujino et al., *GMD*, 2020

FESOM2

Two approaches to kilometre scale ocean modelling

Global modelling with kilometer scale refinement
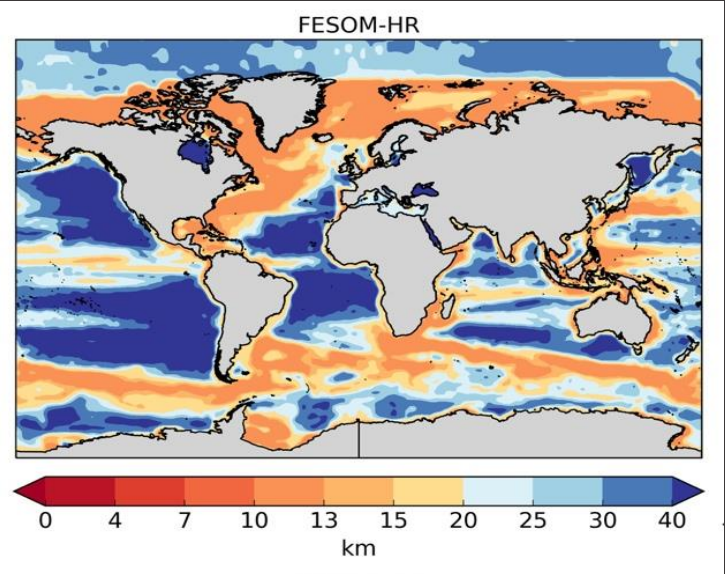(process studies with global feedbacks)

Kilometer scale modelling globally with variable resolution
(all feedbacks glabally integrated)

1 km

4 km

1 2 3 4 5 6 7 8 9 10 12 14 16 18 20 24 28 32 36
Resolution [km]

2 3 4 5 6 7 8 9 10 12 14 16 18 20 22 24 26 28 30 32 34
Resolution [km]

We can do it in coupled and stand alone mode

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AWI

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Global focus, stand alone

Mesh design

FESOM-HR

km

Sein et al., *JAMES*, 2016

Refinement according to SSH var.

Resolution: 1/4°-1/10°

Wet points: 1.3M (1/4°)

SSH variability compared to other high resolution models

FSU-HYCOM variance SSH (m²) (1993–2018)   1/12°

NCAR-POP variance SSH (m²) (1993–2018)   1/10°

AWI-FESOM variance SSH (m²) (1993–2018)   HR

IAP-LICOM variance SSH (m²) (1993–2018)   1/10°
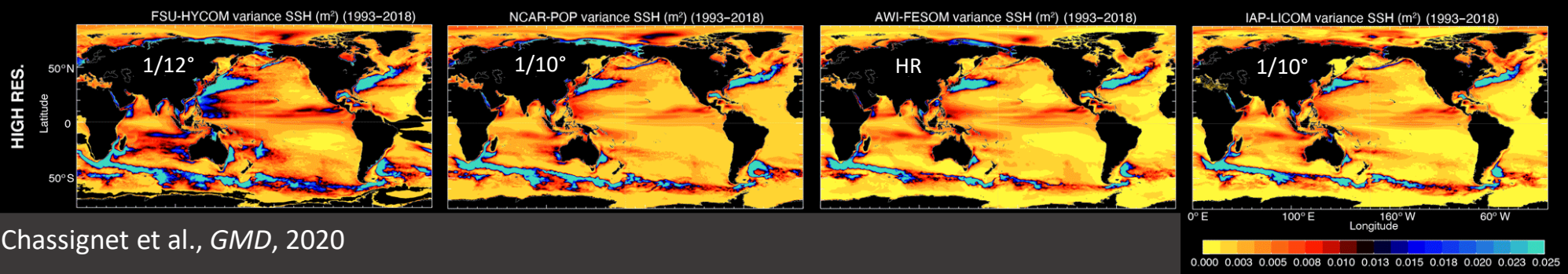
HIGH RES.

Chassignet et al., *GMD*, 2020

FESOM2

Global focus, coupled

Coupled model: **AWI-CM1** – FESOM/ECHAM
Projects: CMIP6, HighResMIP (PRIMAVERA)

HiResMIP Projections (RCP 8.5): 2070–2099 minus 1976–2005

High-resolution   Low-resolution
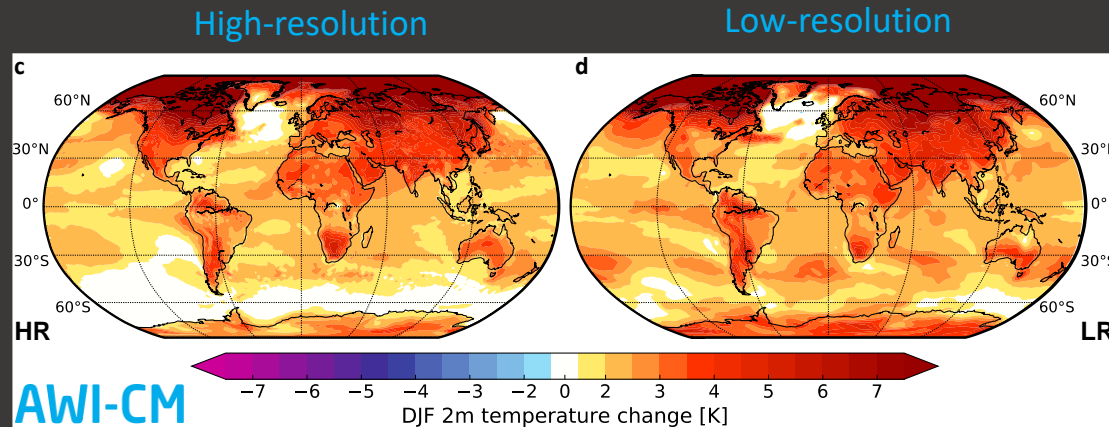
Rackow et al., *Nat Comm*, 2022

