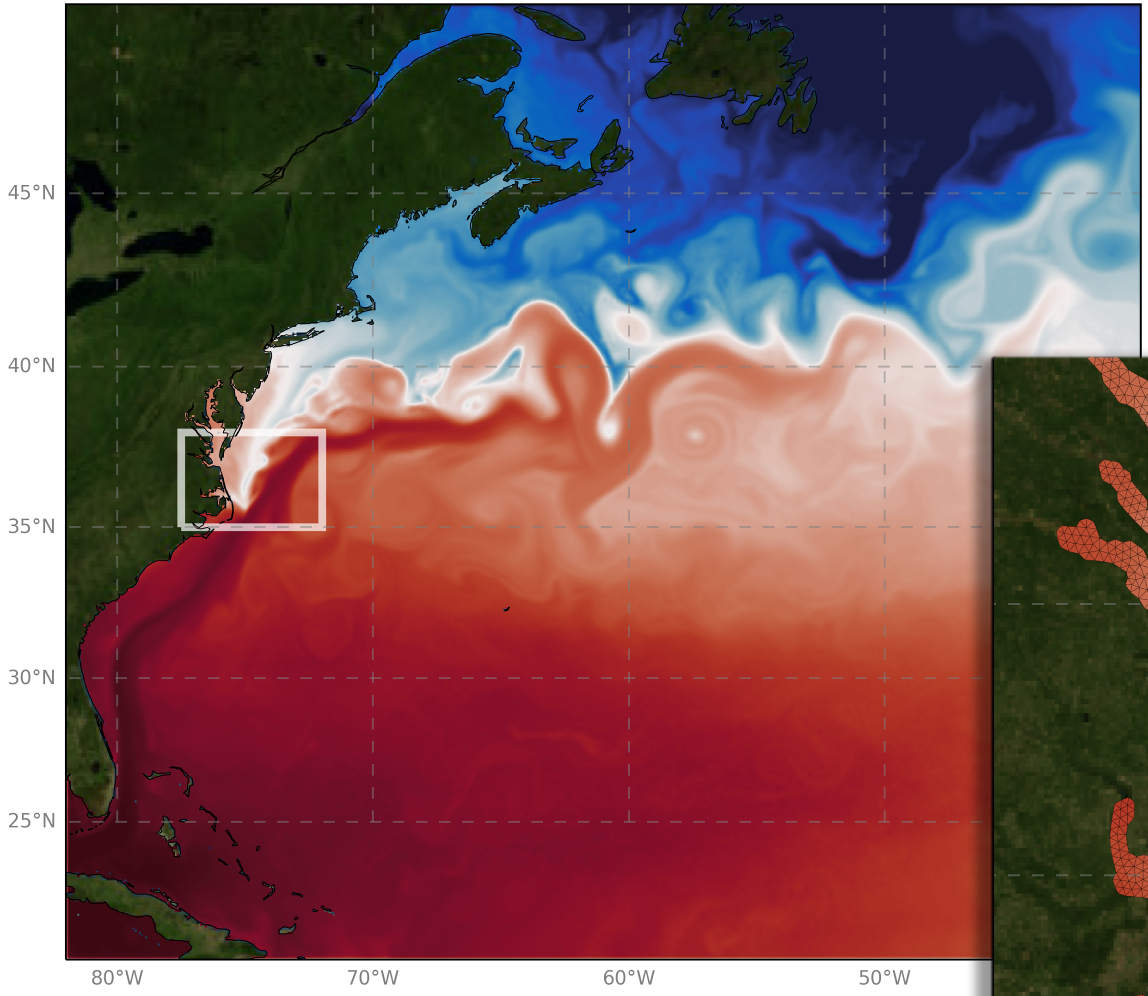
Multi-resolution ocean modeling

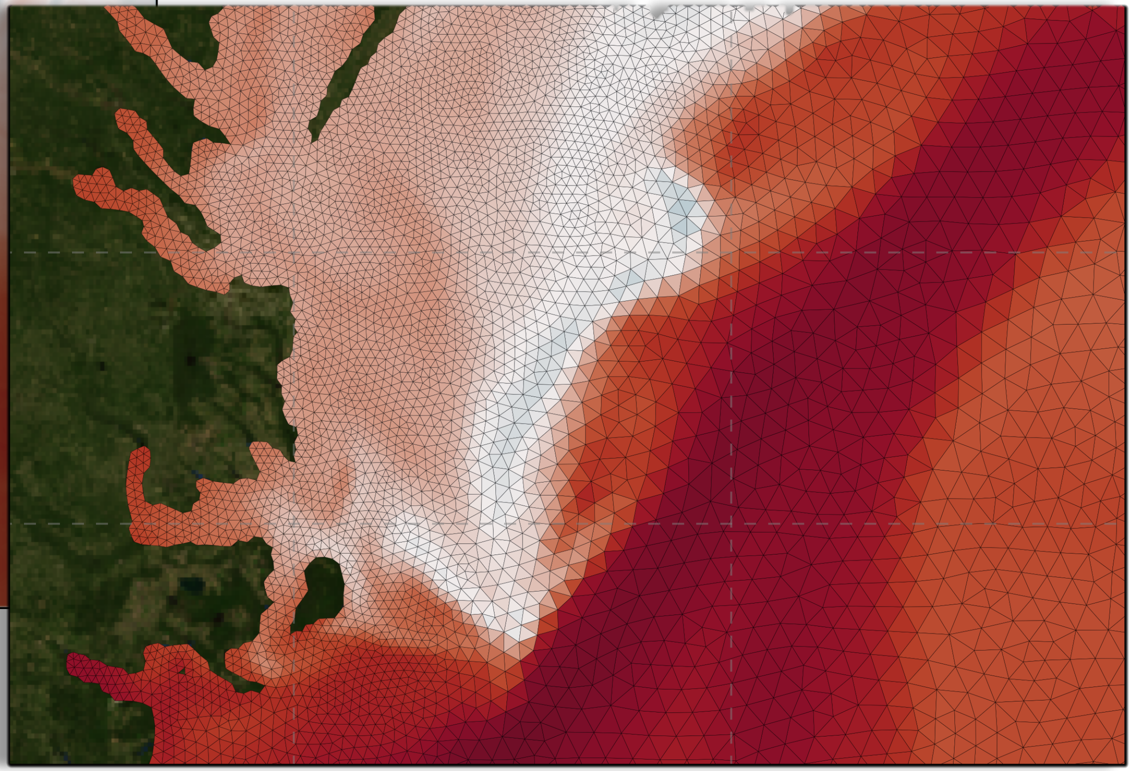
S. Danilov, AWI,

with contributions from N. Koldunov, T. Rackow, P. Scholz , D. Sein, D. Sidorenko, Q. Wang, C. Wekerle

Three new ocean models are formulated on unstructured meshes:
FESOM (Danilov et al. 2004, 2017; Wang et al. 2014)
MPAS-Ocean (Ringler et al. 2013)
ICON-o (Korn 2017)

How to better use variable resolution?





Visualization N. Koldunov

FESOM 1.4 and FESOM 2.0

FESOM

Finite Element
Sea ice-Ocean Model

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

- ✓ > 3x faster than FESOM 1.4
- ✓ ALE vertical coordinate
- ✓ coupled to ECHAM6 and OpenIFS

FESOM2

Finite volumE
Sea ice-Ocean Model

ALFRED-WEGENER-INSTITUT
HELMHOLTZ-ZENTRUM FÜR POLAR-
UND MEERESFORSCHUNG

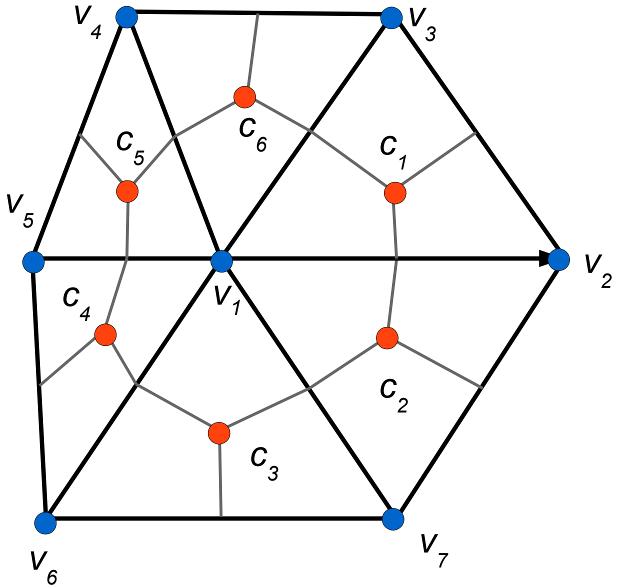
FESOM

Finite Element
Sea ice-Ocean Model

Basic difference: vertical-horizontal data structure of FESOM2.
Neighborhood information is propagated down the column.

Almost no price for 'unstructuredness' if the number of vertical layers is high (and it is).

