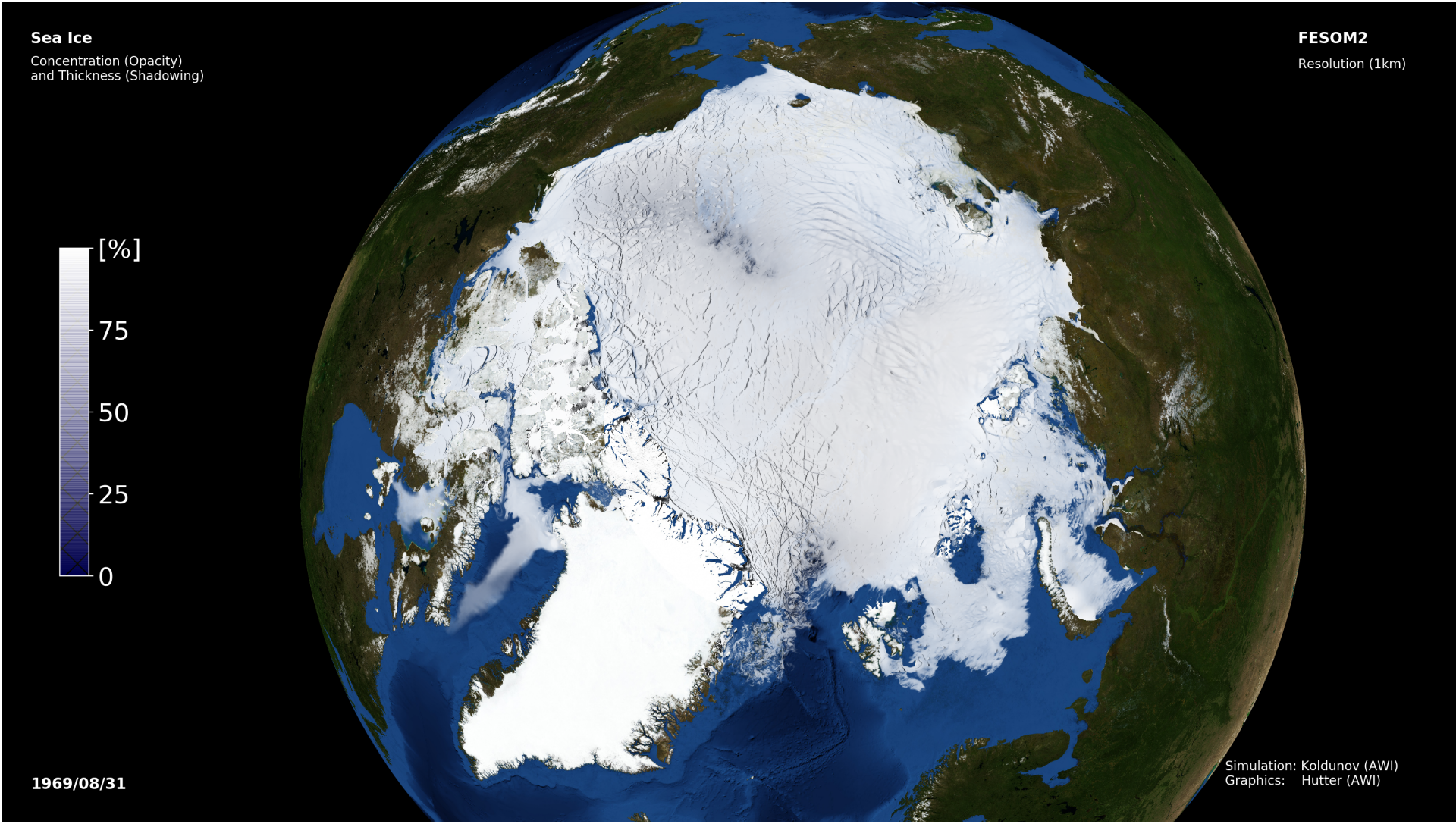
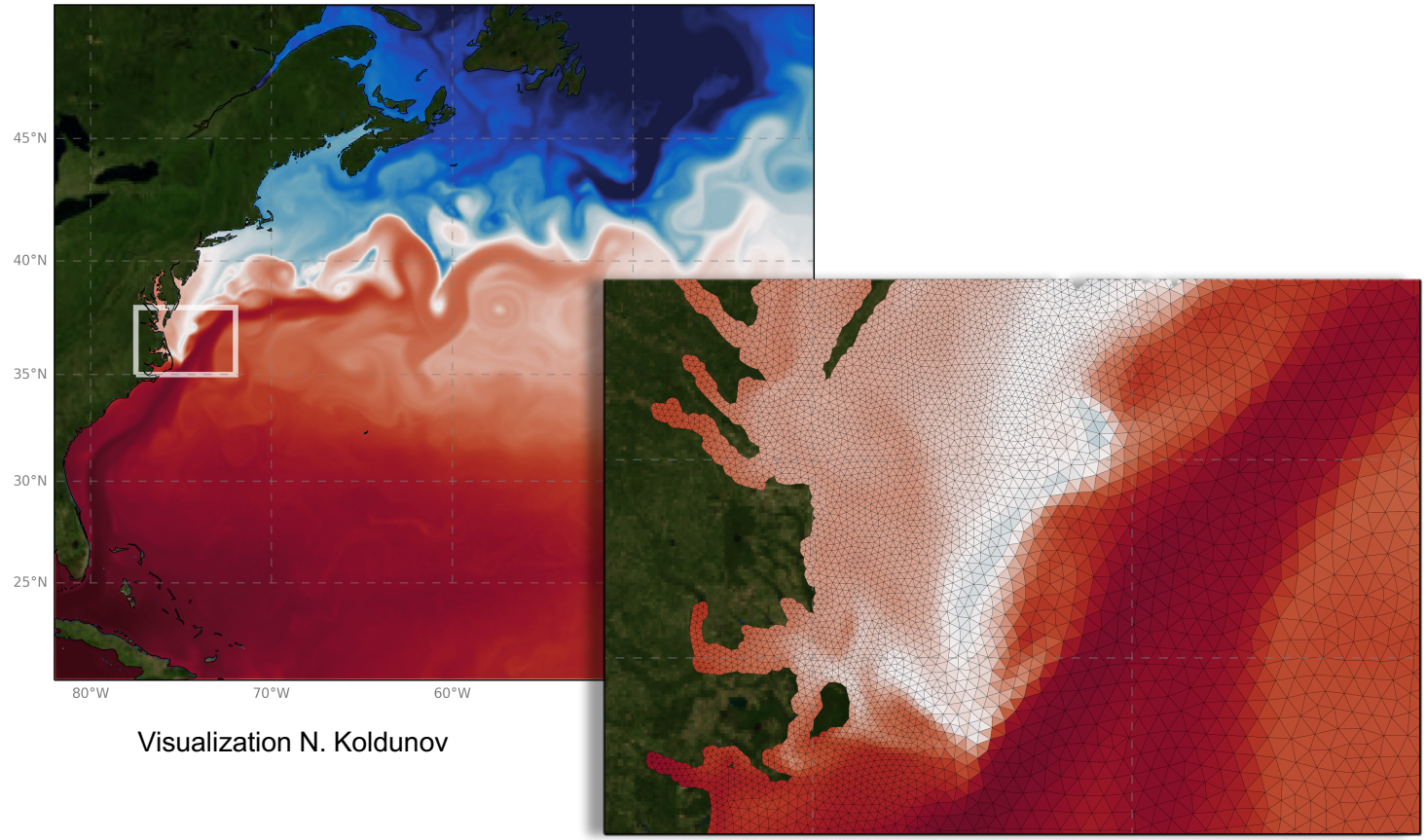
Large-scale ocean modeling on unstructured meshes



S. Danilov, N. Koldunov, P. Scholz, D. Sein, D. Sidorenko, Q. Wang with contributions from V. Aizinger, D. Barbi, O. Gurses, S. Harig, S. Juricke, T. Rackow, N. Rakowski, T. Semmler, J. Streffing, C. Wekerle, T. Jung

HELMHOLTZ ASSOCIATION

FESOM, MPAS-o and ICON-o are new unstructured mesh models intended for large-scale simulations

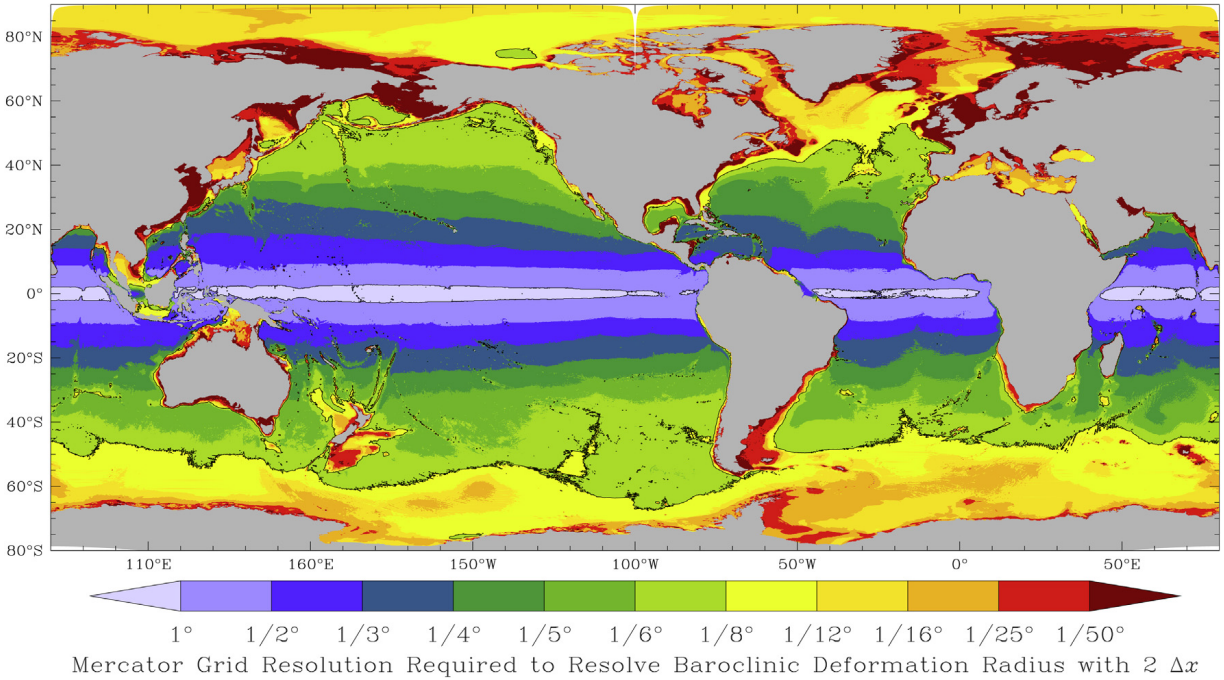


Visualization N. Koldunov

Challenges

- How to use the variable resolution efficiently: where to resolve? How fine to resolve?
- How to be as numerically efficient as structured-mesh models? What are the bottlenecks?
- How to make diagnostics on unstructured meshes as convenient as on structured meshes?

Mercator grid resolution to represent the Rossby deformation radius (R. Hallberg, OM, 2013)



L_d in the ocean varies in wide limits;

The pattern of observed variability (altimetry) is very non-uniform;

Use unstructured meshes to better represent eddy variability

Unstructured meshes can be refined based on:

- Baroclinic deformation radius L_d
- Linear instability wavelength: the Phillips and Charney types of instability
- Geometrical factors (many jets are along the continental break)
- Observed pattern of variability (as derived from altimetry)
- Desired focus on some area (similar to nesting)

FESOM 1.4 and FESOM 2.0

FESOM

Finite Element
Sea ice-Ocean Model

- ✓ well tested and tuned
- ✓ ocean part of AWI-CM1
- ✓ participated in CMIP6
- ✓ many regional and global applications

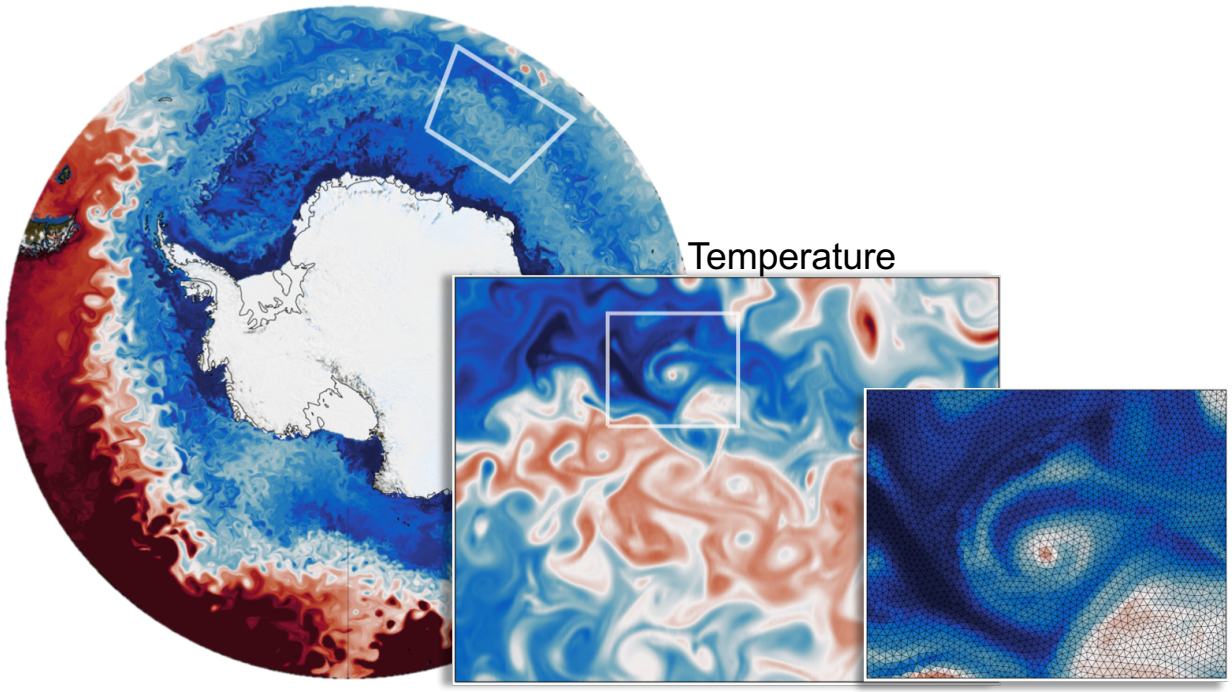
- ✓ > 3x faster than FESOM 1.4
- ✓ ALE vertical coordinate
- ✓ ocean part of AWI-CM2 (coupled to ECHAM6) and AWI-CM3 (OpenIFS)