Change in ensemble mean of eddy kinetic energy between historical (1860–1949) and projected (2061–2090) periods with GHG forcing, according to SSP3–7.0.
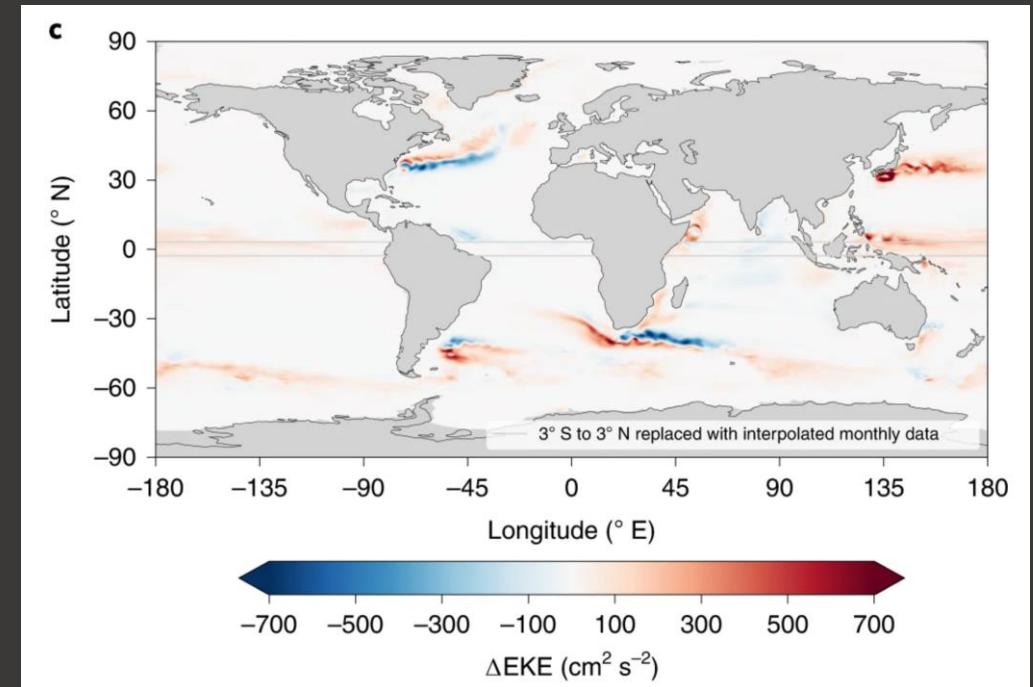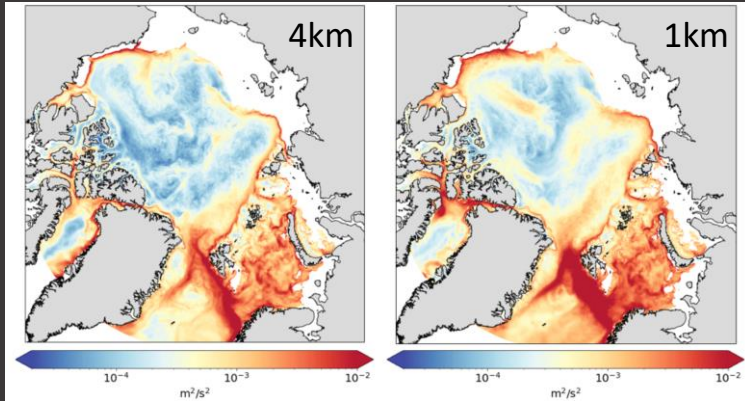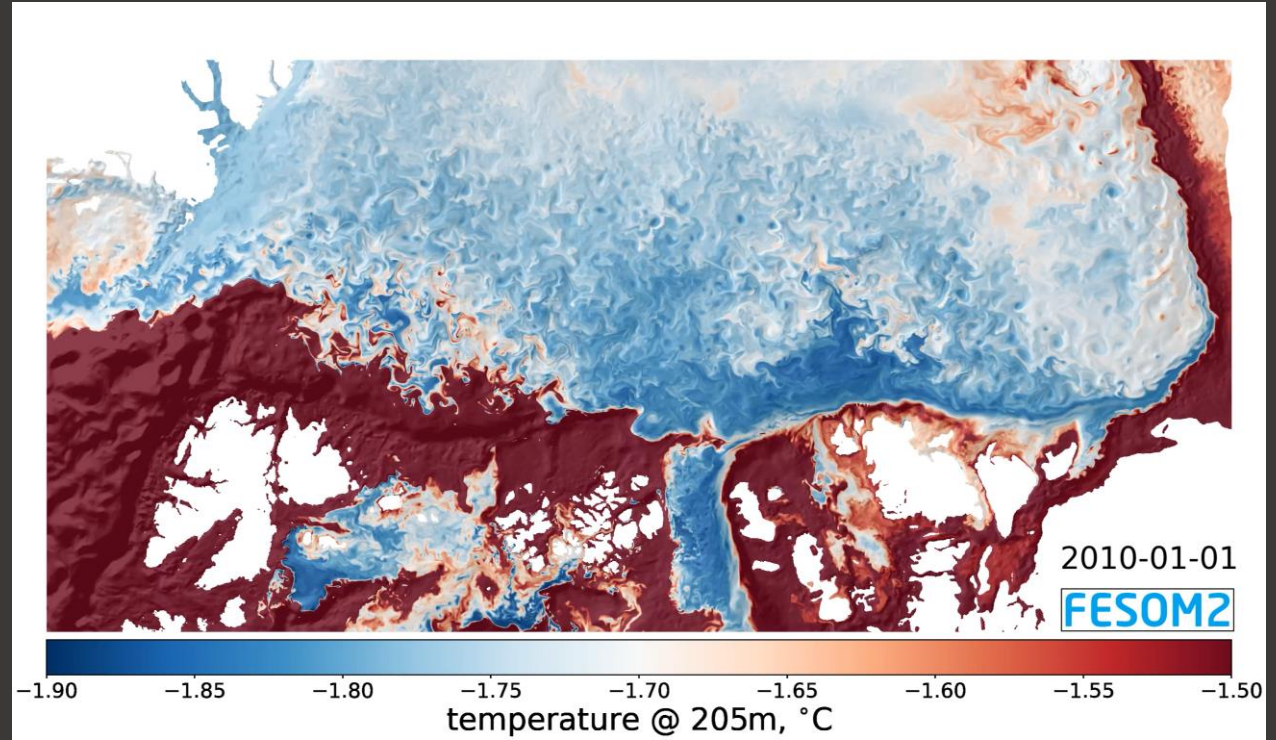