FESOM2: Quasi-B-grid, scalars at vertices and velocities at cell centers.
Scalars use median-dual CV as in FVM.

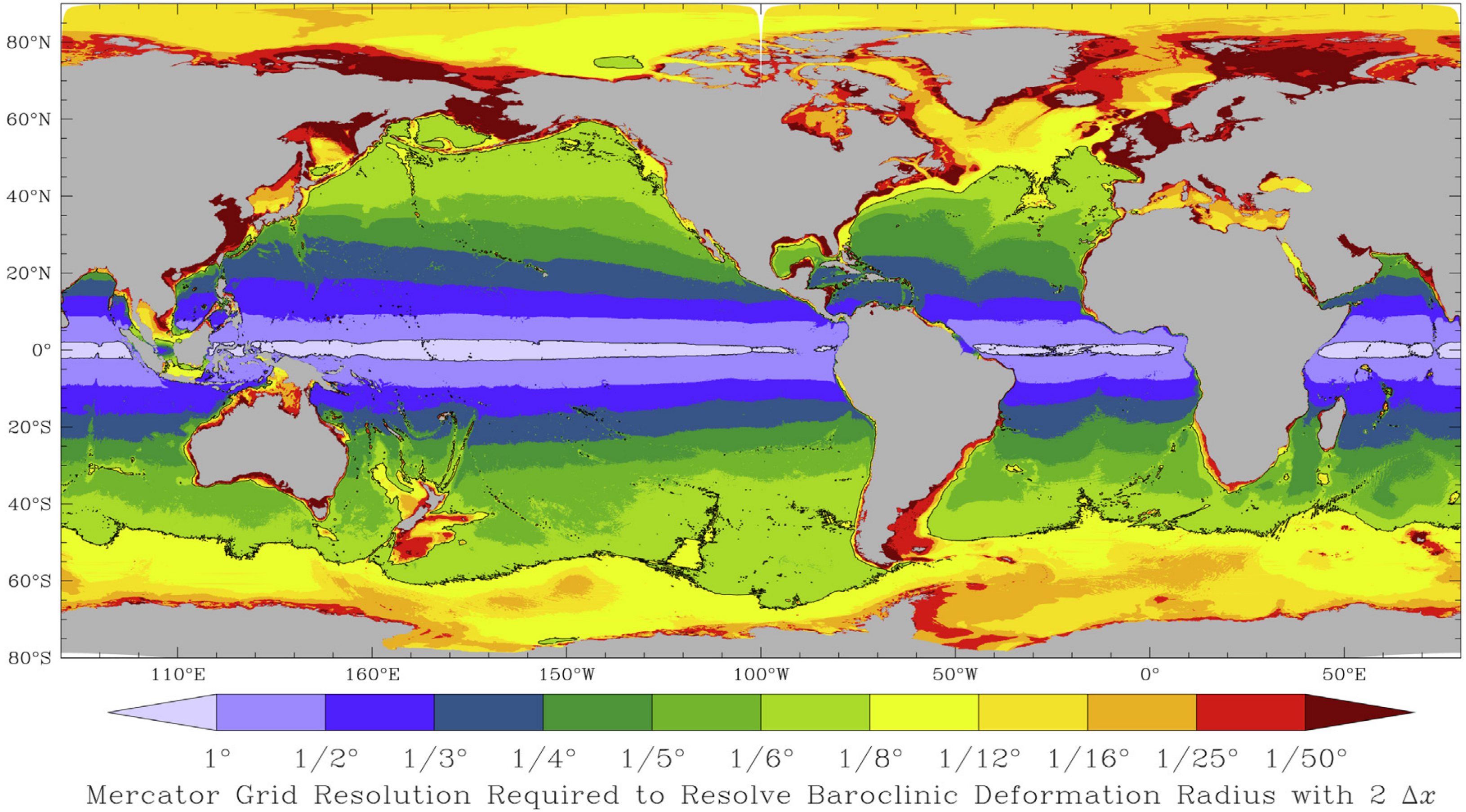


FESOM2

Finite volumE
Sea ice-Ocean Model

HELMHOLTZ
ASSOCIATION

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



L_d in the ocean varies in wide limits;

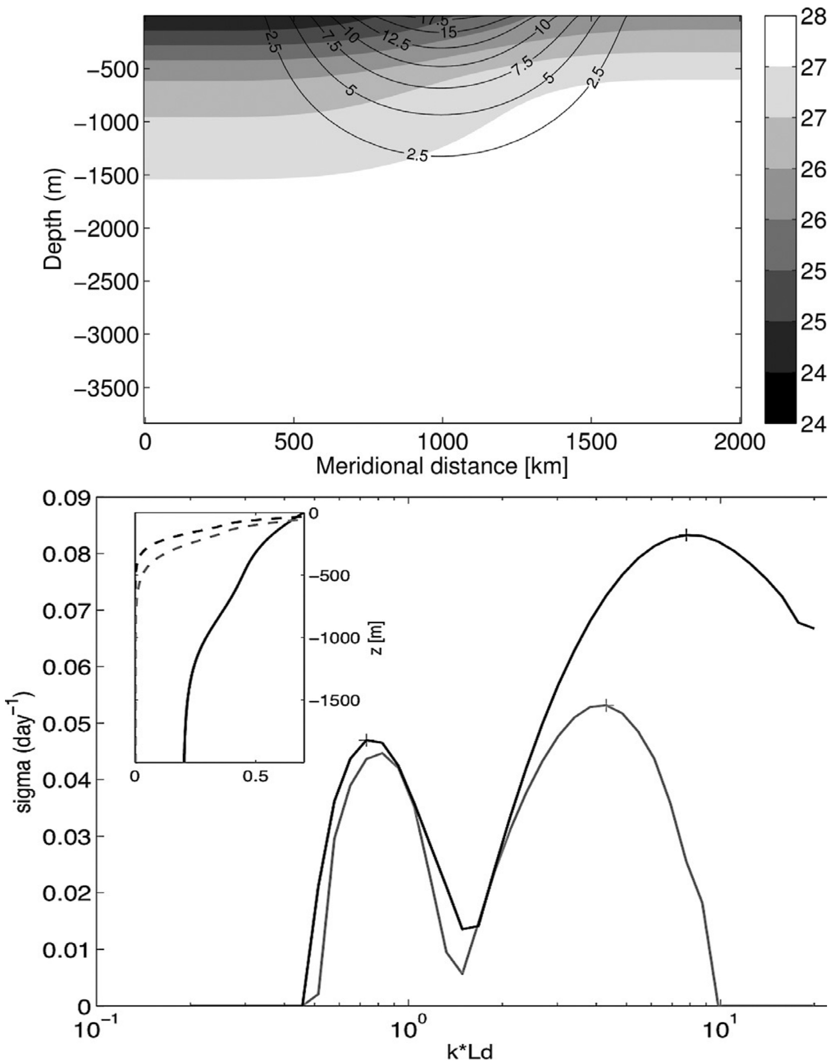
The pattern of observed variability (altimetry) is very non-uniform;