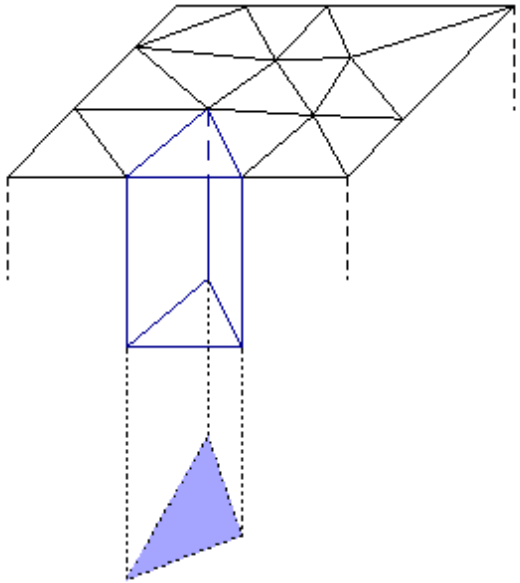
FESOM2

Finite volumE
Sea ice-Ocean Model

Global model setups

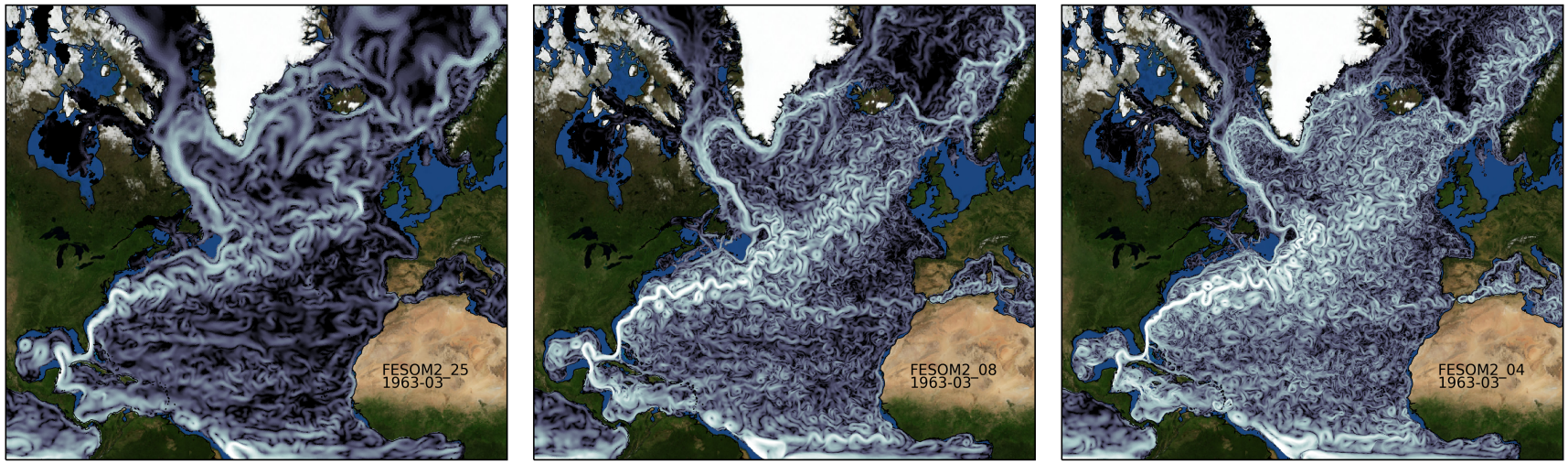
- A global sea ice - ocean model using an unstructured triangular mesh: **FESOM**
- A global coupled model: **AWI-CM** = **FESOM** coupled to a high resolution atmosphere, **ECHAM6/IFS/OpenIFS**





How to select mesh resolution?

Global meshes with finer resolution in NA:
Snapshots of velocity amplitude at NA resolutions of ¼ degree, 8 km and 4 km



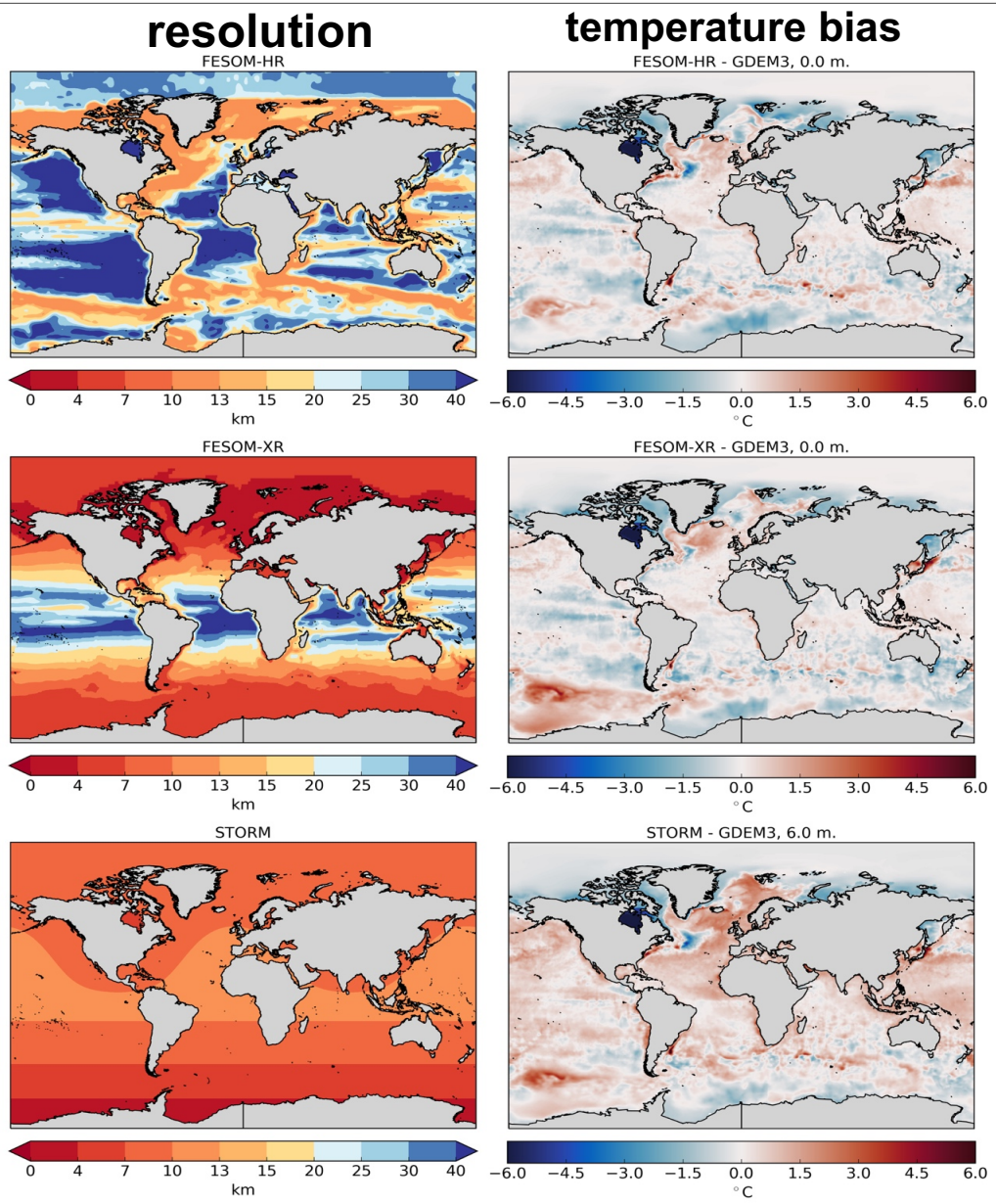
Simulations by O. Gurses

How to design a global mesh?

Refinement according to SSH variability (Sein et al. 2016)

Refinement according to the Rossby radius and SSH variability

MPIOM "STORM" 0.1° (von Storch et al., 2012)



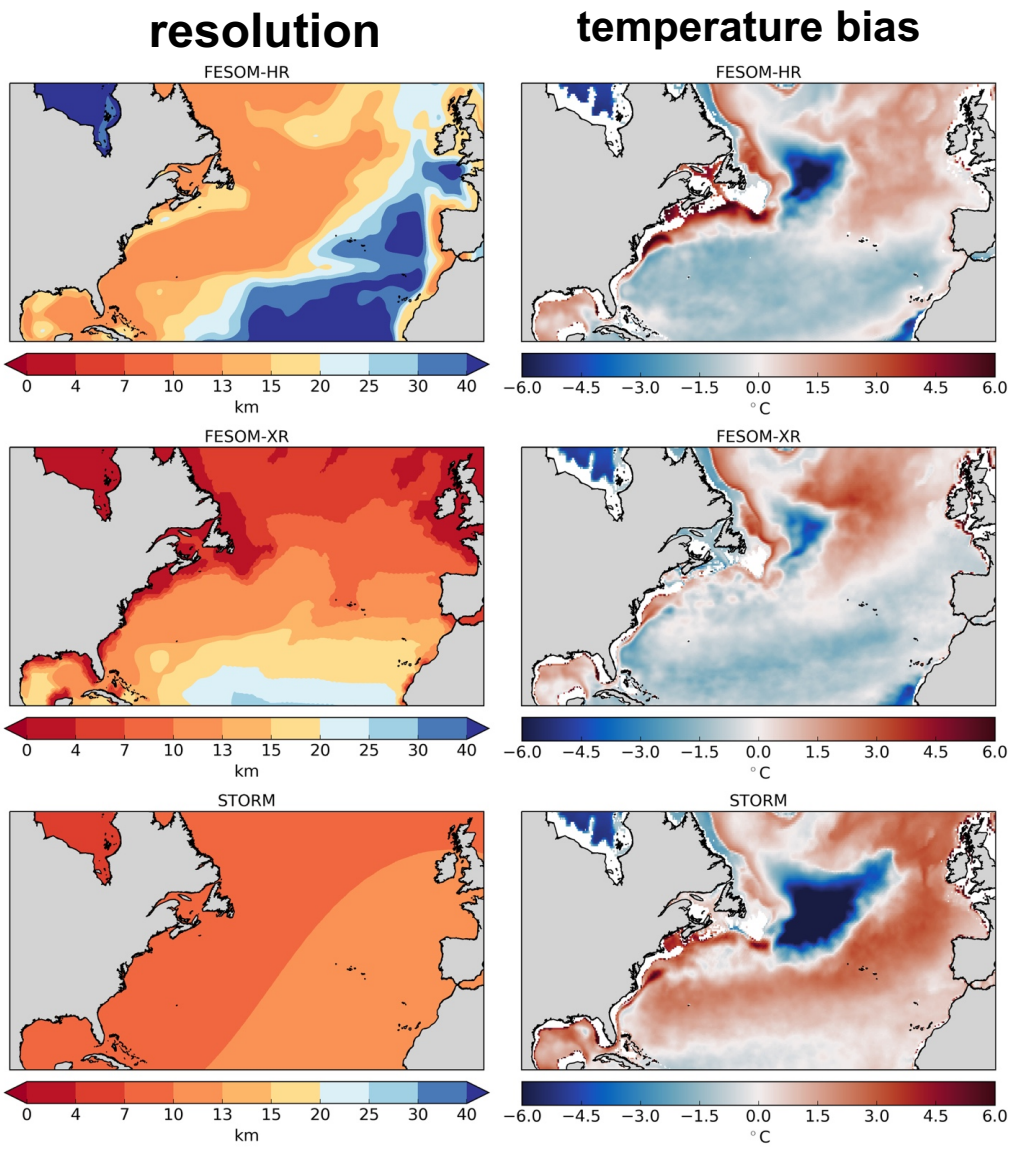
Sein et al., 2017

How to design a global mesh?