Beech et al., *Nat Clim Chang*, 2022

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Regional focus, stand alone

Arctic Ocean at 1km resolution (30 km global)

1 km   4 km

Resolution [km]
1 2 3 4 5 6 7 8 9 10 12 14 16 18 20 24 28 32 36
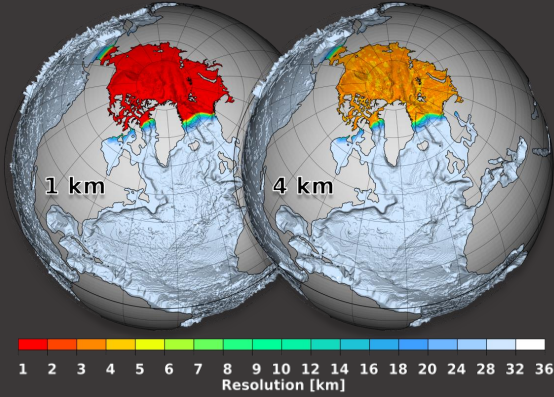
- 11M vertices
- 1 SYPD on 7000 cores

temperature @ 205m, °C
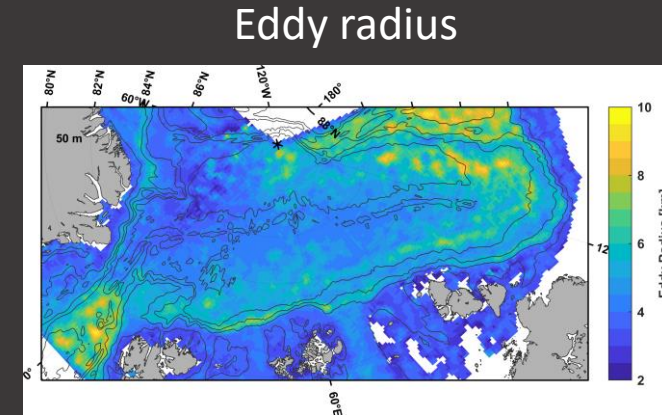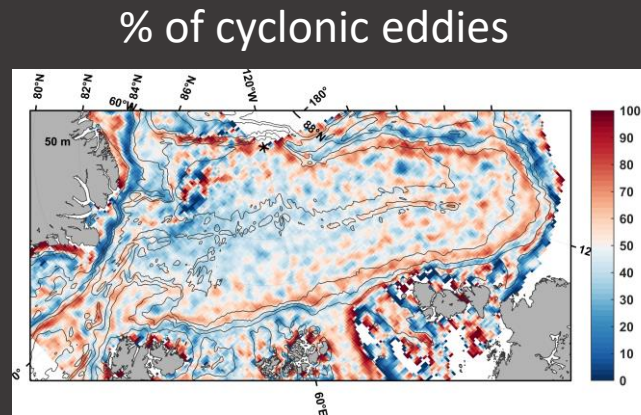−1.90 −1.85 −1.80 −1.75 −1.70 −1.65 −1.60 −1.55 −1.50