Use unstructured meshes to better represent eddy variability

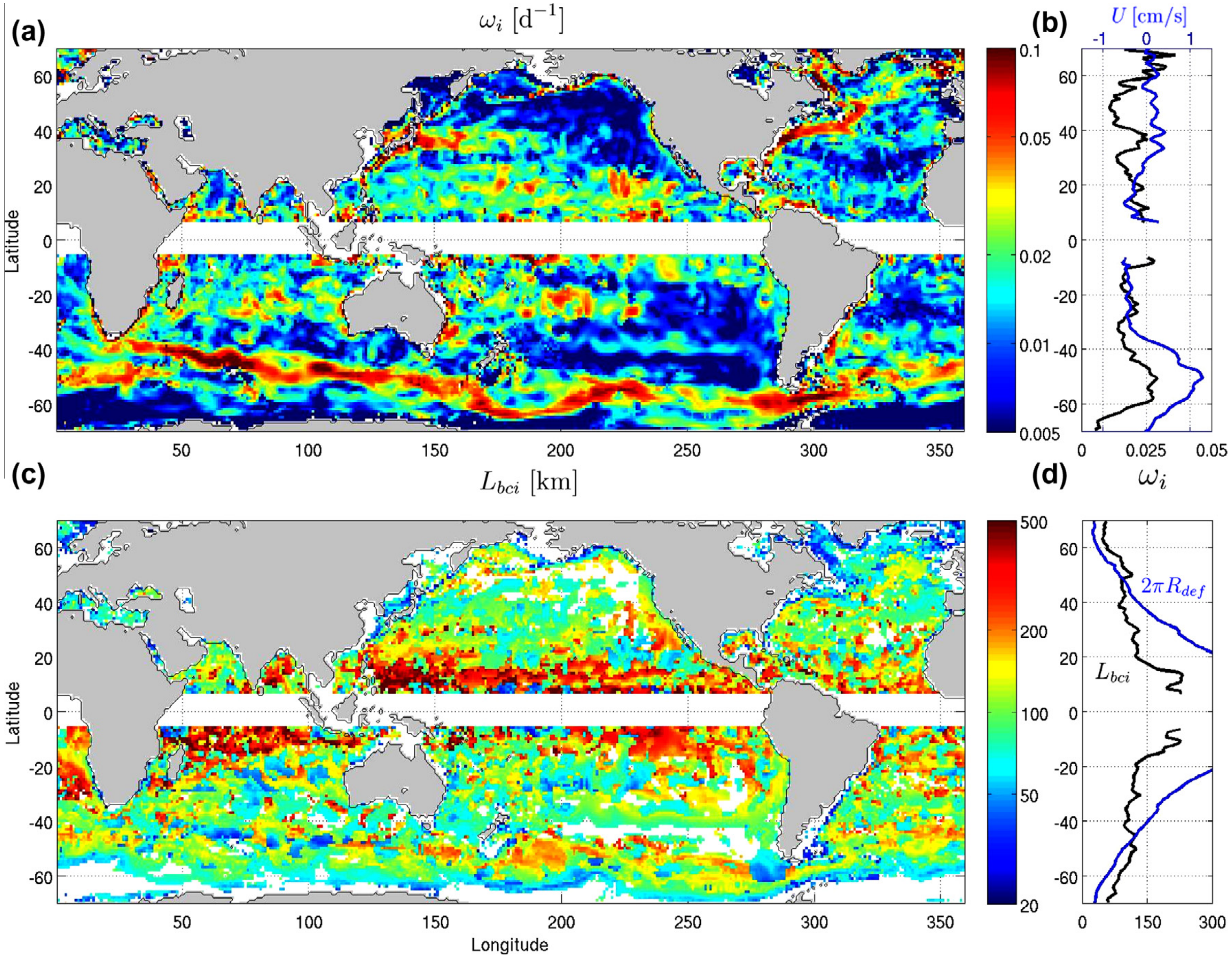
Unstructured meshes can be refined based on:

- 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)

kL_d of maximum instability varies in wide limits



Y. Soufflet et al., OM, 2016



L. Vollmer, C. Eden, OM, 2013

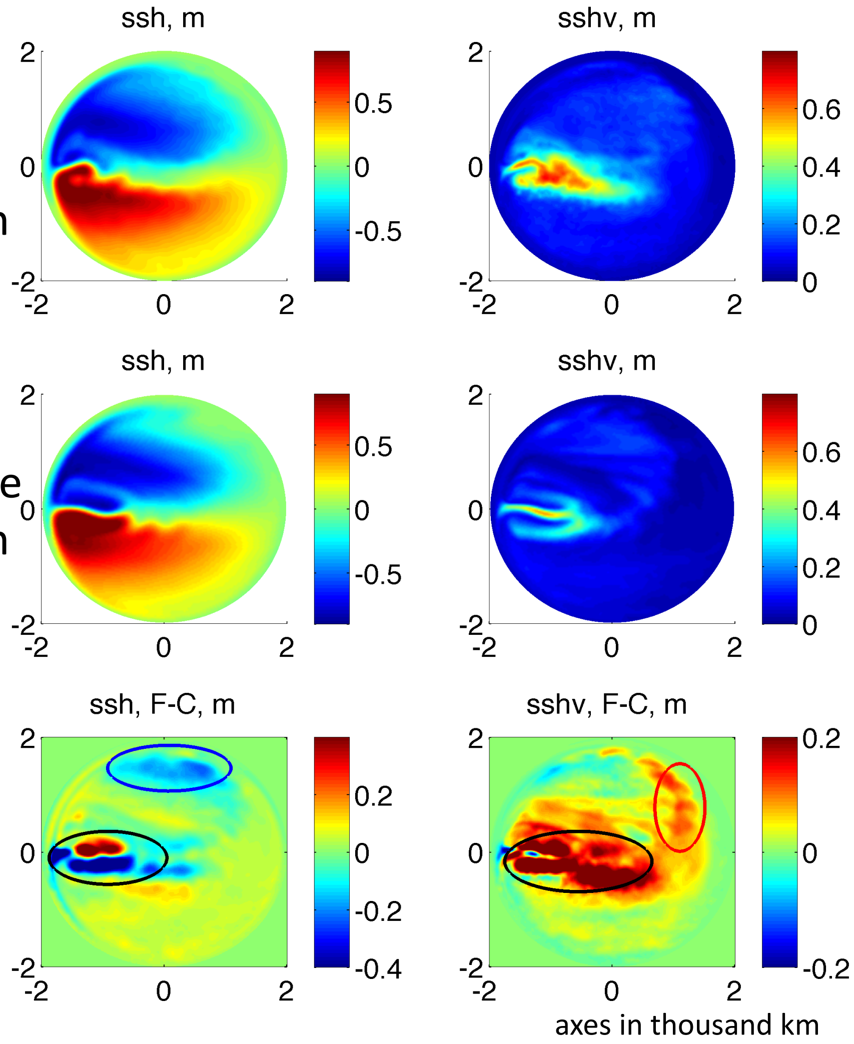
Meshes based on the observed variability

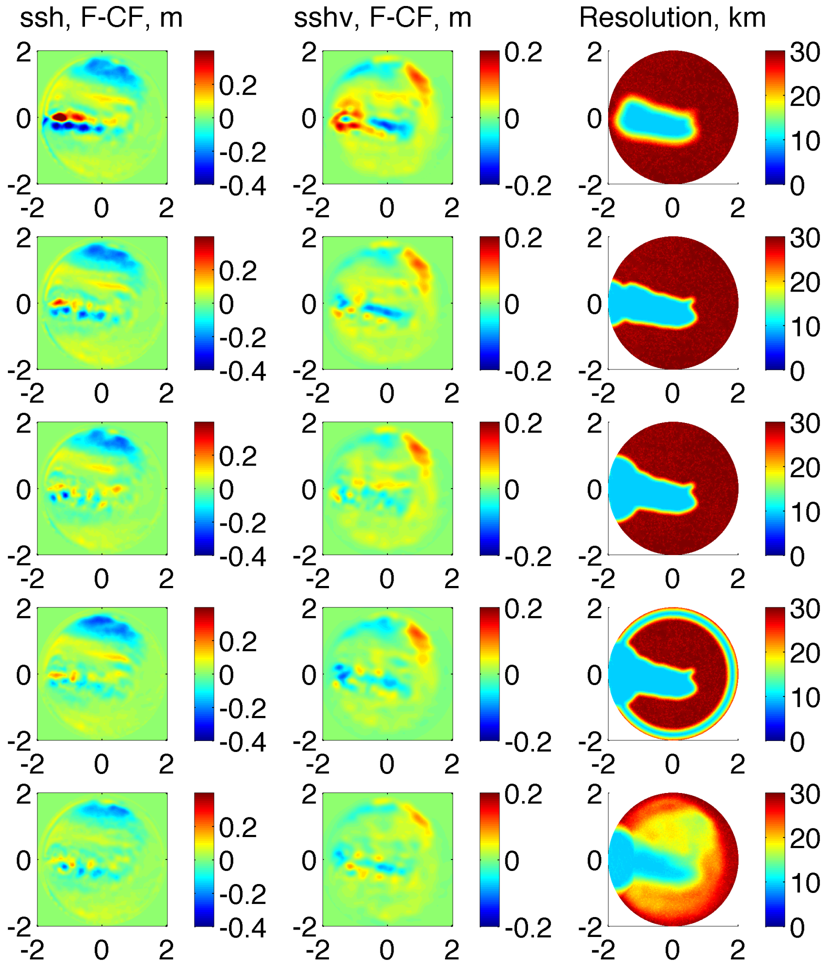
Wind-driven double-gyre flow in stratified basin with L_d=25 km