Refinement according to SSH var.
1,3 M vertices

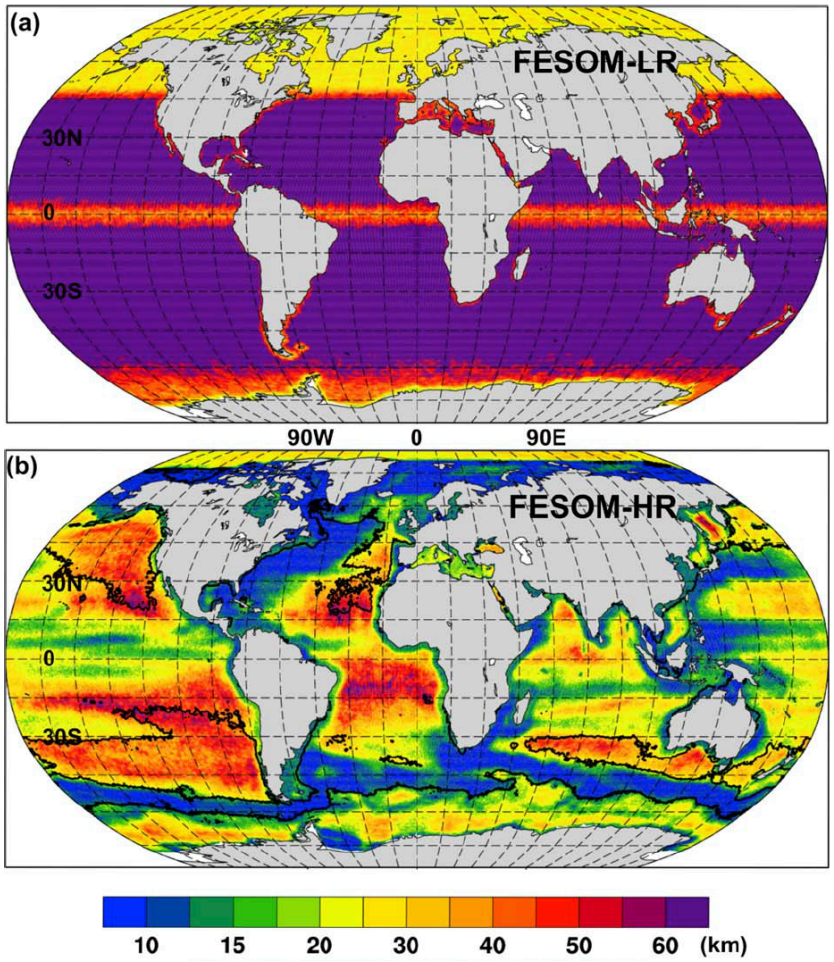
Refinement according to the Rossby radius and SSH var.
5M vertices

MPIOM "STORM" 0.1°
(von Storch et al., 2012)
5,5M wet points

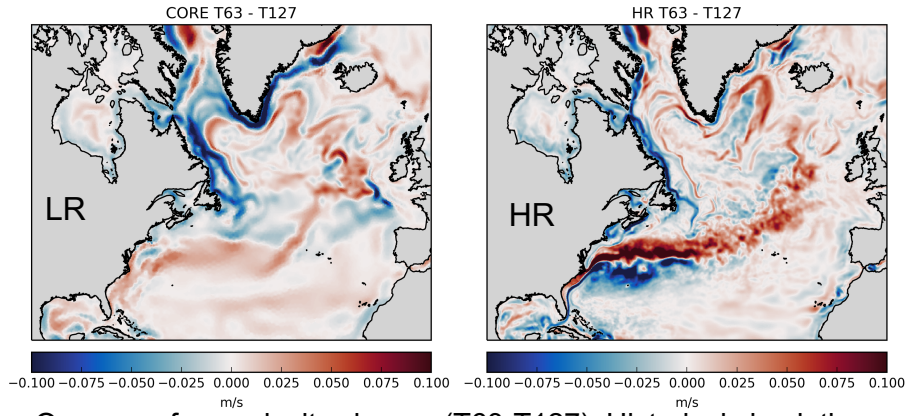


Sein et al., 2017

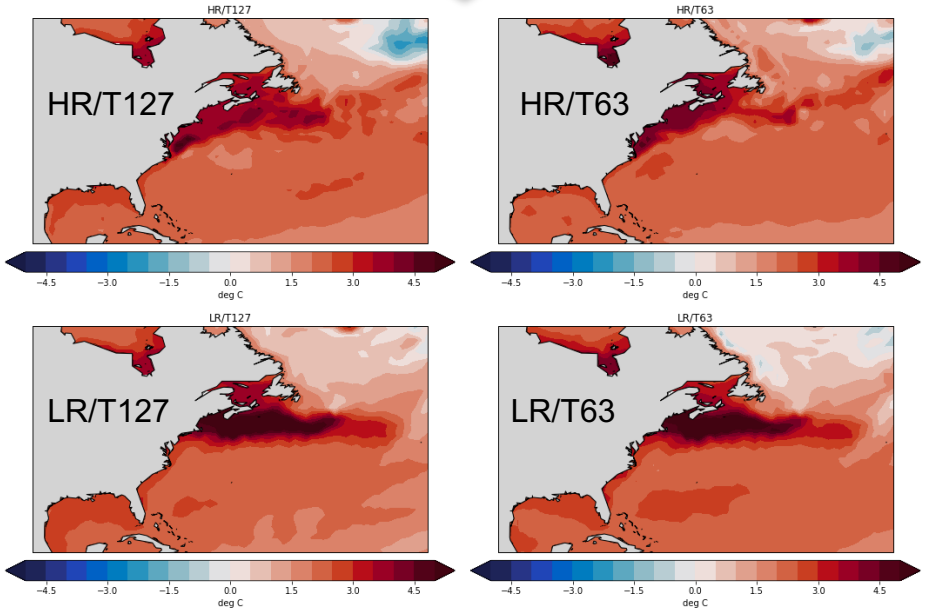
HR vs LR in the North Atlantic



LR (a) and HR (b) ocean resolution



Ocean surface velocity change (T63-T127). Historical simulations.



Climate change (RCP8.5). SST

Sein et al. 2018

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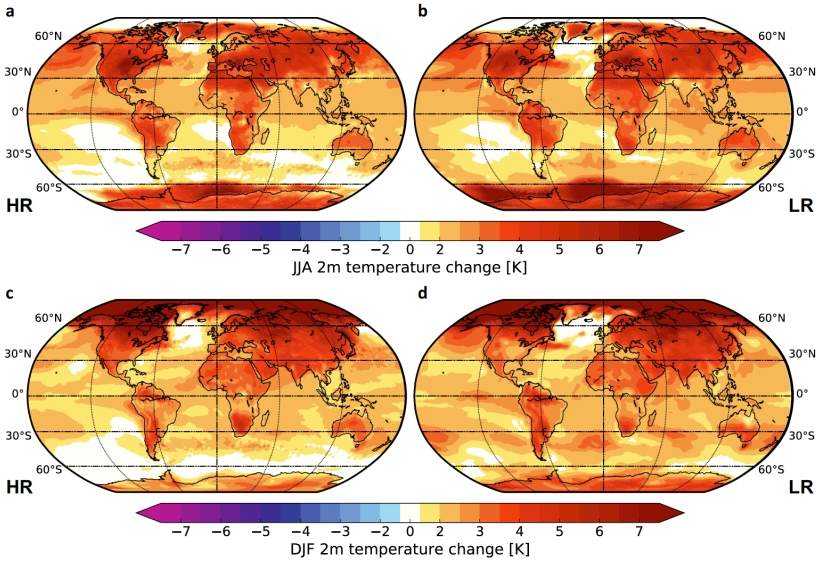
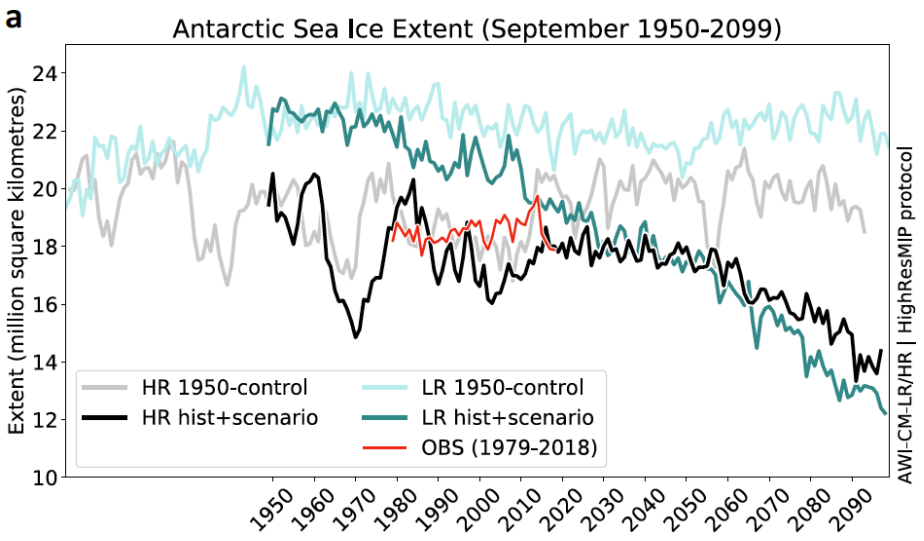
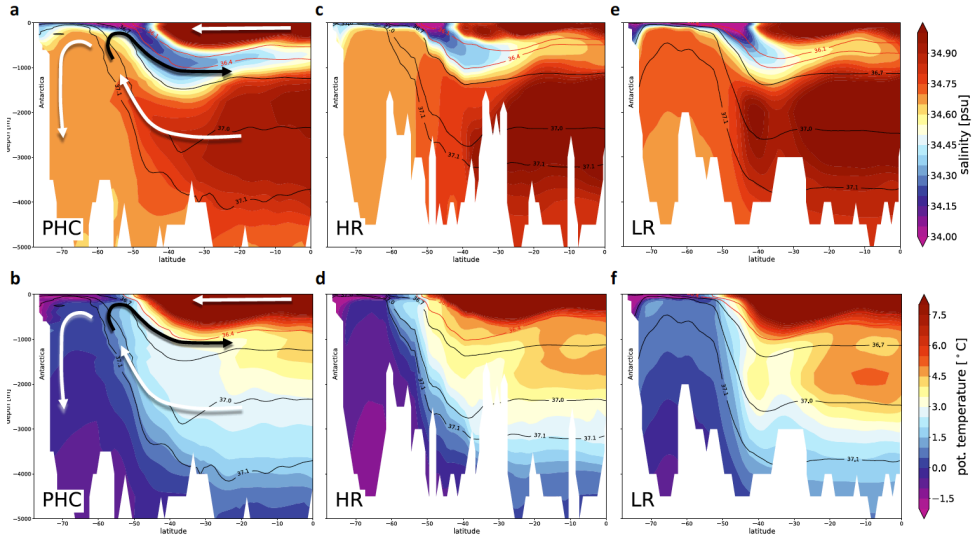
What do we gain from the ocean resolution? Example: Southern Ocean





Projections of 2m temperature (2070–2099, relative to 1990–2019)



LR shows a pool of much warmer subsurface waters southward of 60S than HR that is up to 1C warmer in the upper 500 m than observed. Rackow et al., 2021 (submitted)

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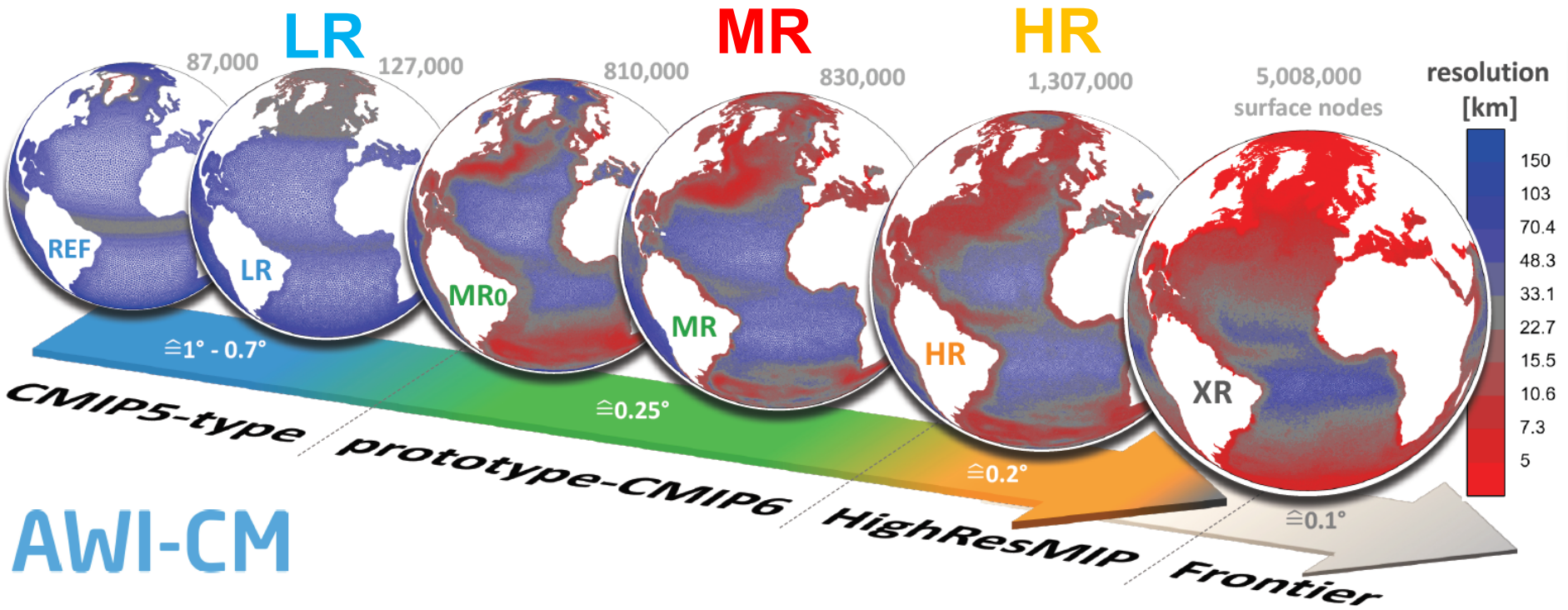
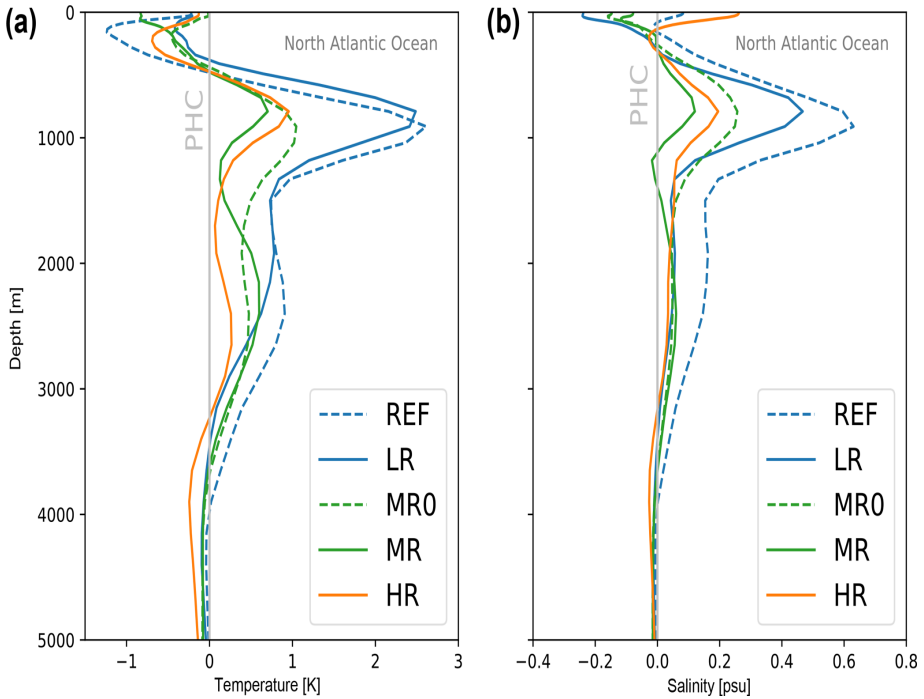
FESOM, flexible mesh layout