2010-01-01

FESOM2

4km   1km

Eddy kinetic energy (EKE) at 150 m depth in the simulations with (a) 4 km and (b) 1 km resolution.
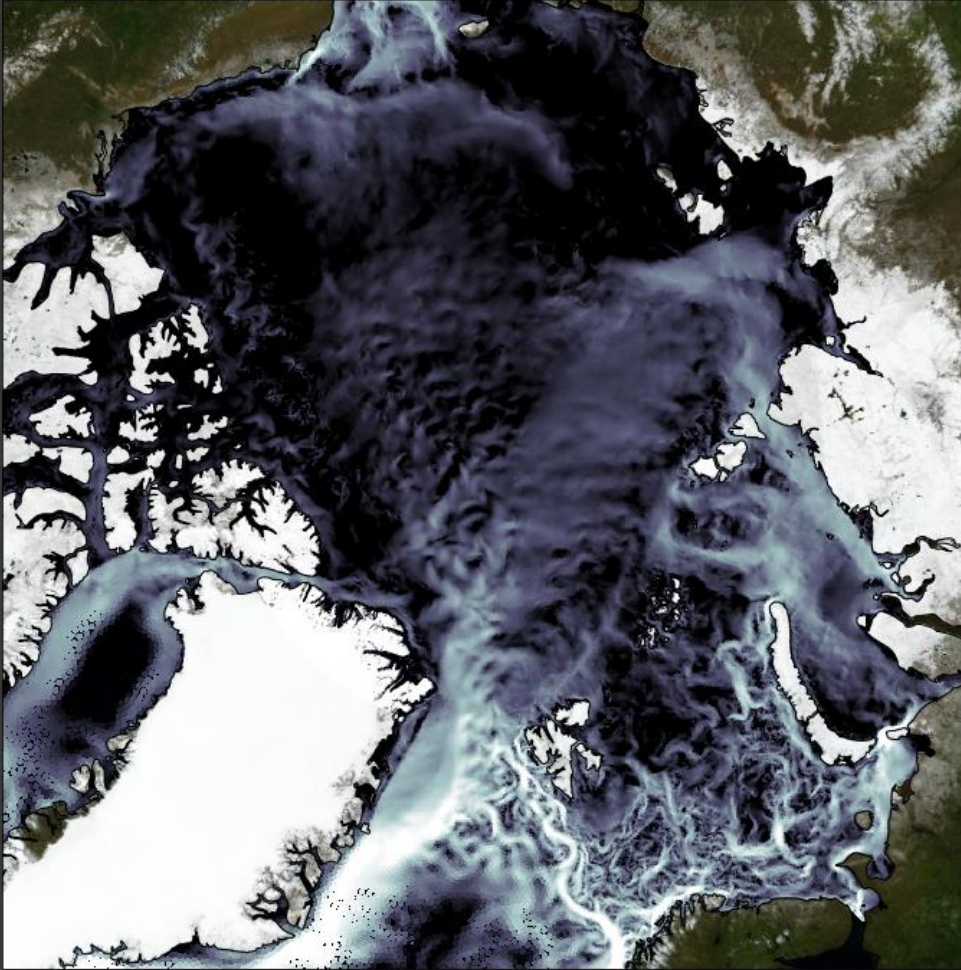
Wang et al., *GRL*, 2020

% of cyclonic eddies

Eddy radius

Müller et al., in prep

FESOM2   AWI   HELMHOLTZ RESEARCH FOR GRAND CHALLENGES
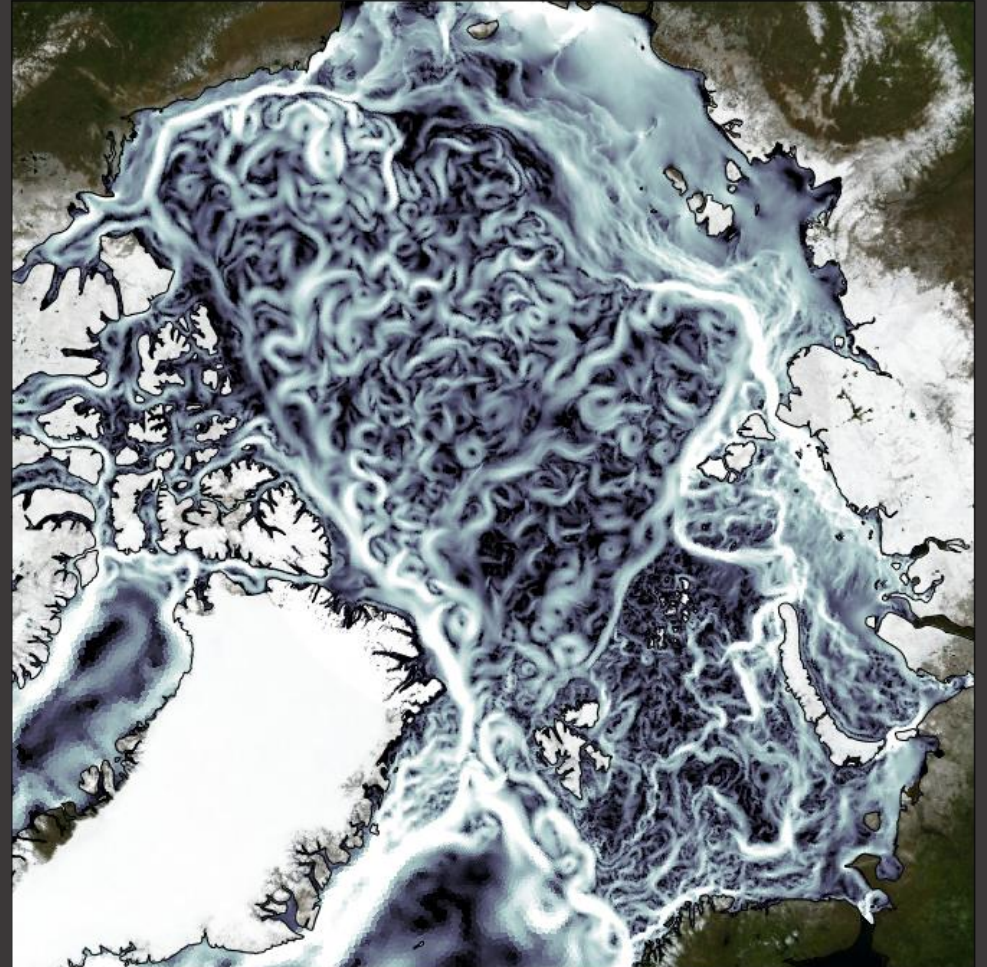
Regional focus, on the way to coupled