Difference Fine-Coarse

Fine 10 km

Coarse 30 km

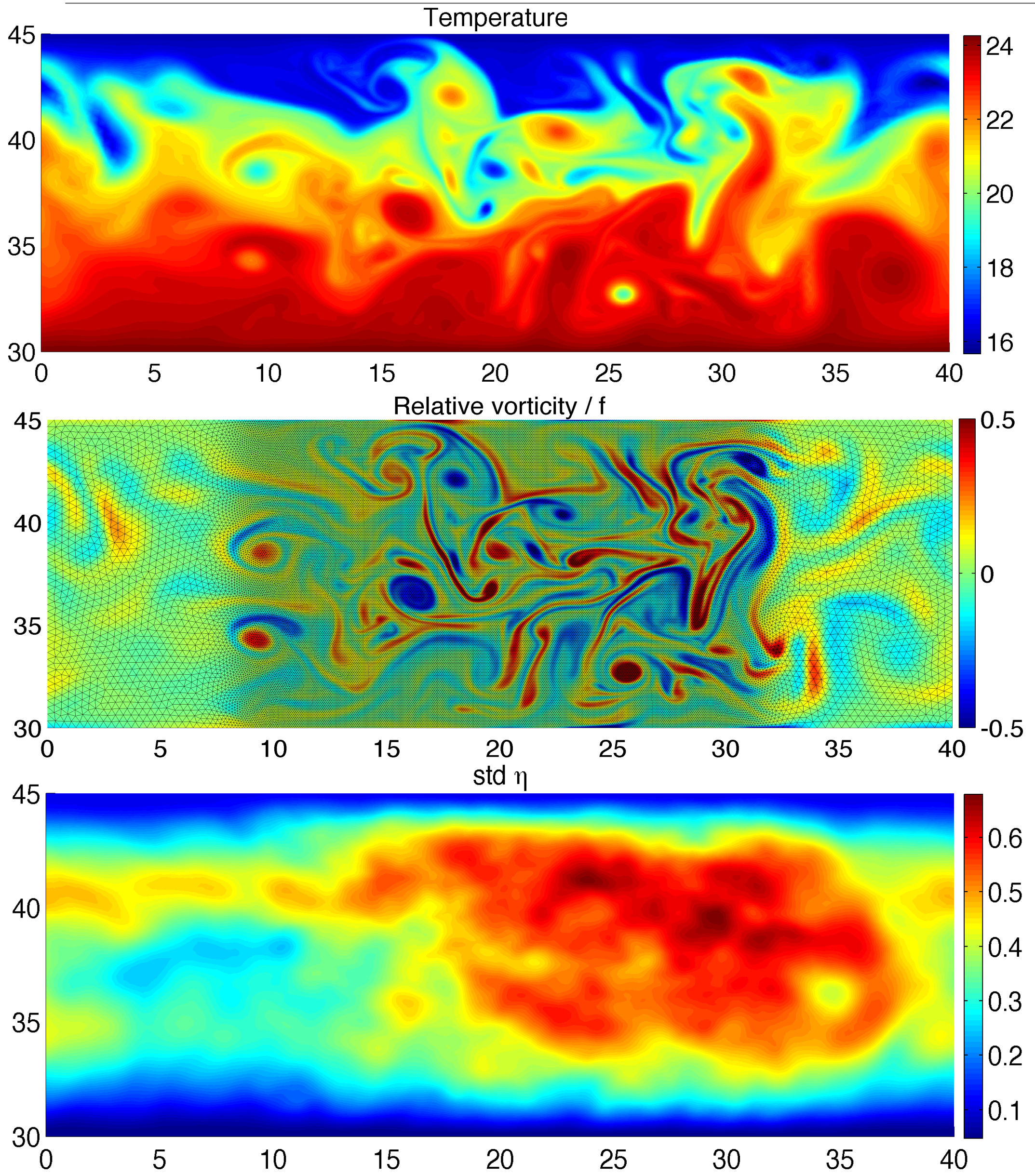


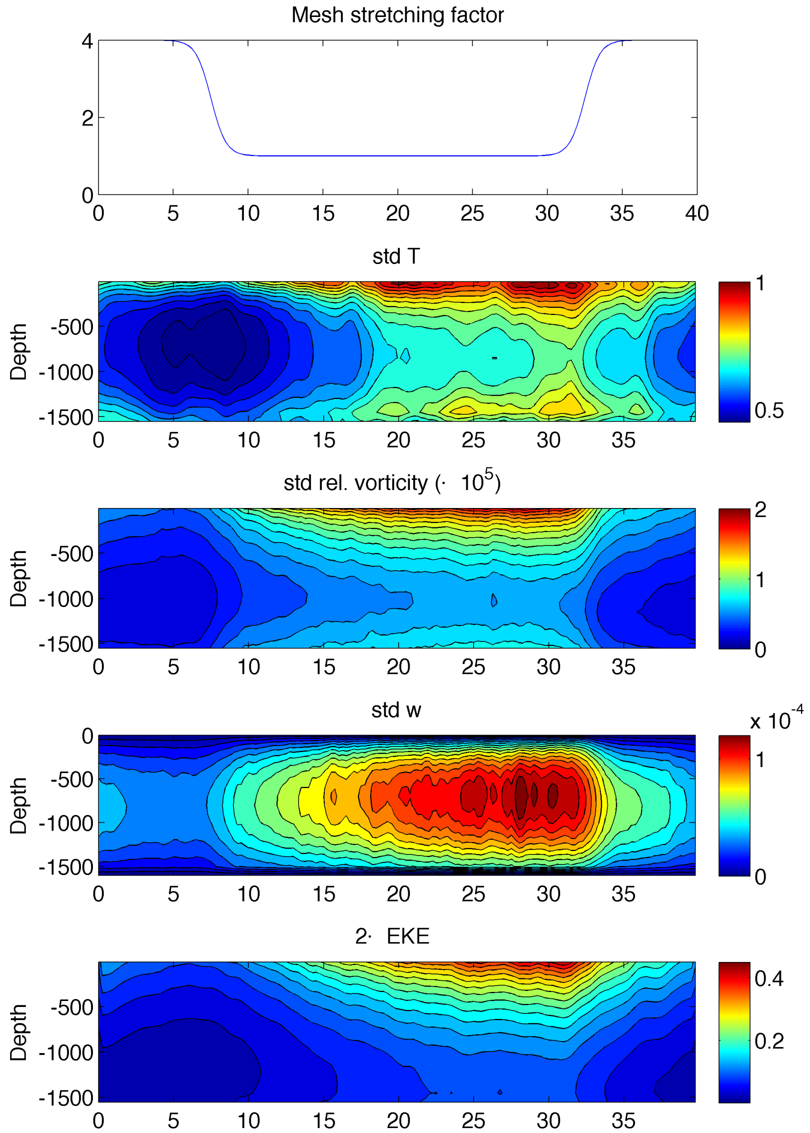


The difference can be strongly reduced through local refinement

Sein et al. 2016

Zonally re-entrant baroclinic channel: it takes some distance downstream to equilibrate





Meridional and time mean profiles:

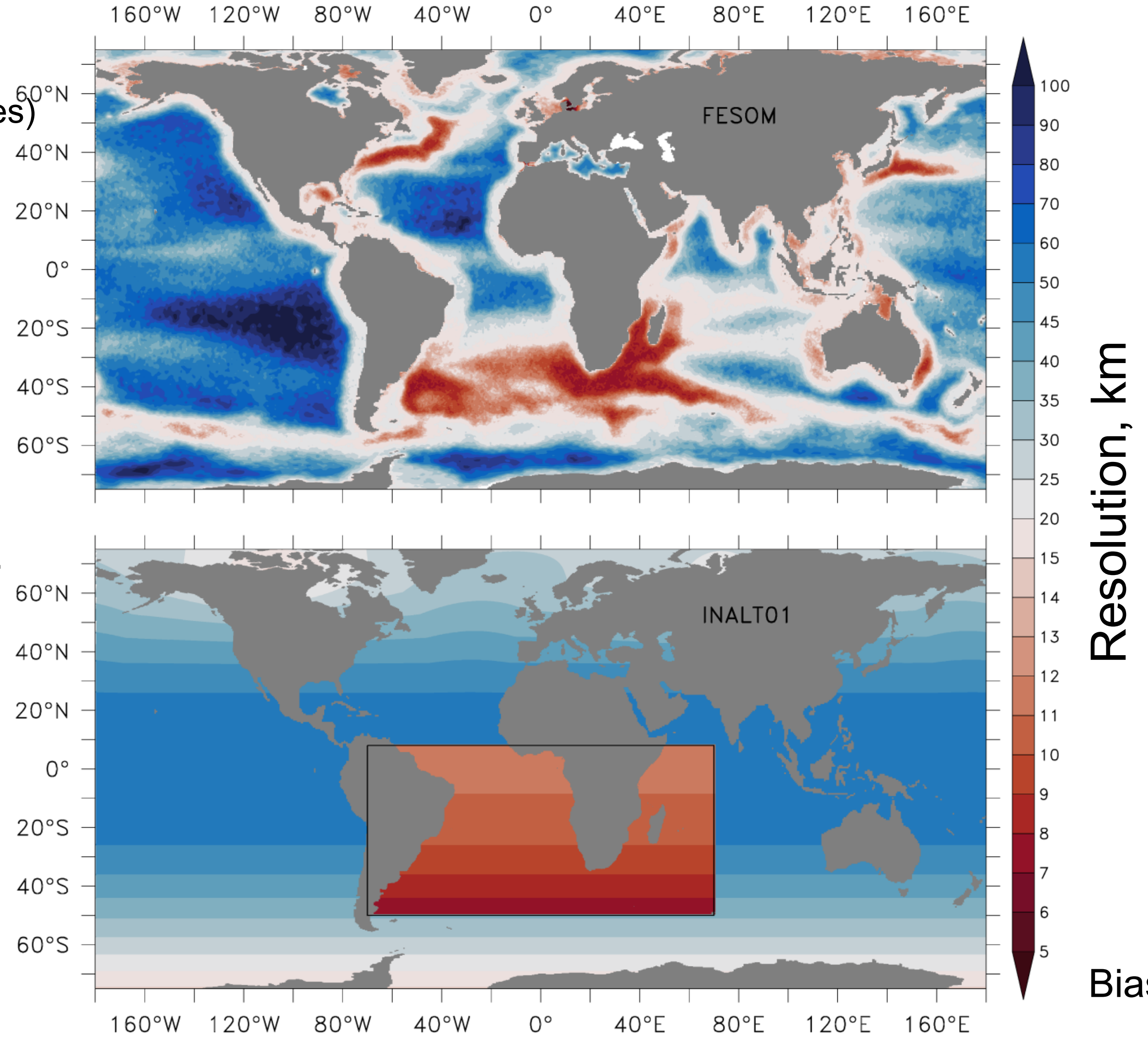
Resolution from 1/3 to 1/12 degree, L_d=25 km