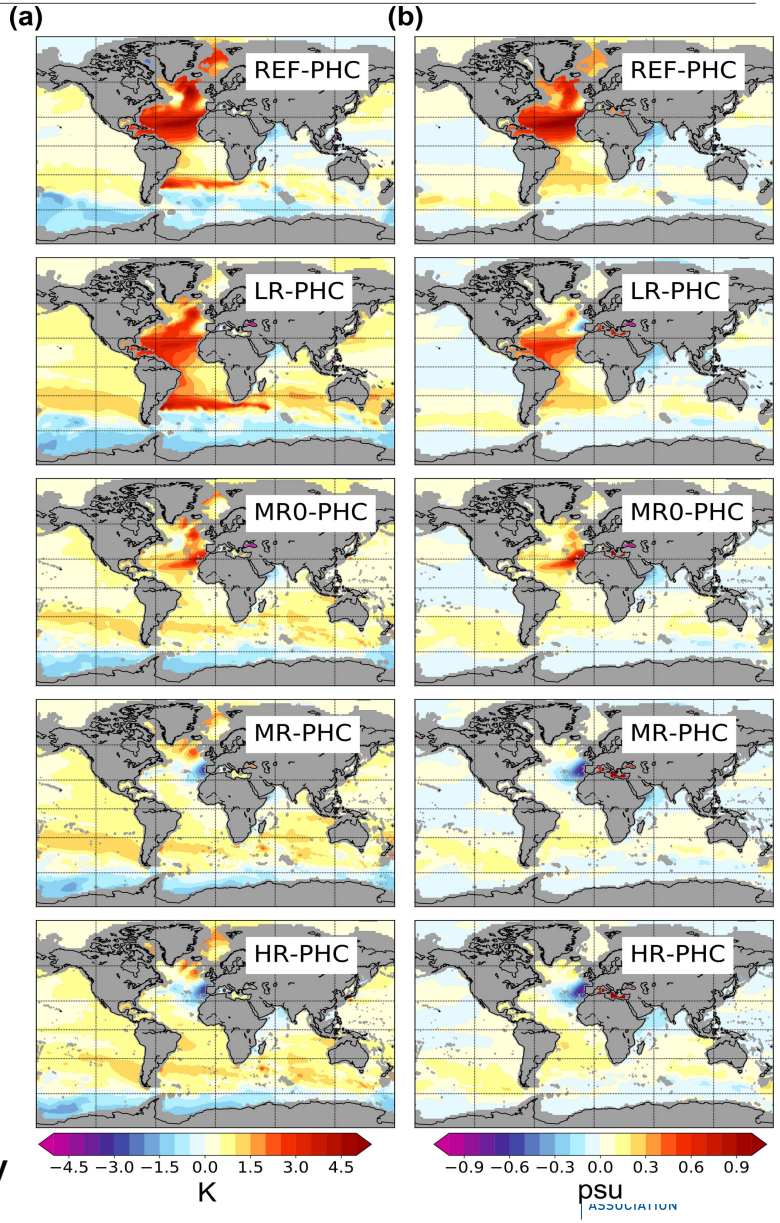
current configurations *(Rackow et al. 2019)*



resolution is smoothly varied in the global ocean according to specified functions

FESOM: role of ocean resolution





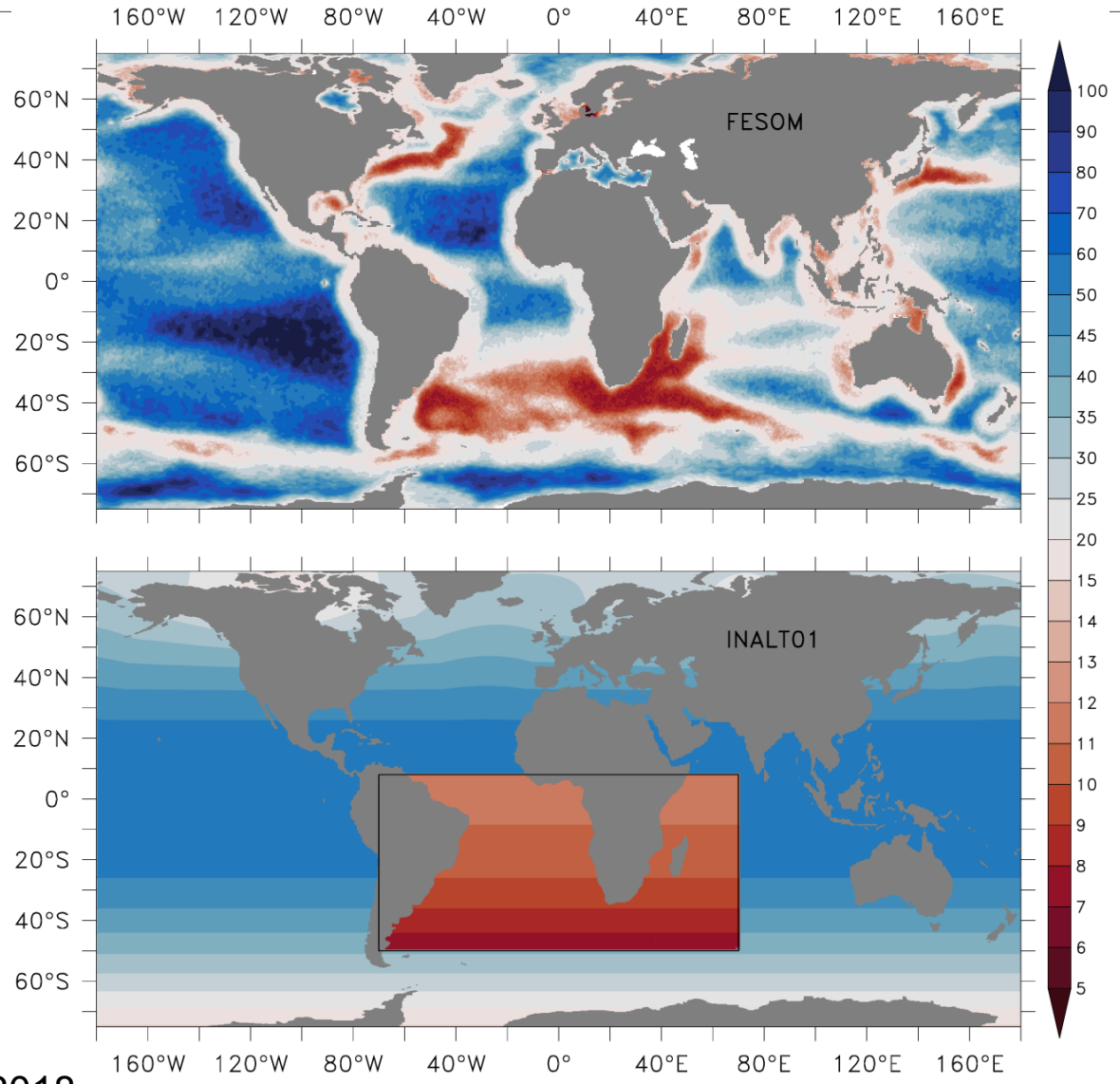
increased resolution reduces model bias!
Rackow et al., 2019