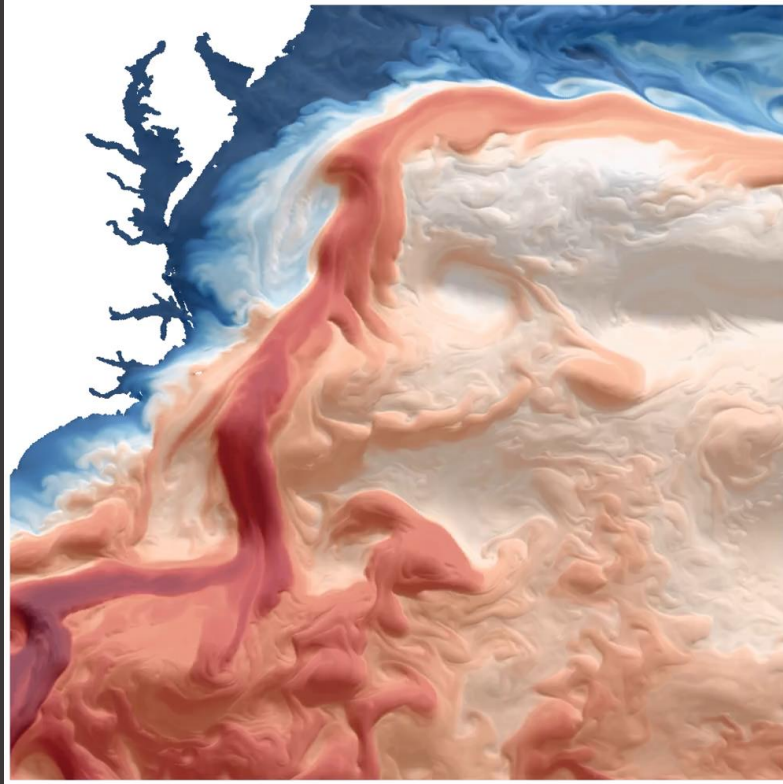## Surface ocean currents in 4km resolution Arctic setup forced by AS fields from CMIP6 model.

2022
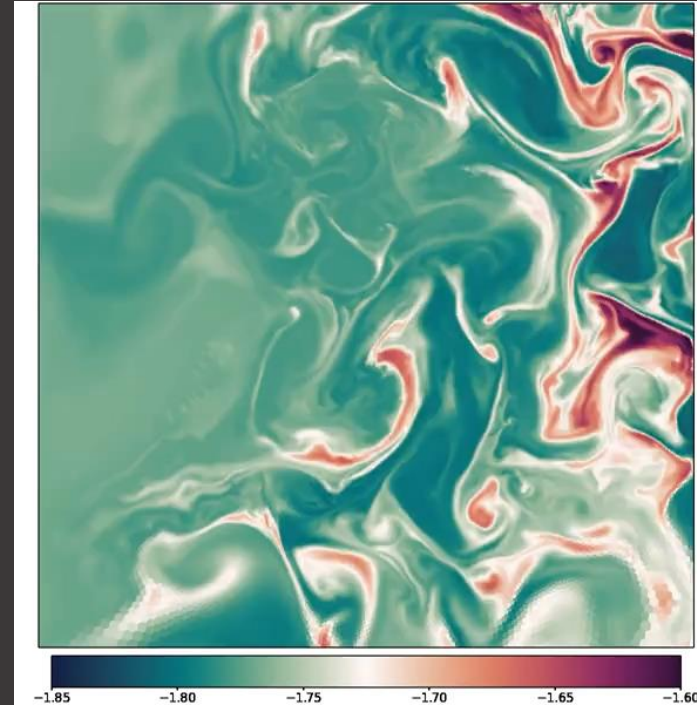
2100

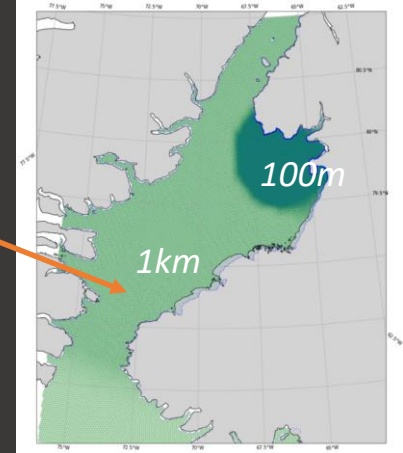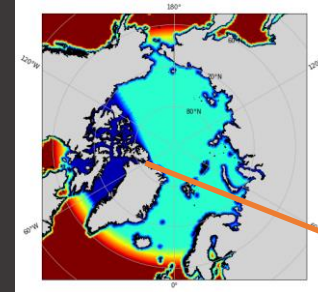*Li et al., 2022, in prep*