Danilov, Wang 2015

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



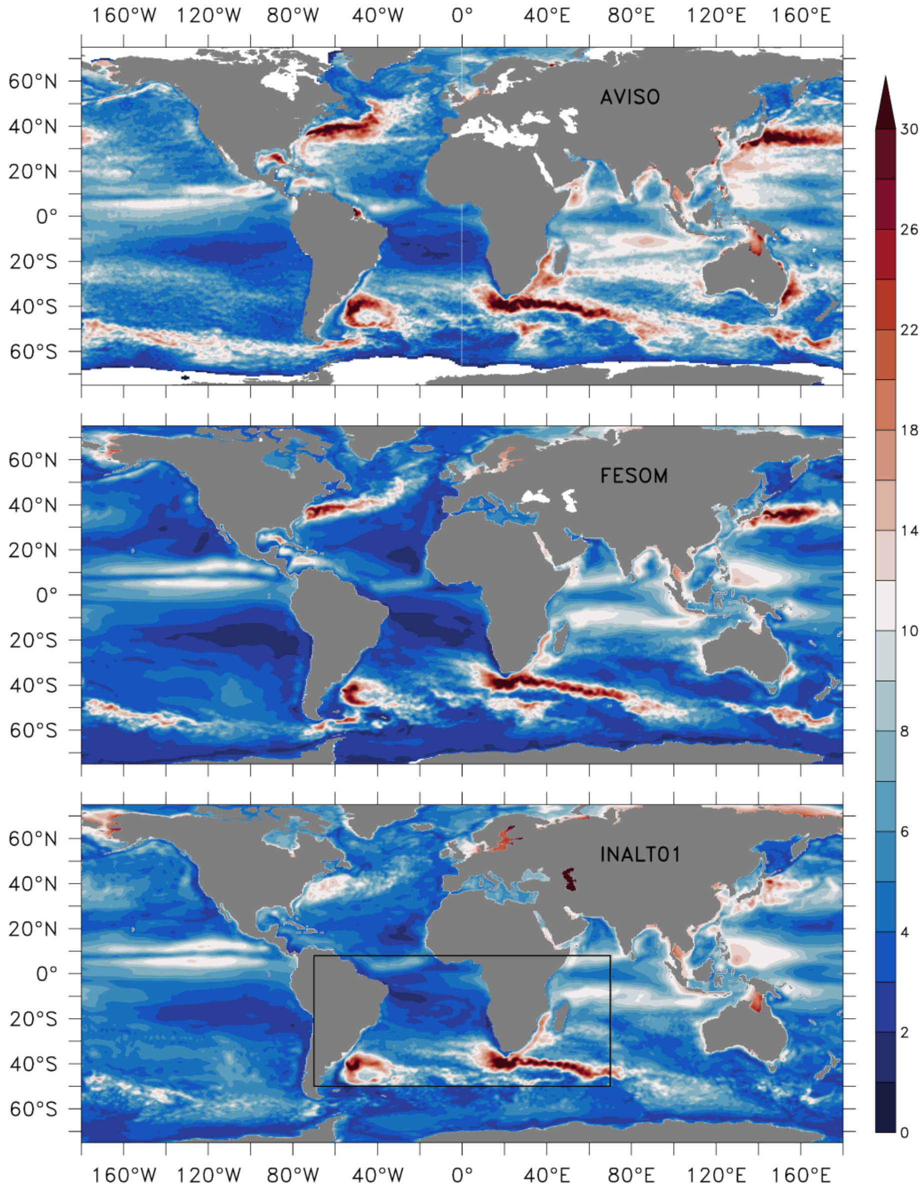
Biastoch et al. 2018

Agulhas Current and Leakage:
FESOM vs traditional nesting

AVISO

FESOM

NEMO



SSH variability

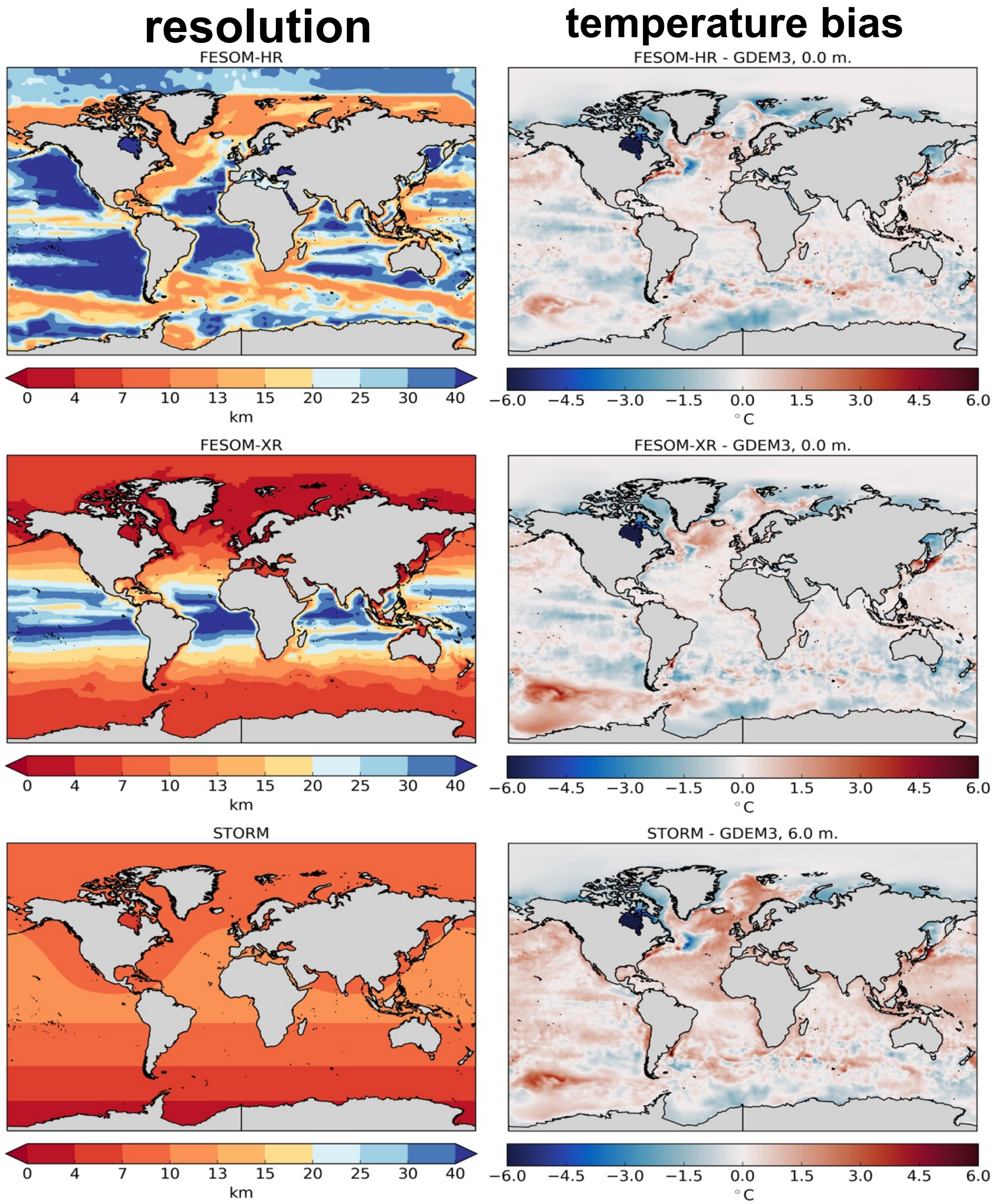
Biastoch et al. 2018

How to design a global mesh?