difference to climatology 1000m

Agulhas Current and Leakage:
FESOM vs traditional nesting

FESOM
(MR 0.8 M 2D vertices)
28M 3D vertices

NEMO/AGRIF
25M wet 3D cells
in the nest



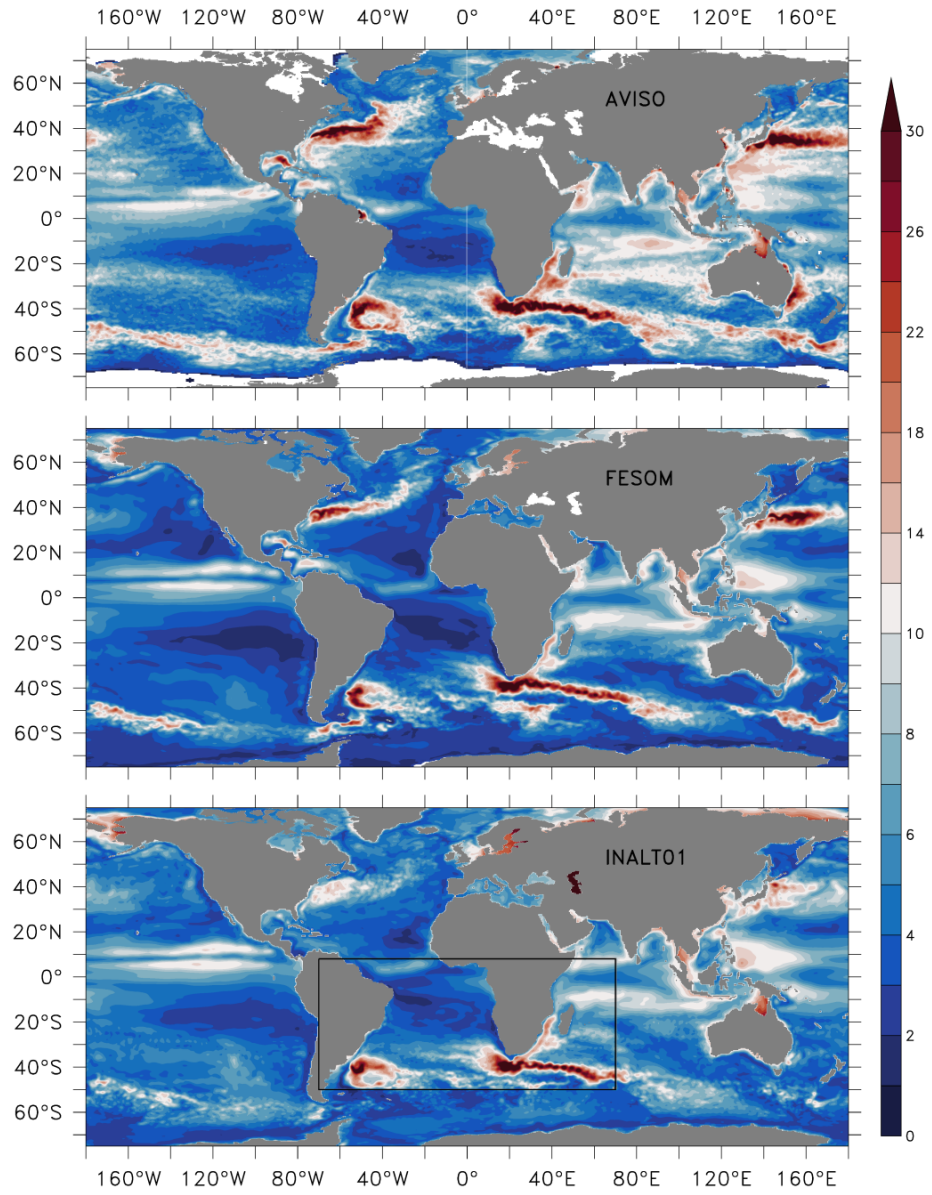
Biastoch et al. 2018

Agulhas Current and Leakage:
FESOM vs traditional nesting

AVISO

FESOM

NEMO



SSH variability

Biastoch et al. 2018

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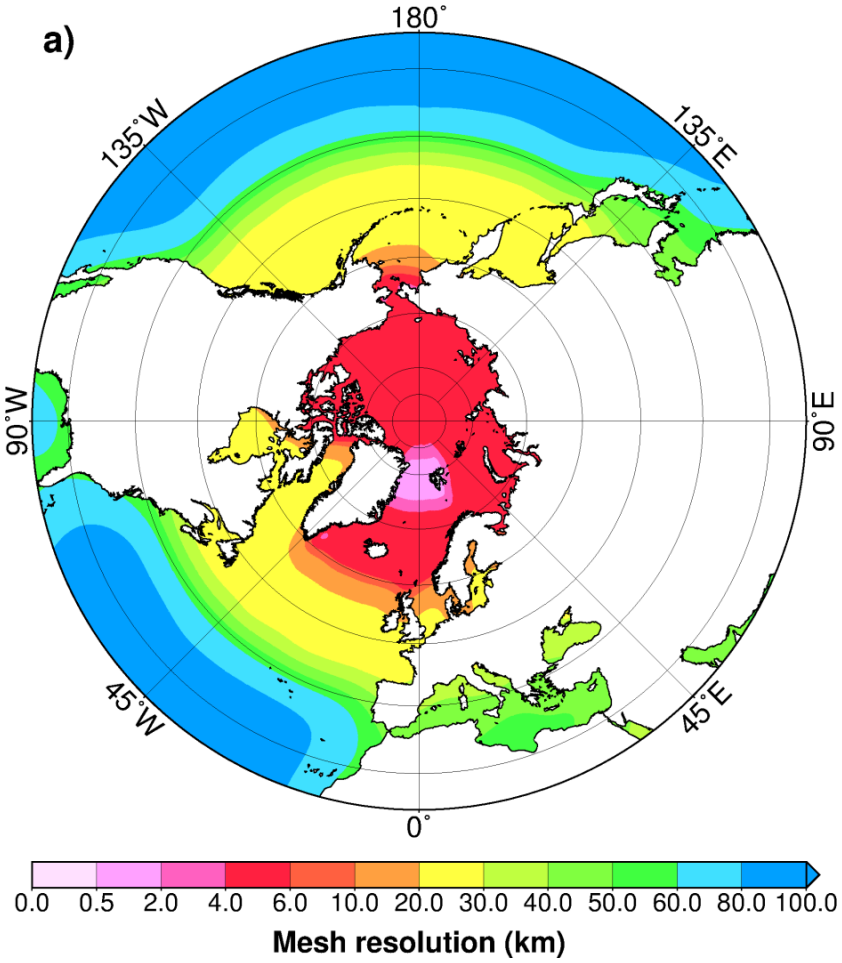
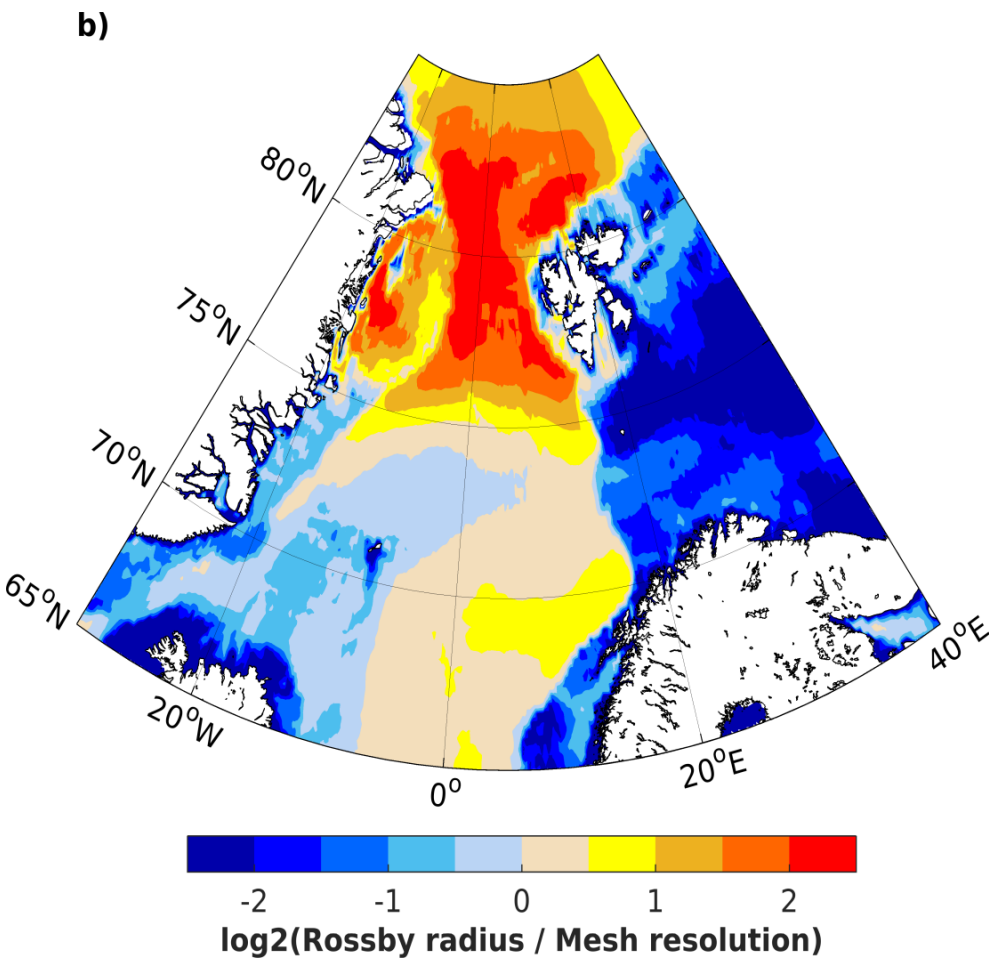
Eddy resolving in the Fram Strait