Regional focus, stand alone

1km in SWOT Crossover region, Gulf Stream

100m in a small region of Nares strait

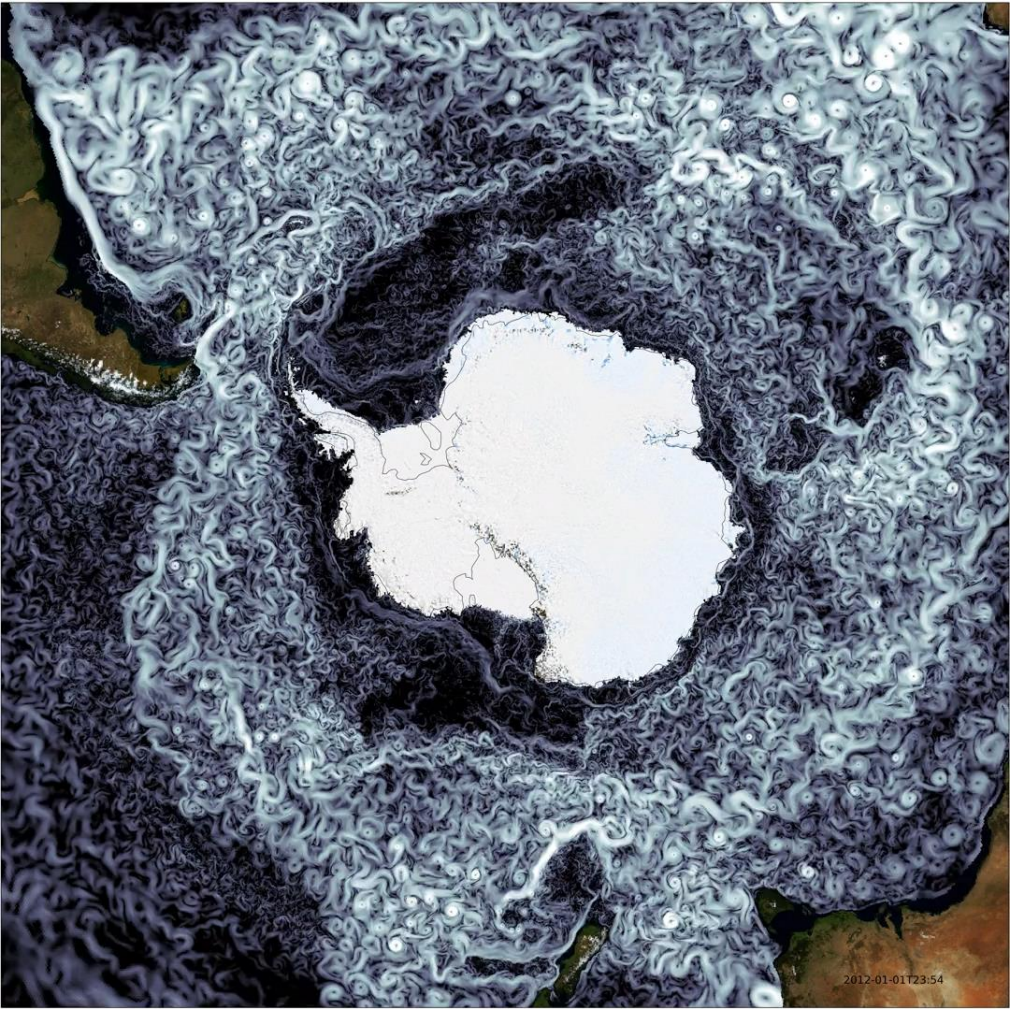Uchida et al., *GMD*, 2022

3M vertices, 1 SMPD on 2304 cores

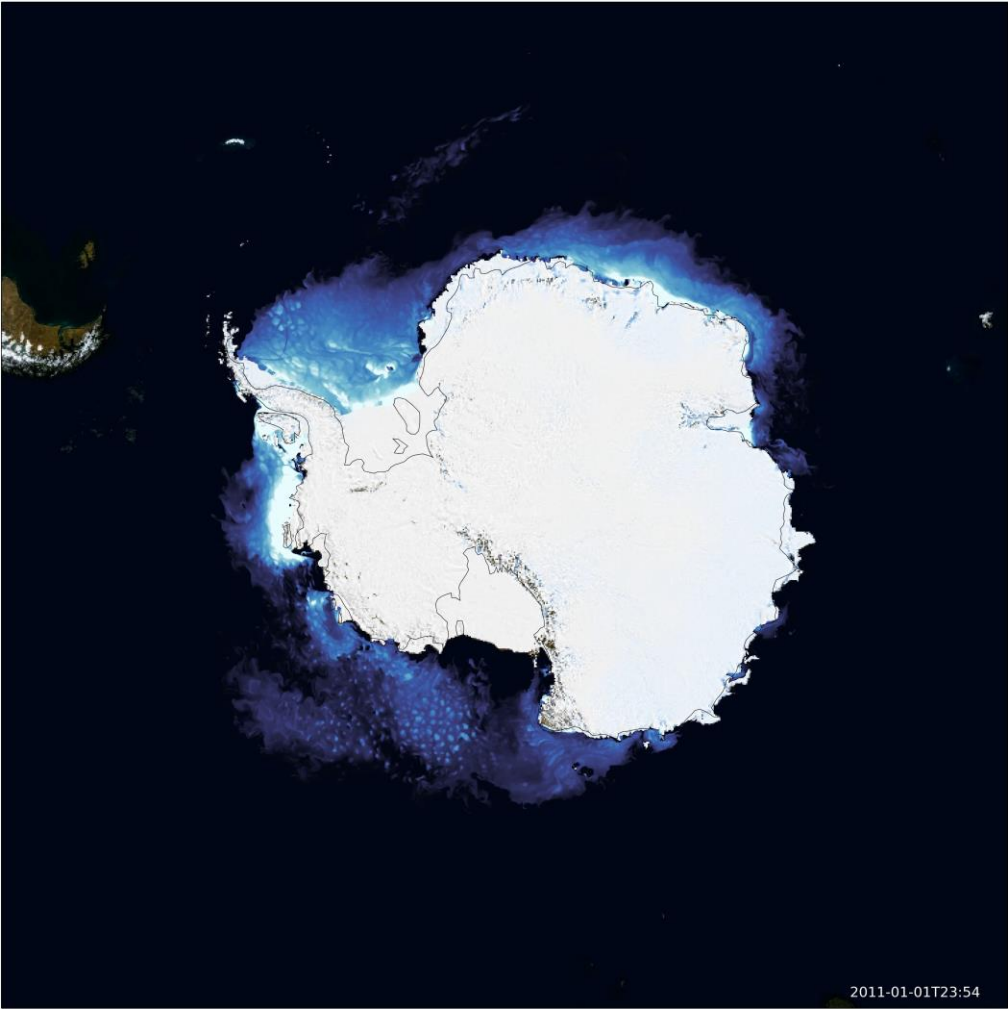0.5M vertices, 2 SMPD on 768 cores

Follow up of work started in:
Kirillov et al., *Oce.Sci*. 2022

FESOM2

Regional focus, stand alone

Southern ocean with 3 km resolution

11M nodes, 1 SYPD on 8192 cores.