Refinement according to SSH var.
(1.3 M vertices)

Refinement according to Rossby radius and SSH var.
dx=max{Ld/2, 4km}
(5.0 M vertices)

MPIOM “STORM” 0.1°
(von Storch et al., 2012)
(5.5M wet vertices)



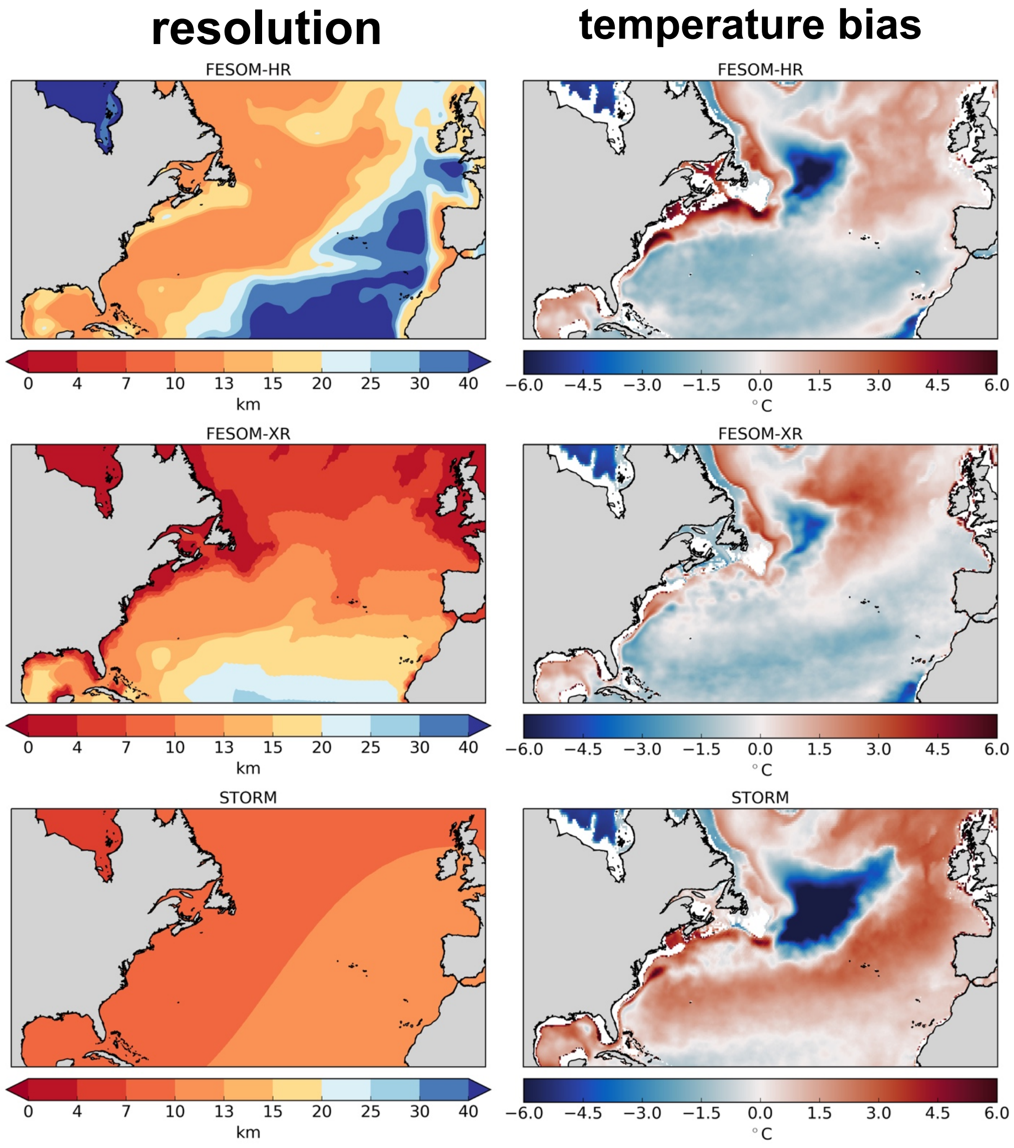
Sein et al., 2017

How to design a global mesh?

Refinement according to SSH var.
1,3 M vertices

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

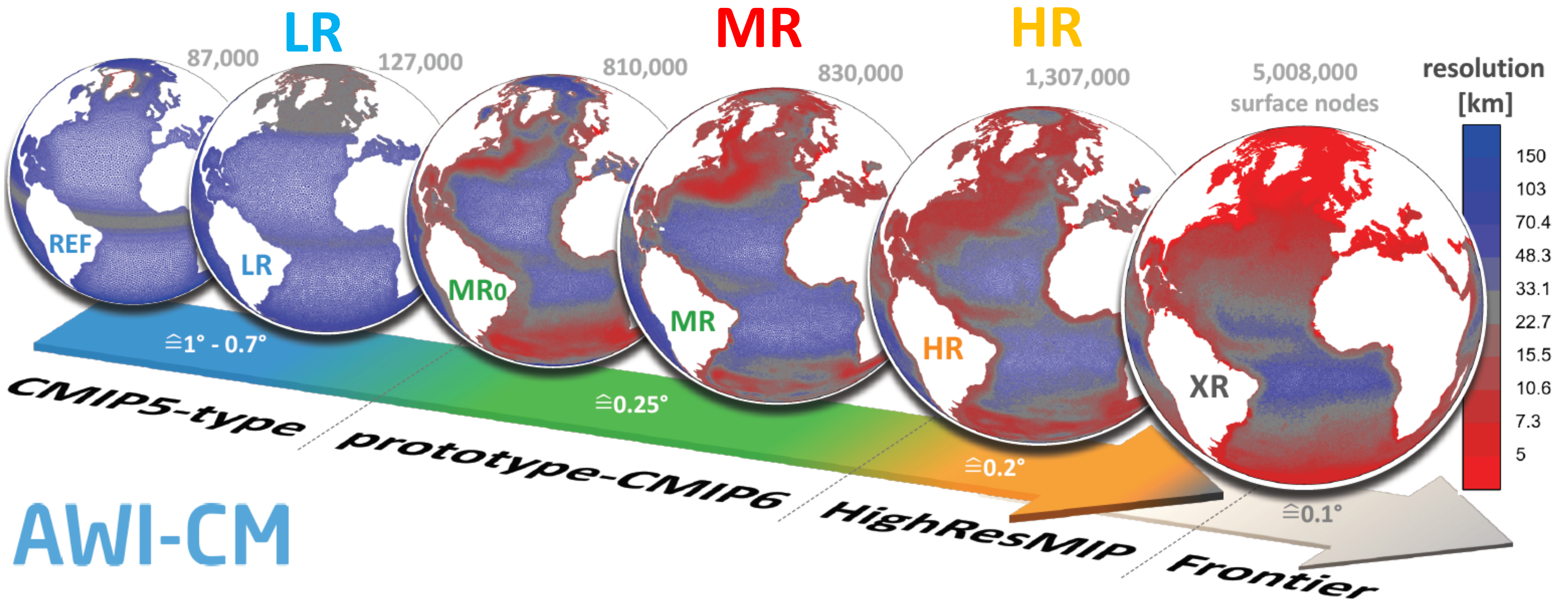
MPIOM "STORM" 0.1°
(von Storch et al., 2012)
5.5M wet points



Sein et al., 2017

FESOM, flexible mesh layout

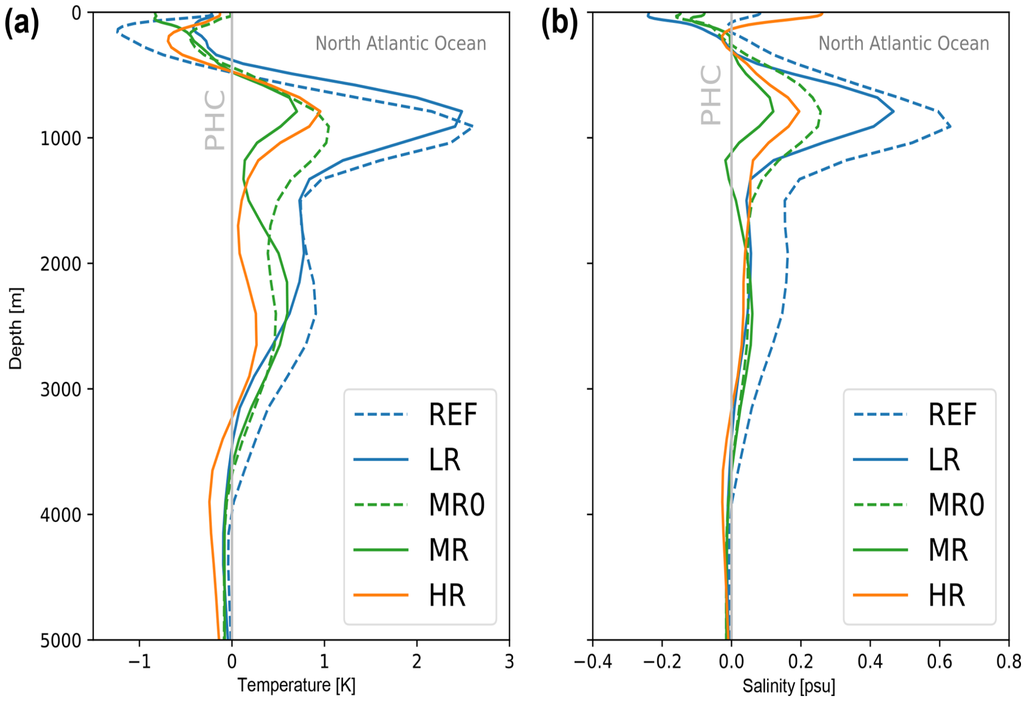
Variable-resolution configurations *(Rackow et al. 2019)*