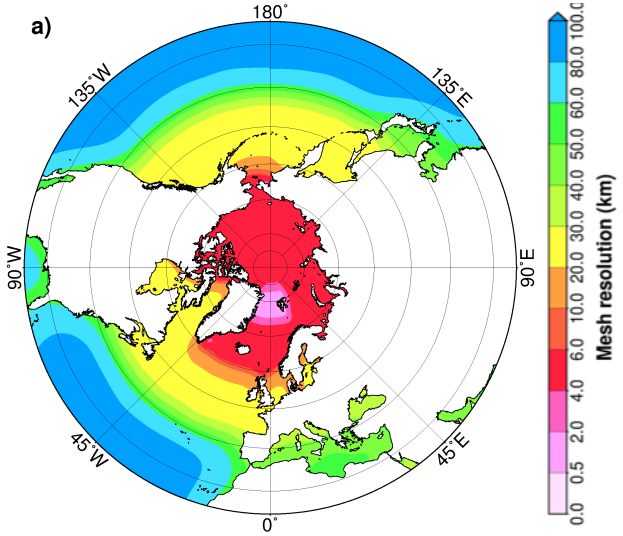


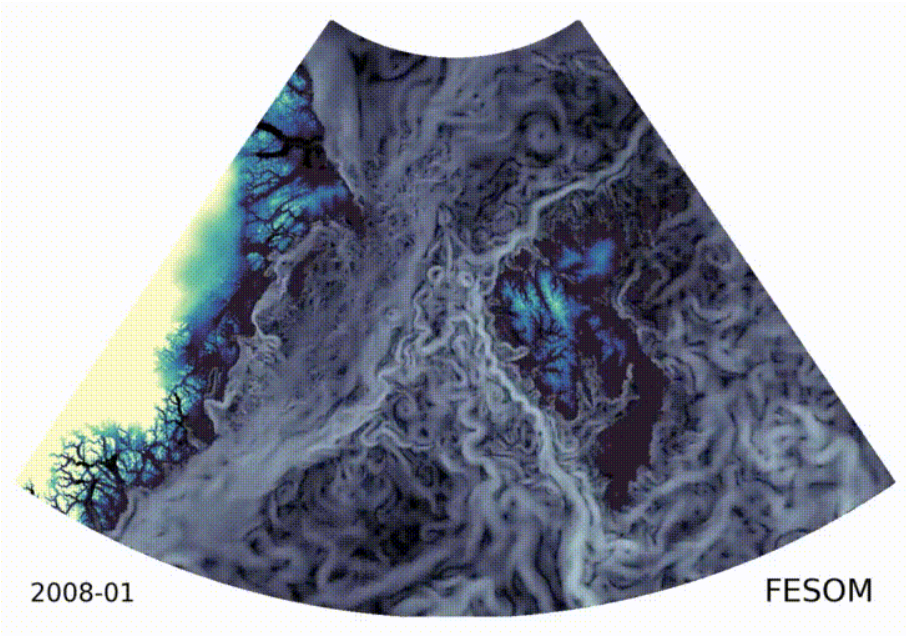


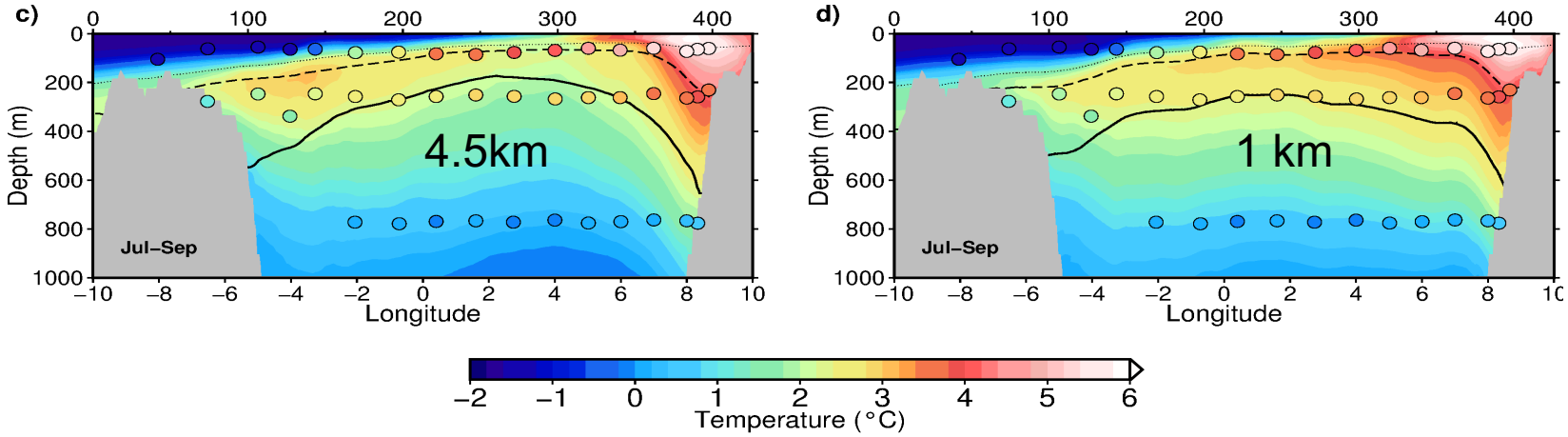
Wekerle et al., 2017

Featured applications

Global model with Arctic focus

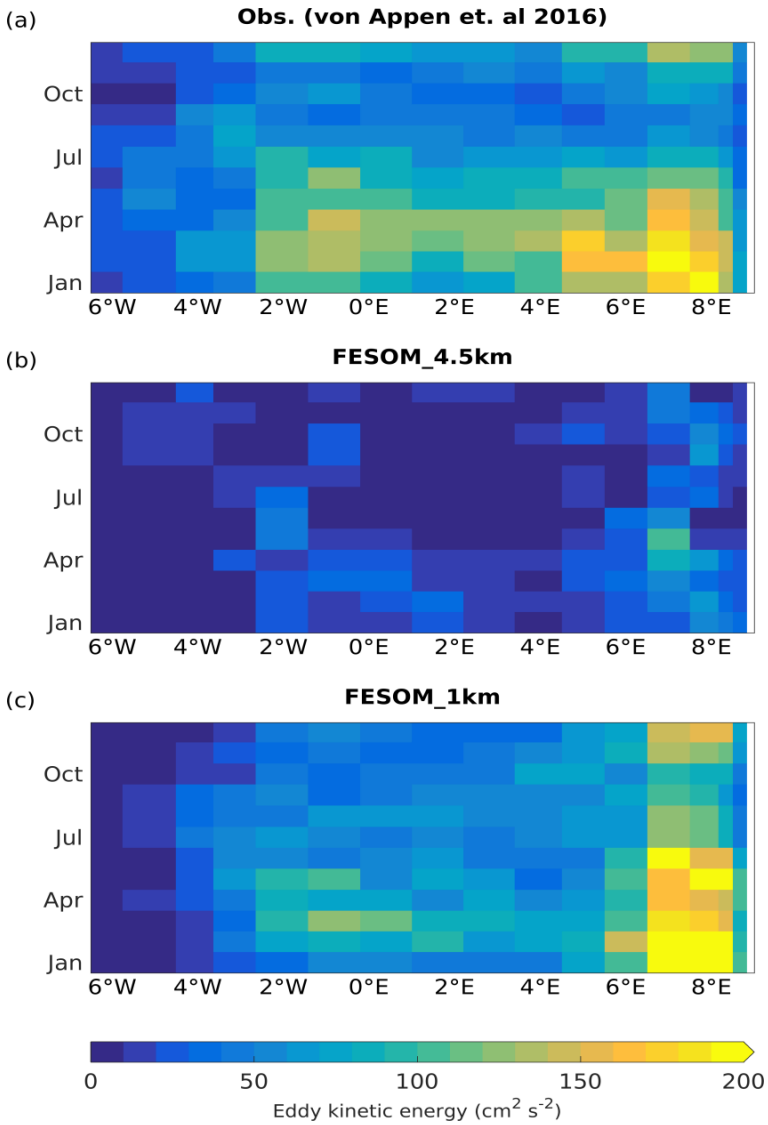


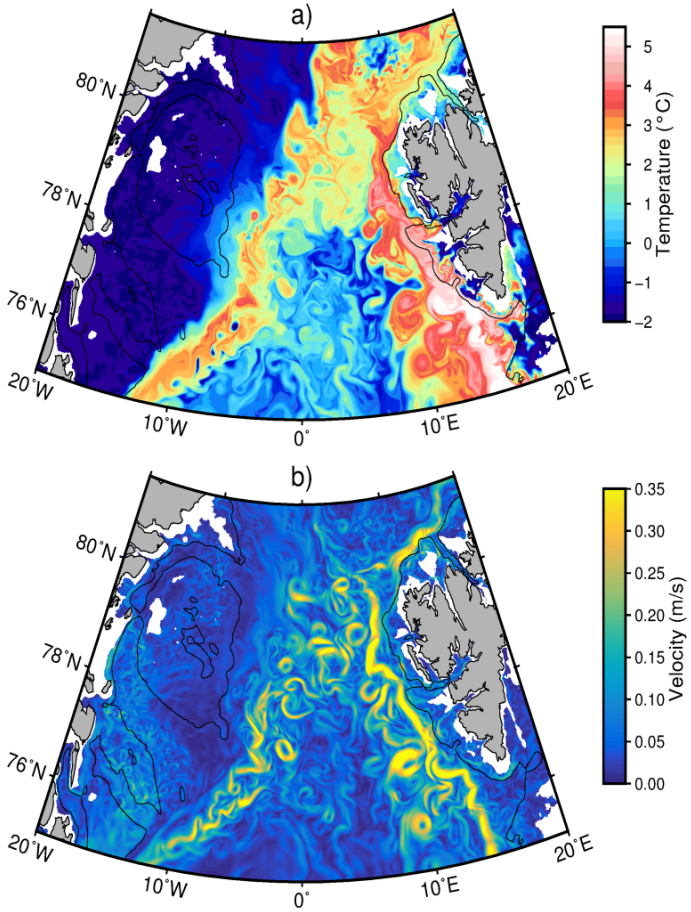




Wekerle et al. 2017, JGR

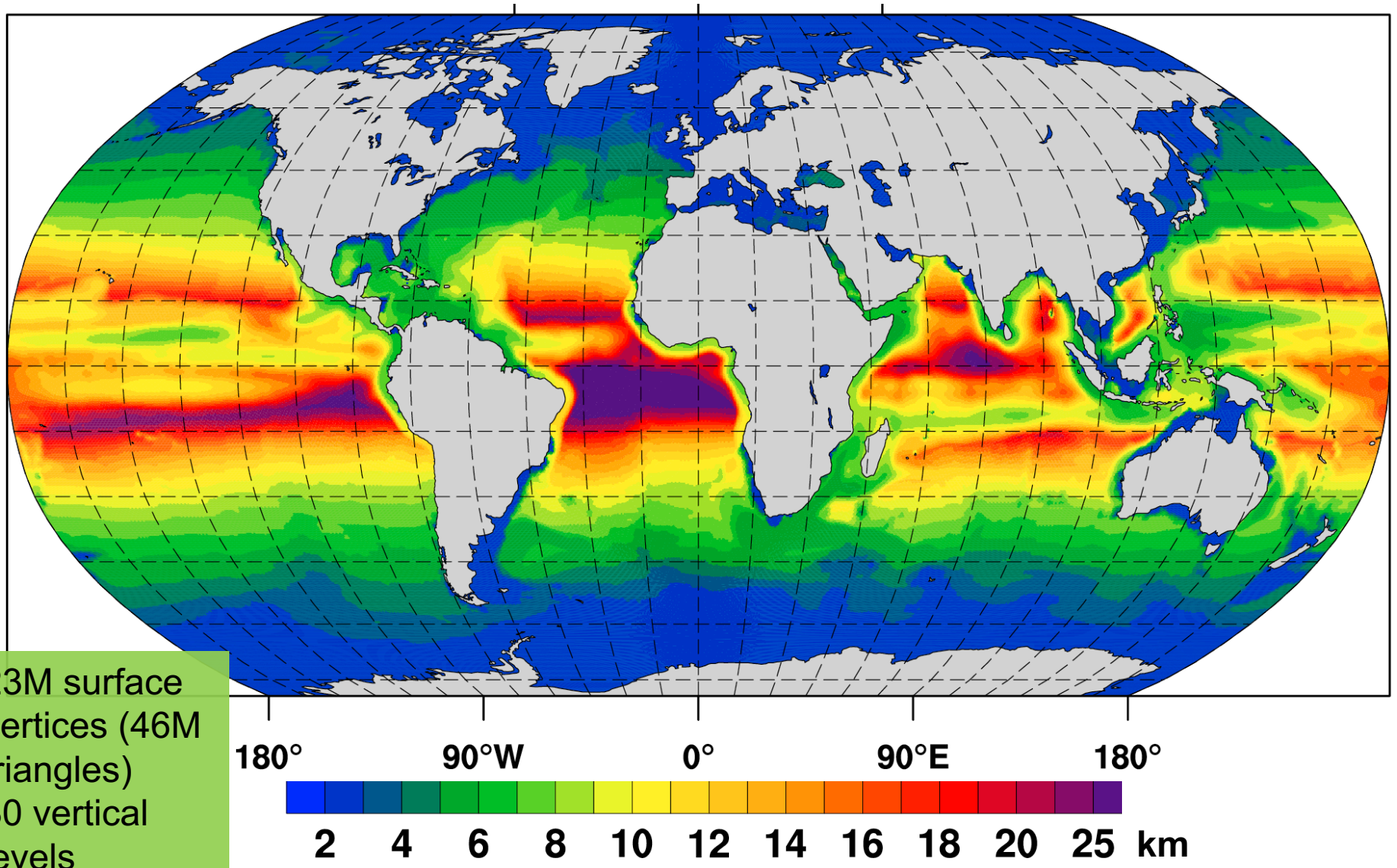
Eddy resolving in the Fram Strait





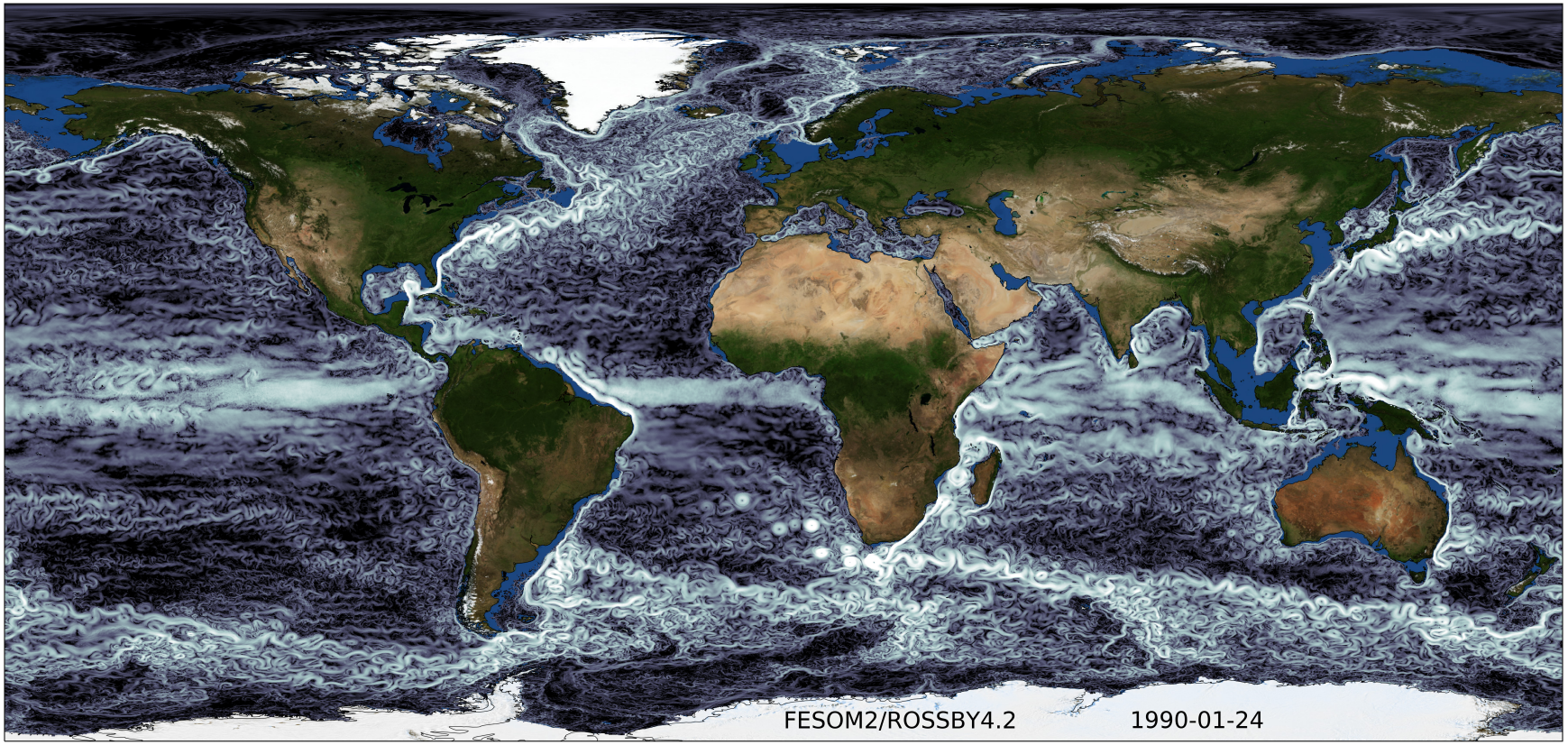
Wekerle et al., 2017

ROSSBY 4.2 resolution: max(Ro/4,2km)

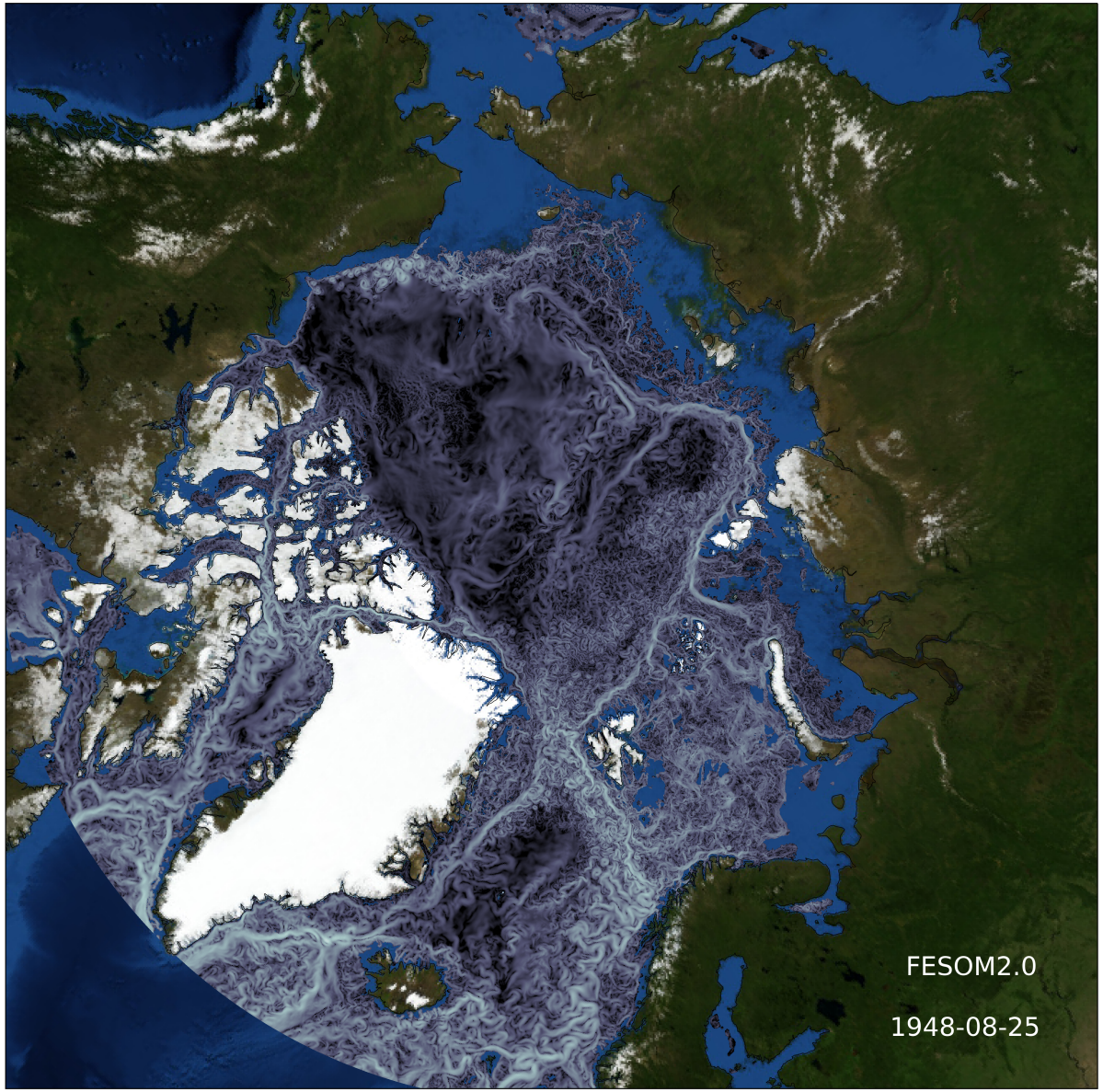


23M surface vertices (46M triangles)
80 vertical levels

100 m ocean velocity from ROSSBY4.2

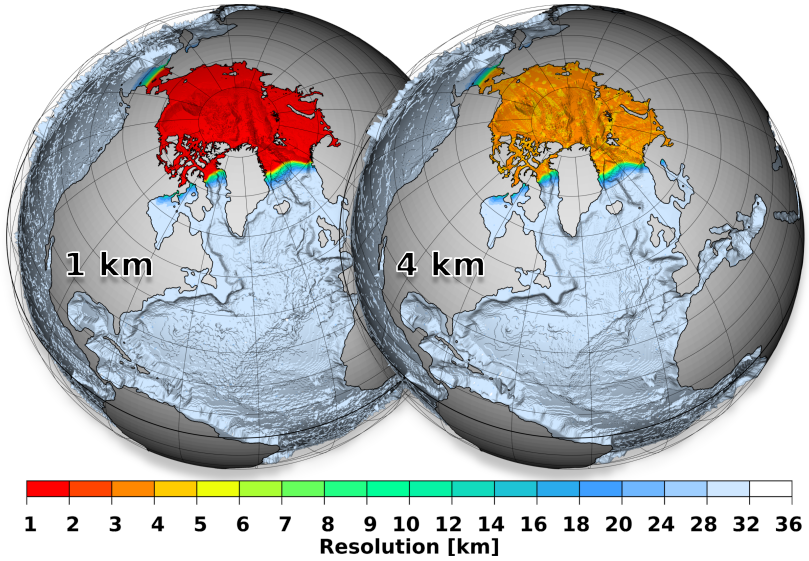


FESOM2 throughput: 1 SYPD on 400 nodes. Scalable up to 2000 nodes (72000 cores) with 4 SYPD