FESOM2

Global focus coupled, way forward

OpenIFS/FESOM2 (AWI-CM3)

DART: 3M vertices. Coupled with TCo319L137 can do 4.6 SYPD on 6769 cores

Streffing et al., *GMD*, 2022

IFS/FESOM2 (Digital Twin of the Earth)

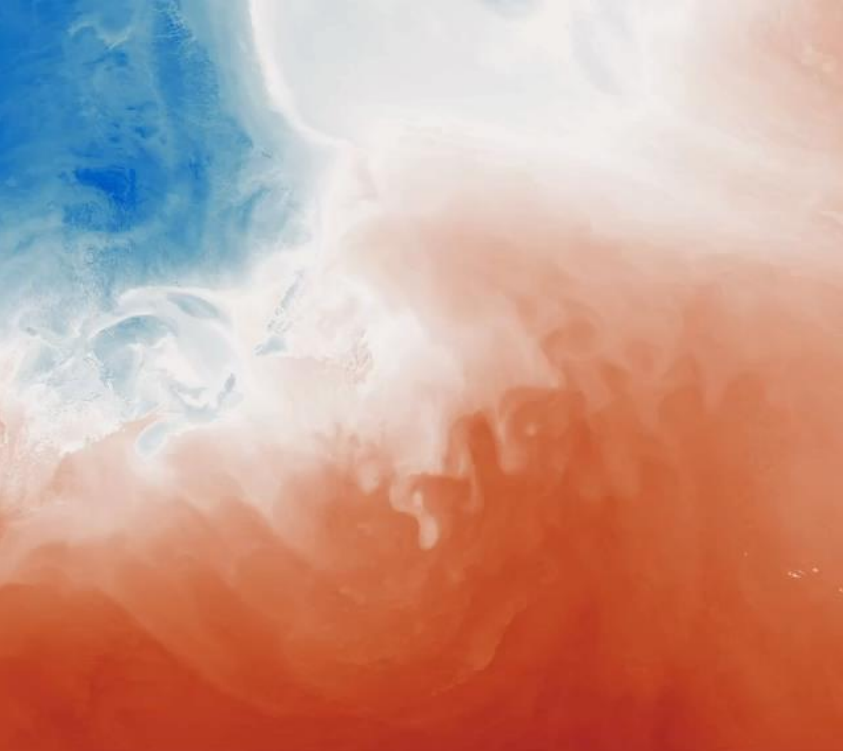NG5: 7.5M vertices. 1 SYPD on 6912 cores (stand alone)

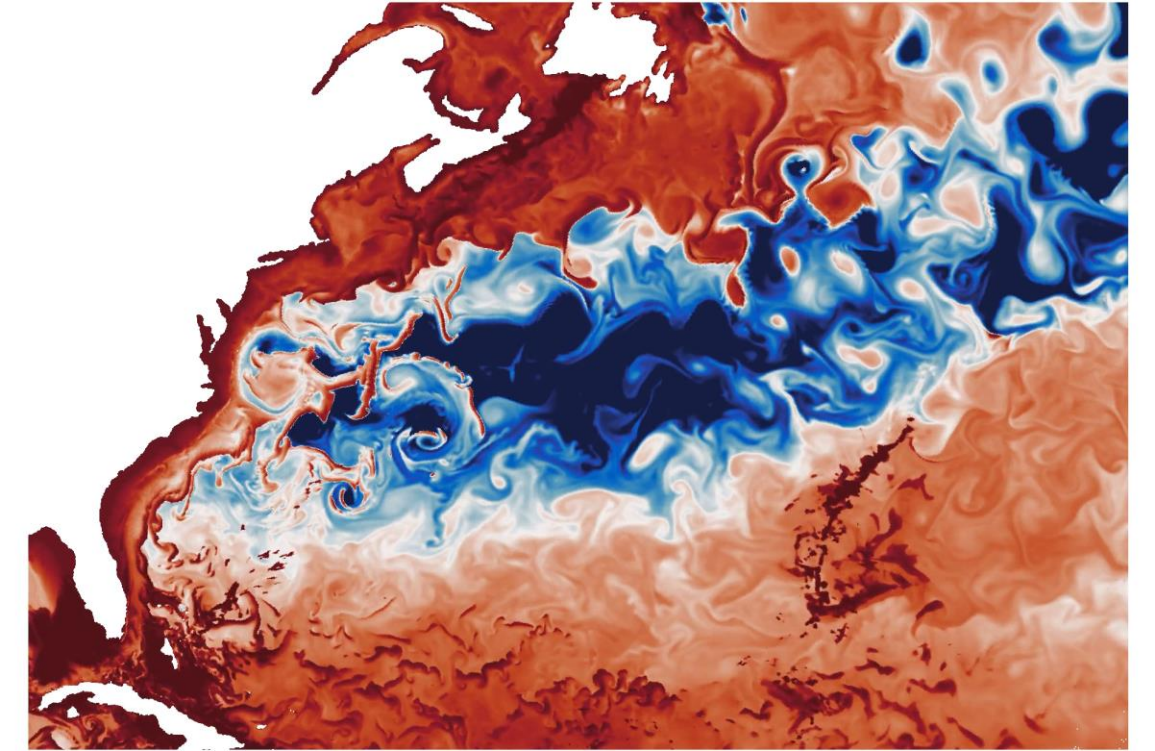# Global focus coupled, way forward

TcO3999 (2.5 km) and NG5

Atmospheric temperature

Mixed Layer Depth

Global focus coupled, way forward

Progects:

EU funded. Plans of doing 30 years of simulations with IFS/FESOM at 4.5 km Atmosphere and 12-4.5 km ocean (NG5). Experemental setup with 2.5 km AS and up to 2 km Ocean.