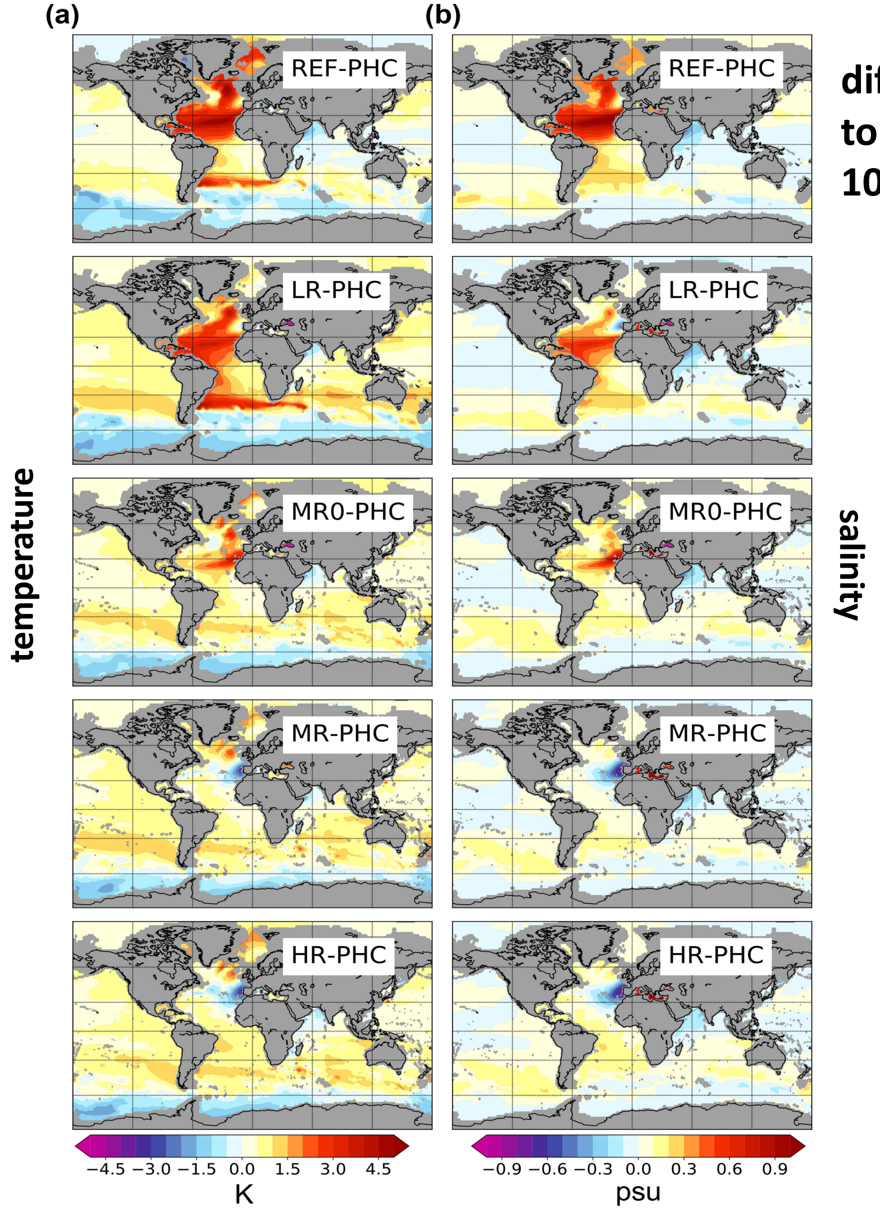


resolution is smoothly varied in the global ocean according to specified functions

FESOM: role of ocean resolution

global profiles

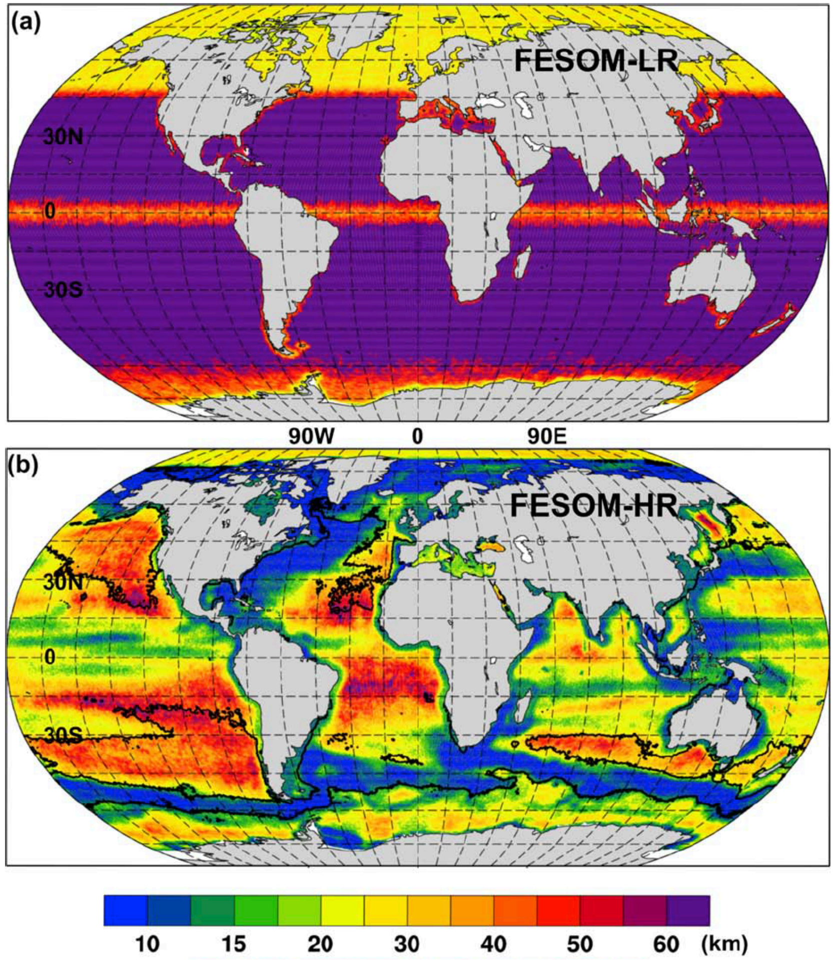




difference to climatology at 1000m

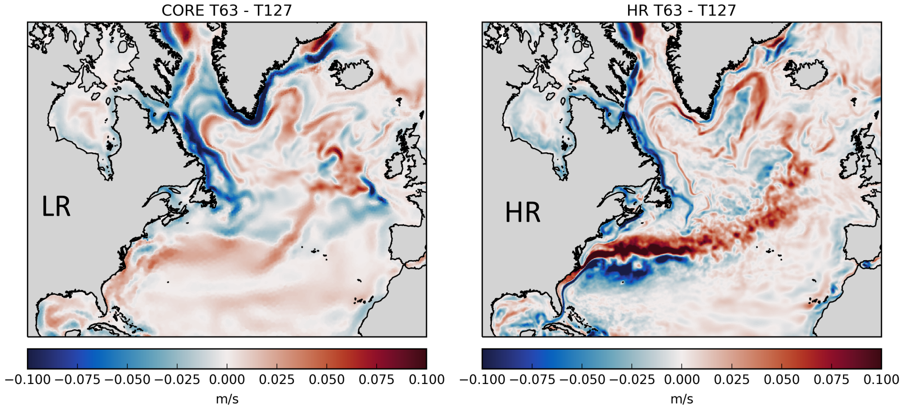
increased resolution reduces model bias!
Rackow et al., 2019