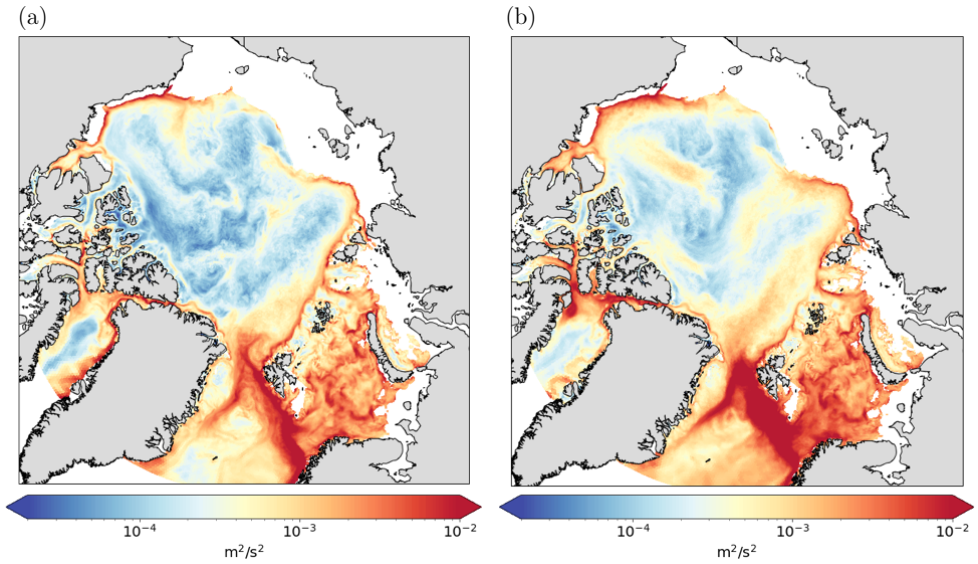
A snapshot of log10(|u|) @100 m in 1 km Arctic in FESOM2
Mesh with 11M surface vertice
(N. Koldunov)

EKE in the Arctic Ocean



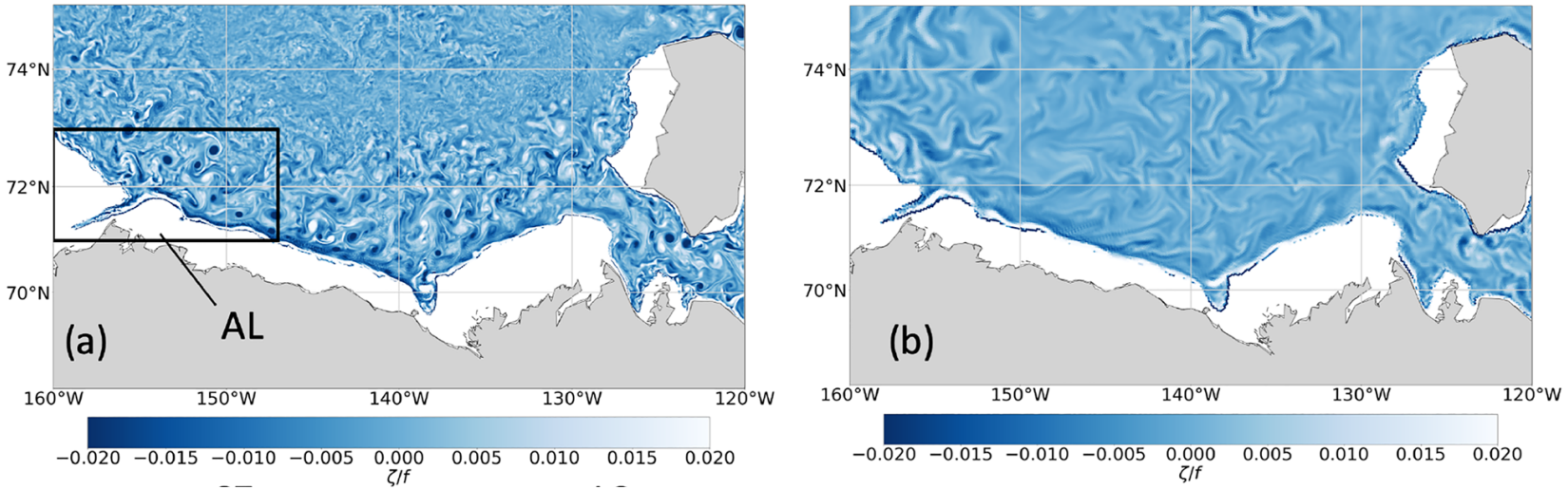
Wang et al. 2020

EKE on 4 km (left) and 1 km (right) meshes



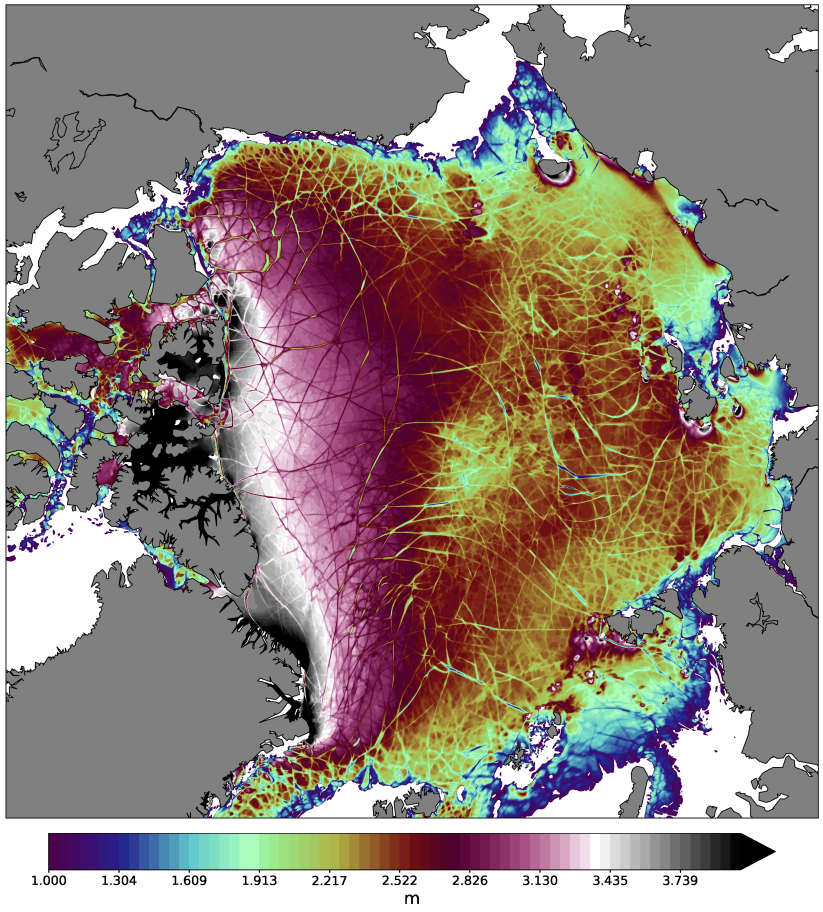
FESOM2 1 km Arctic setup

Relative vorticity in runs on 1 km and 4 km meshes

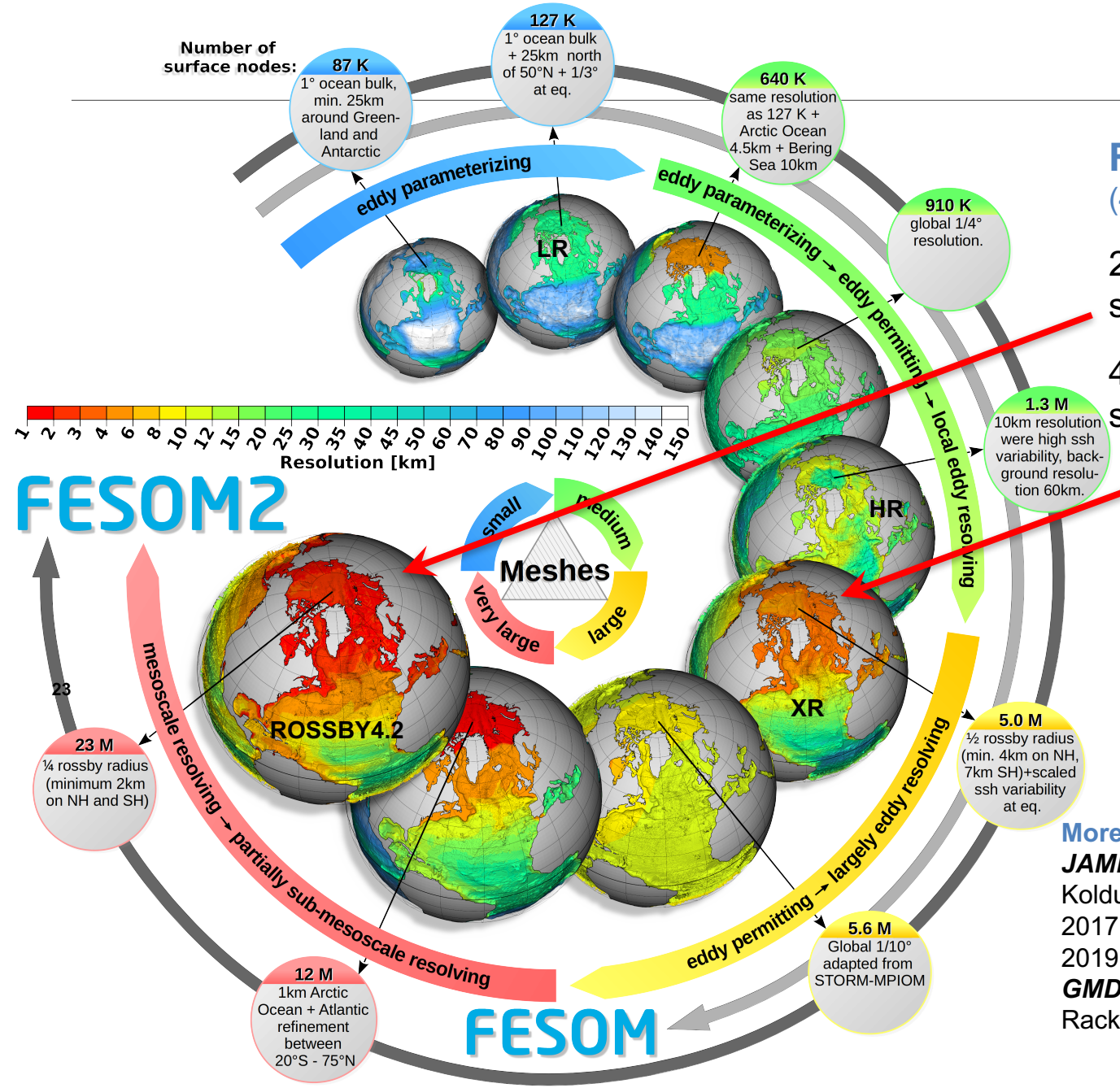


Resolution much finer than L_d (about 8-10 km) is needed in the Arctic Ocean (Wang et al. 2020)

FESOM2 1 km Arctic simulations



Ice thickness,
snapshot, mEVP solver



FESOM2 throughput

(4 times faster then FESOM):

2km resolution with 23M surface nodes up to 4 y/day

4km resolution with 5M surface nodes up to 12 y/day

More details in:

JAMES:

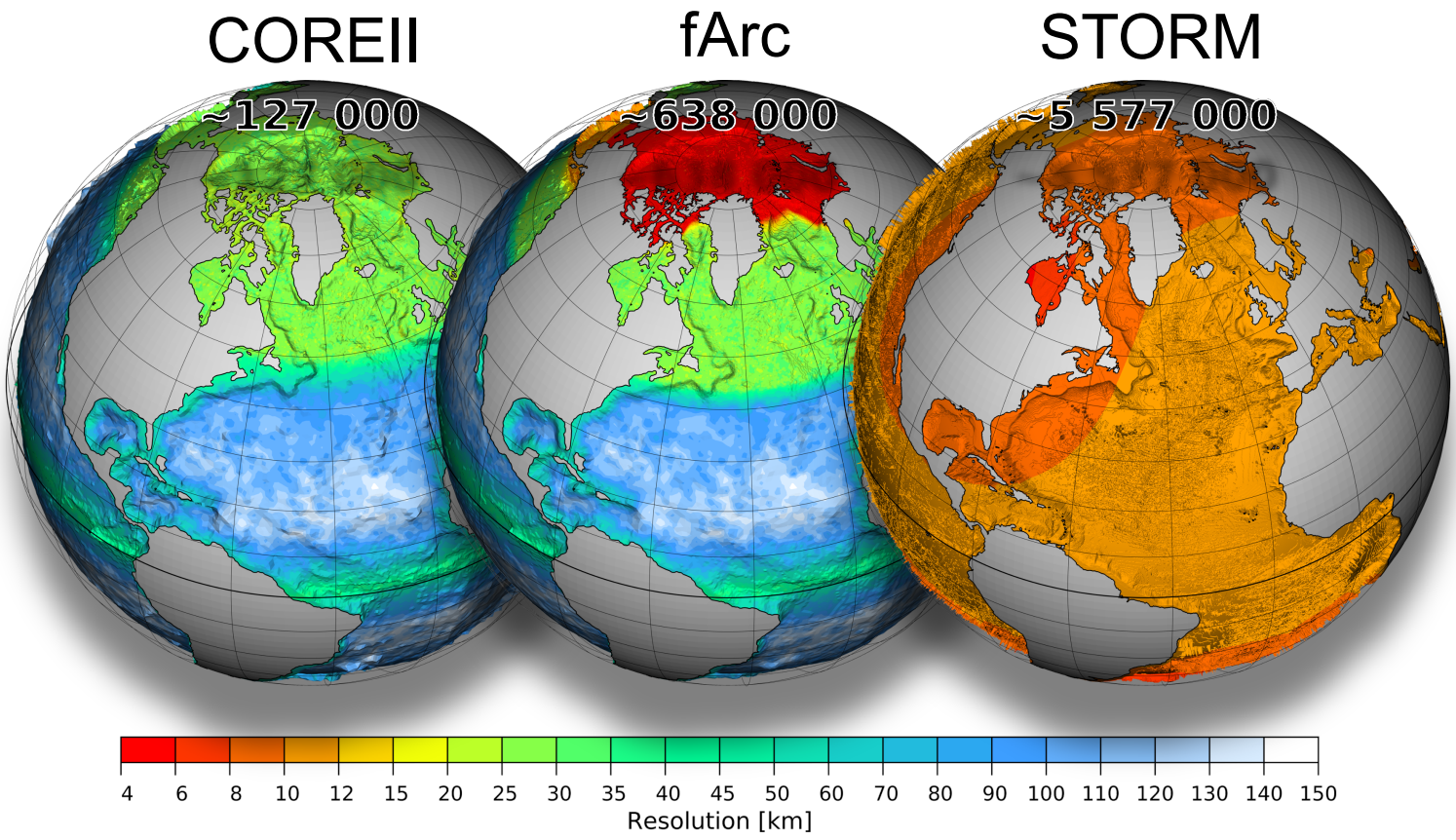
Koldunov et al. 2019; Sein et al., 2016, 2017, 2018; Sidorenko et al., 2018, 2019 (submitted)