German National funding (BMBF). Plans of running and tuning IFS/FESOM km scale simulations.

EERIE

EU funded. Plans of doing 150 years of simulations (HighResMIP protocol) with IFS/FESOM at 10 km Atmosphere and 12-4.5 km ocean (NG5).

ALEPH

Joint progect with IBS Center for Climate Physics, Pusan National University. Plans of doing HighResMIP type simulations with OpenIFS/FESOM at 10 km Atmosphere and 25-5 km ocean (DART). Also 10 years with 2.5 km atmosphere.

Project still to be confirmed (still in negotiation)

EU funded. Plans of doing several decades of 10 km IFS/FESOM (with NG5), 5 km IFS/FESOM (with NG5) and decade of 2.5 km resolution IFS/FESOM (probably also NG5).

FESOM2   AWI HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Finite volumE Sea Ice Ocean Model
FESOM2
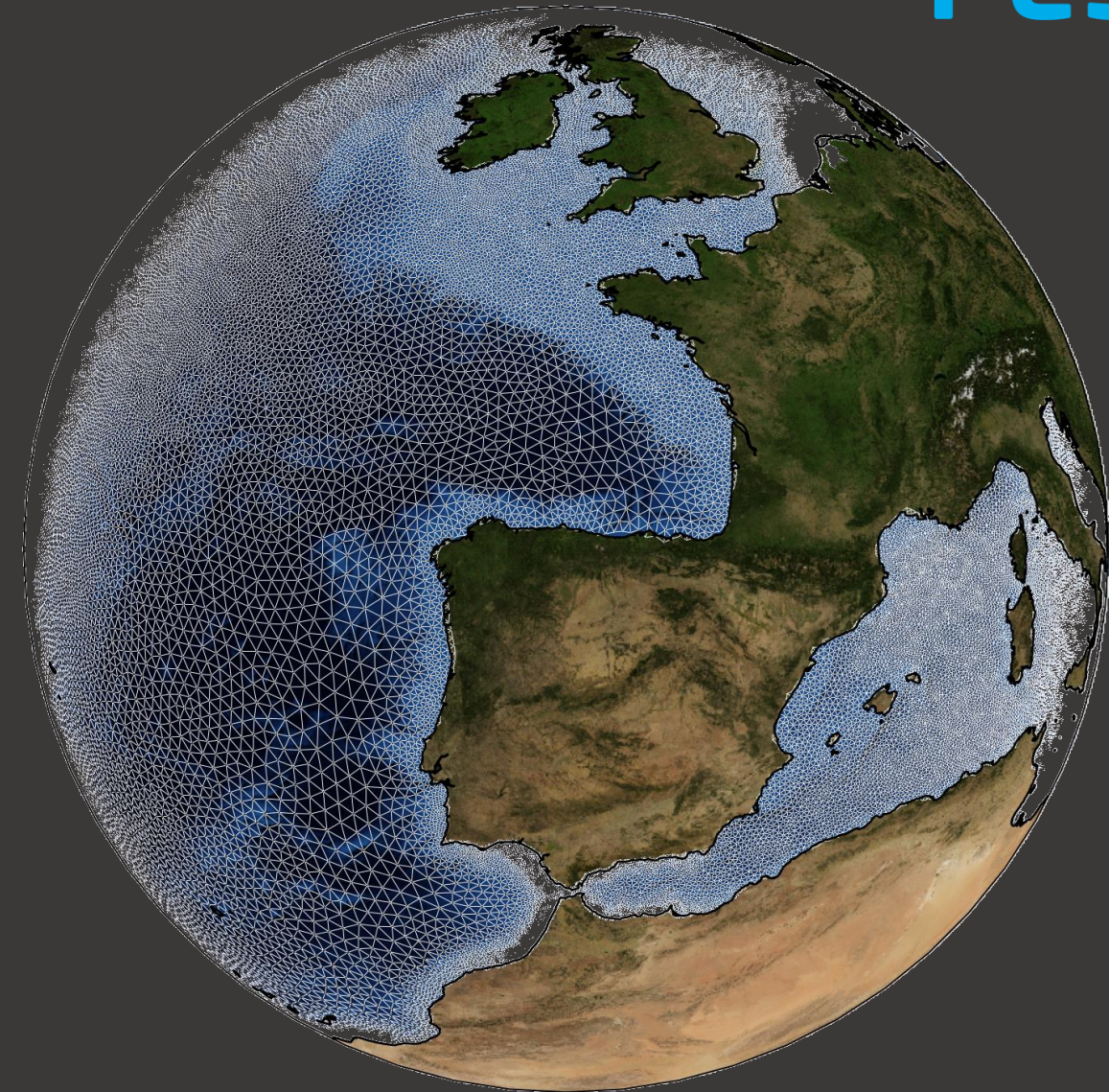
FESOM 2.3 will include:

- ✓ **Single precision option**
- ✓ **Tuned global ocean tides**
- ✓ **Interactive icebergs, drift and melt/cooling**
- ✓ **Sub-cycling instead of solver for the sea surface height**
  Additional momentum advection versions
- ✓ **Vanishing quasi sigma coordinate**
- ✓ **Extend GPU to other parts of FESOM (natESM/EERIE)**

FESOM2

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