GMD:

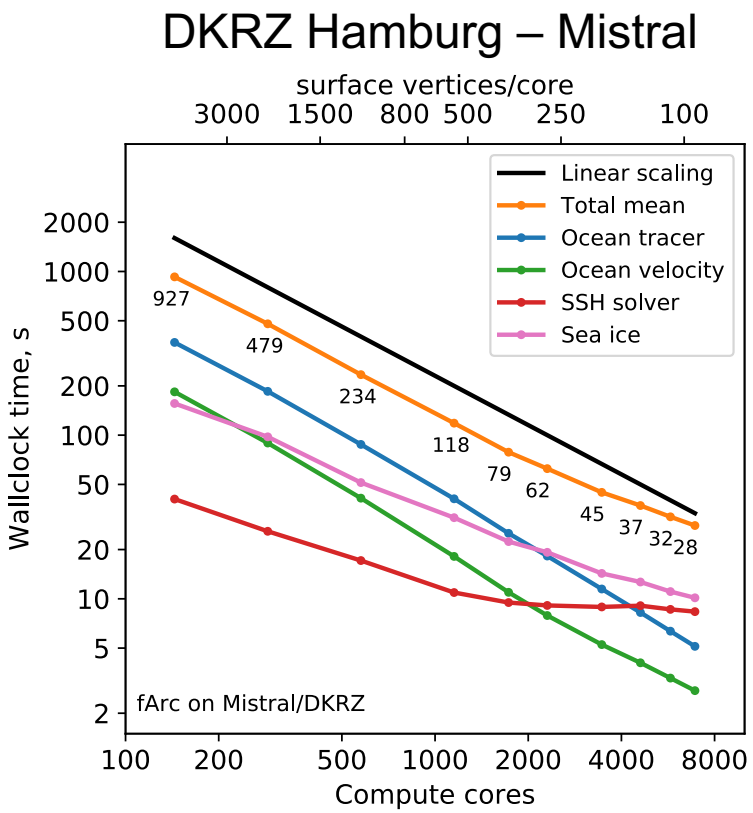
Rackow et al., 2019; Scholz et al. 2019

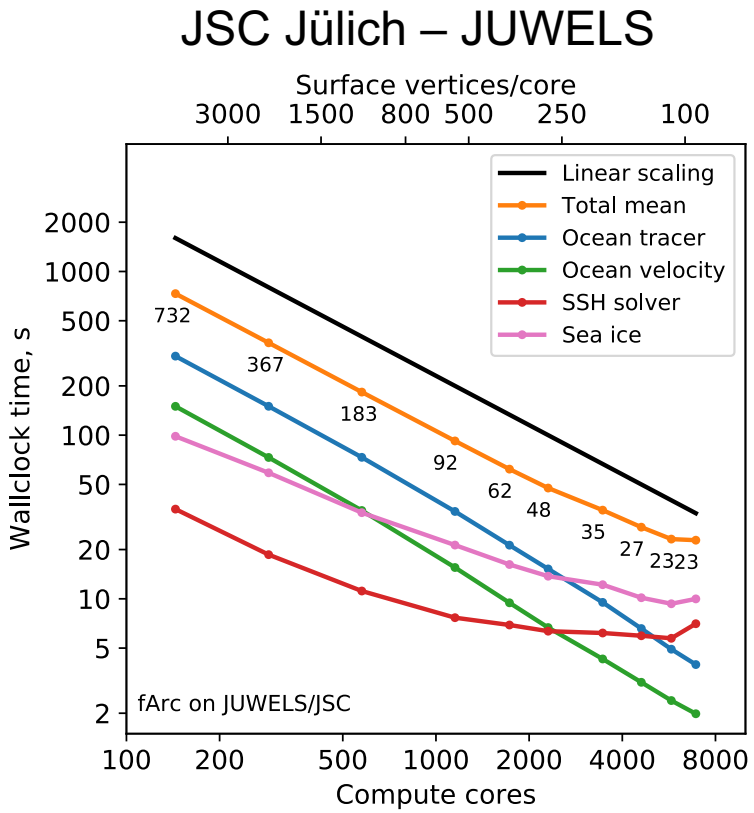
Scaling and performance

Meshes used for scalability study



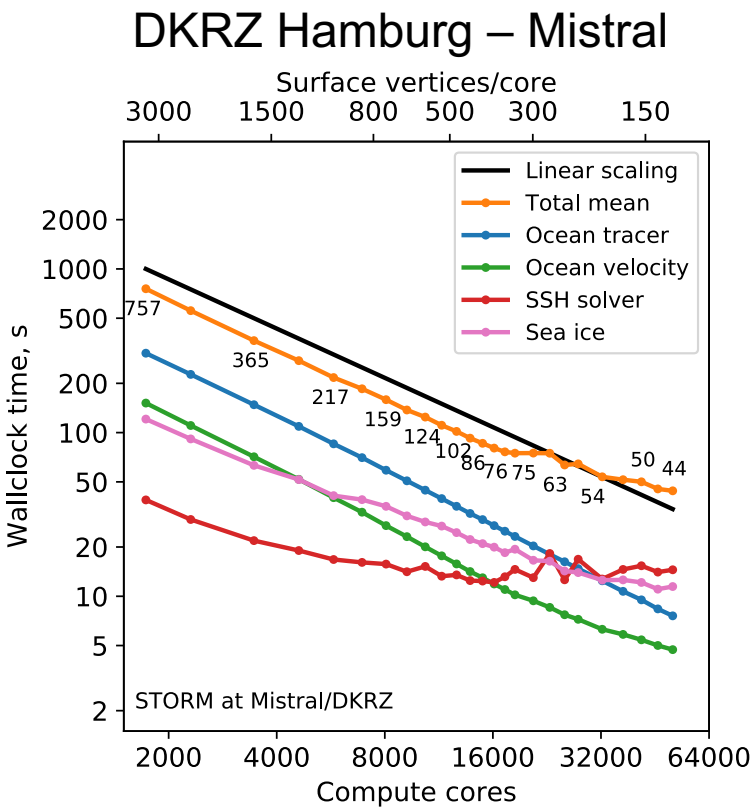
0.6Mio (fArc) surface vertices: scaling

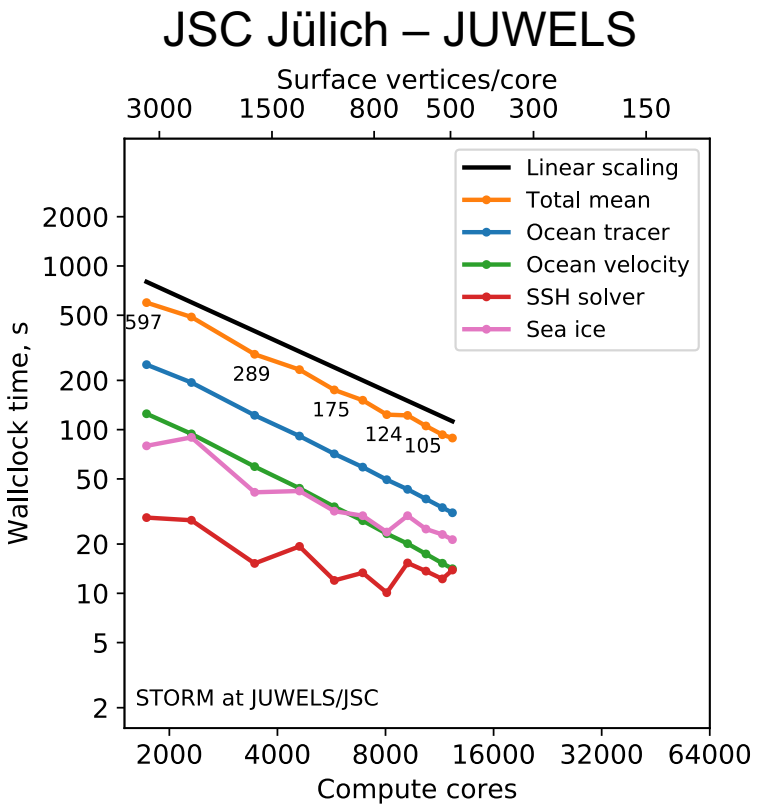




Koldunov et al., 2019, GMD

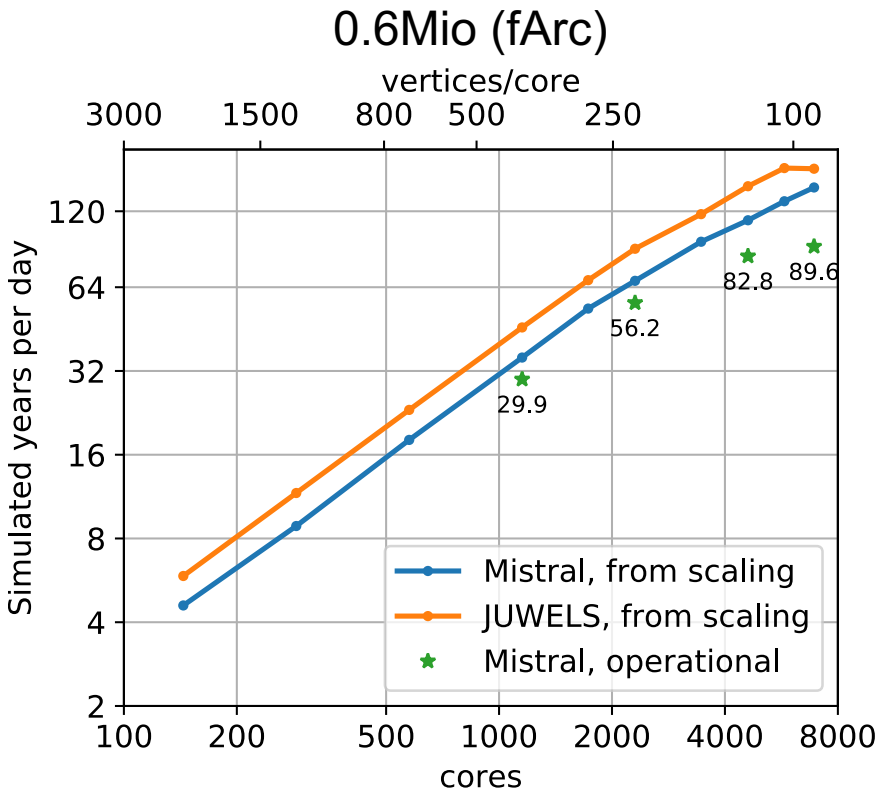
5.5Mio (STORM) surface vertices: scaling

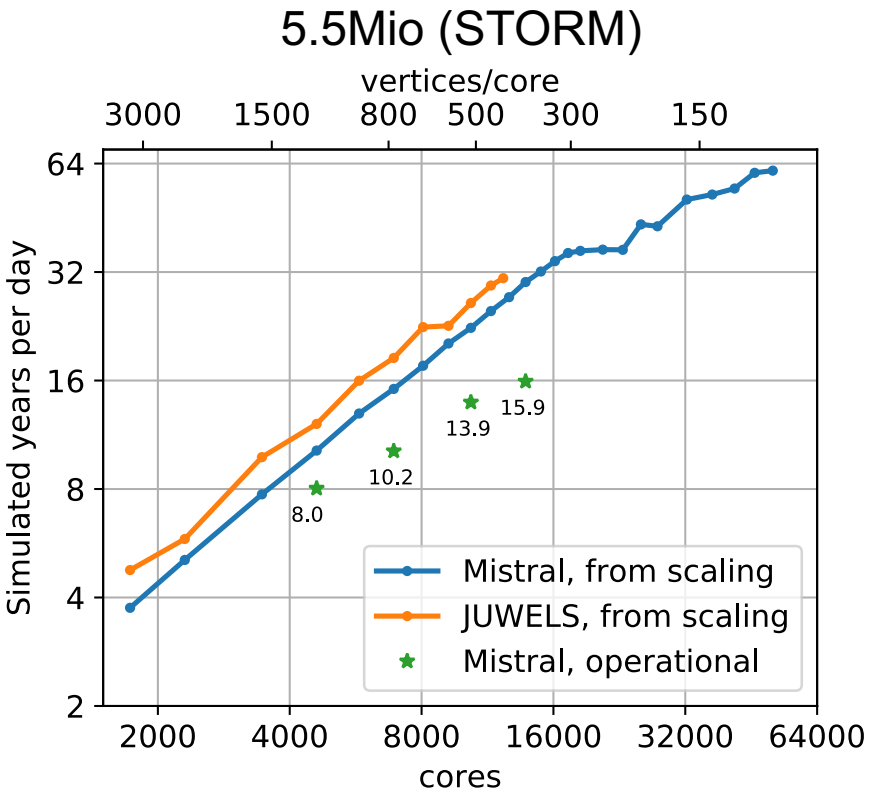




Koldunov et al., 2019, GMD

FESOM2 throughput





Koldunov et al., 2019, GMD

Conclusions

Unstructured-mesh ocean models are mature enough to be used in practice. They are nearly as numerically efficient as structured-mesh models.

Variable resolution on meshes with global focus is helpful in ocean modeling, but optimalchoice is still a subject of research.

They can be used as an alternative of nesting or regional setups without the need of open boundaries