HR vs LR in the North Atlantic

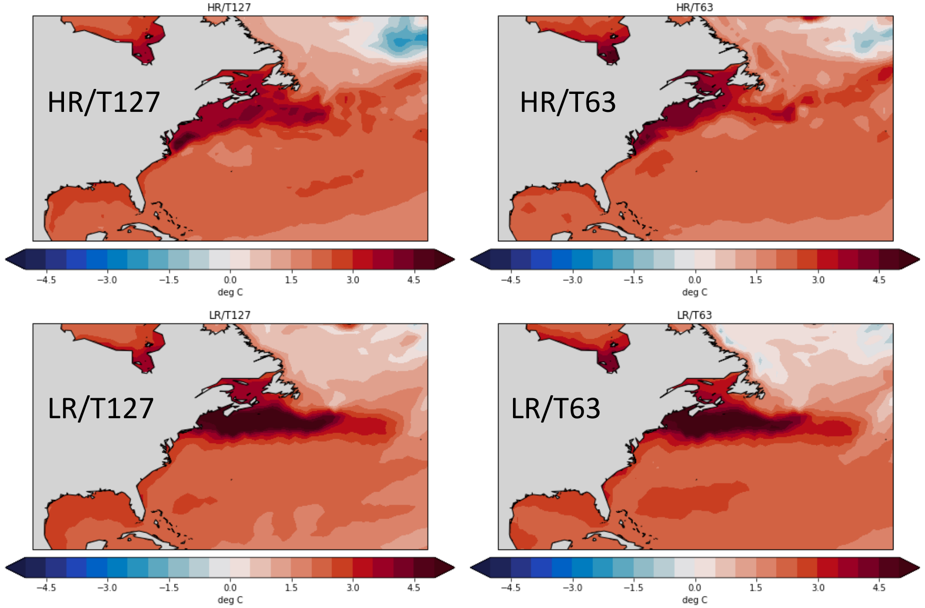


LR (a) and HR (b) ocean resolution

Sein et al. 2018



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

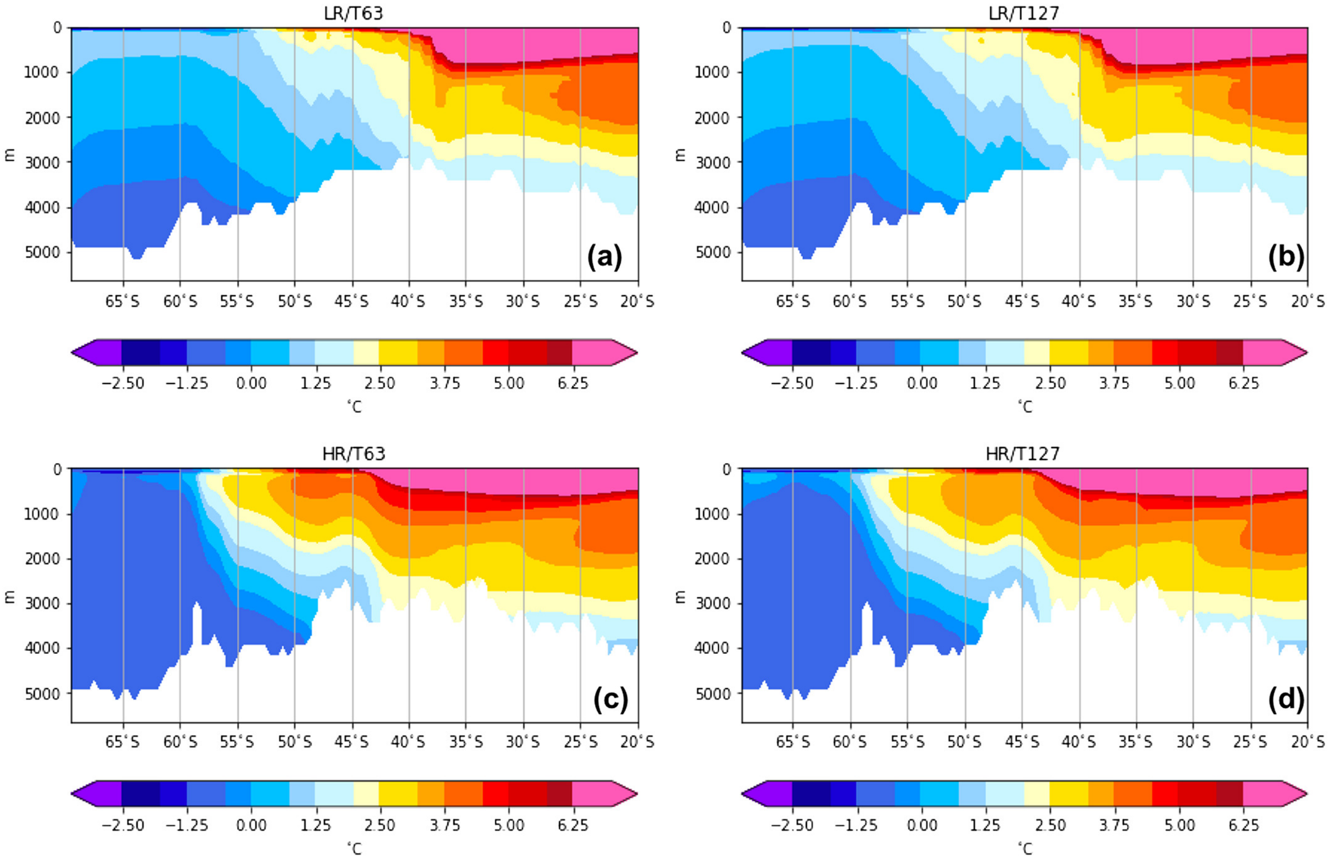


Climate change (RCP8.5). SST

FESOM: role of ocean resolution

LR (coarse)

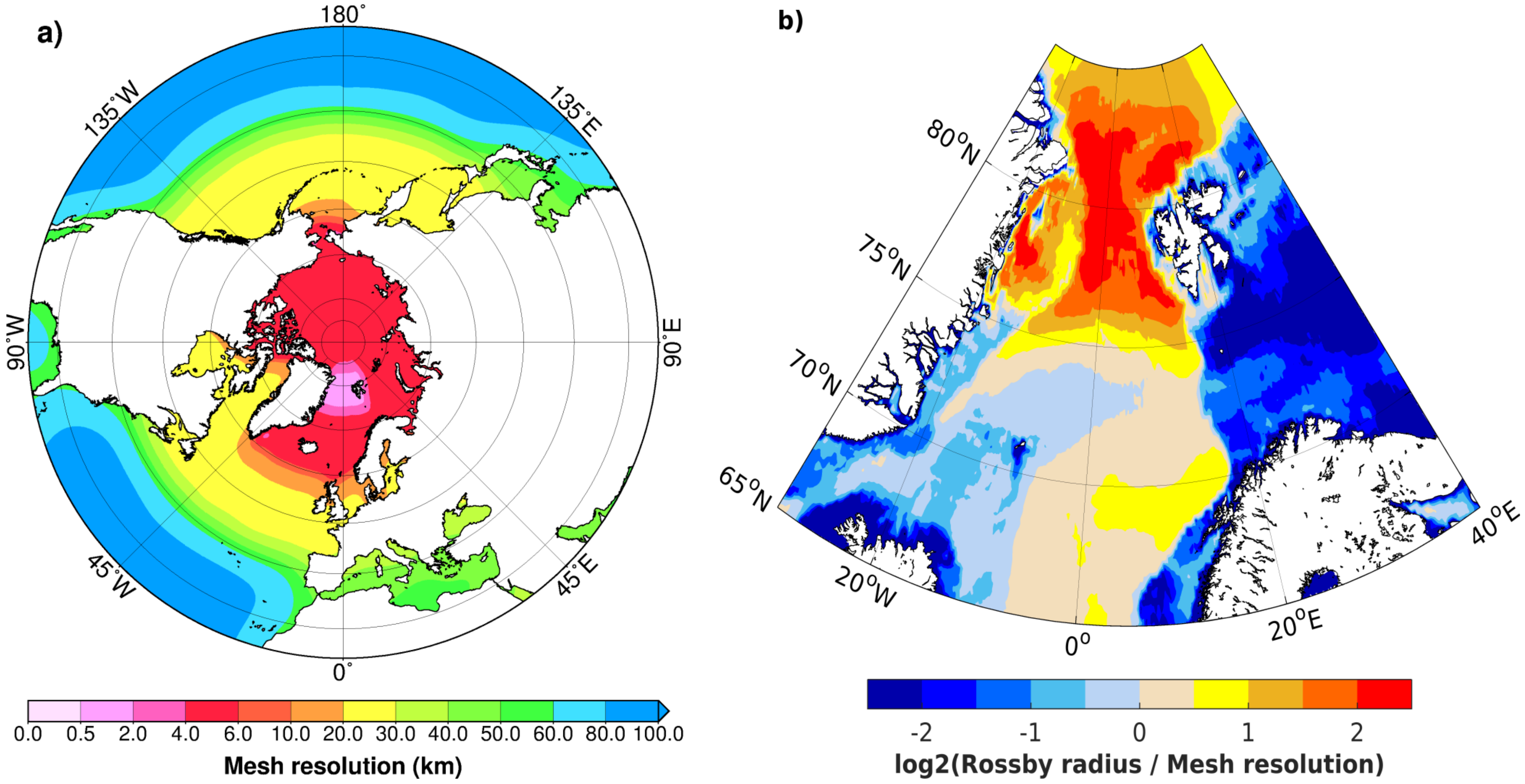
HR (fine)



Sein et al., 2018

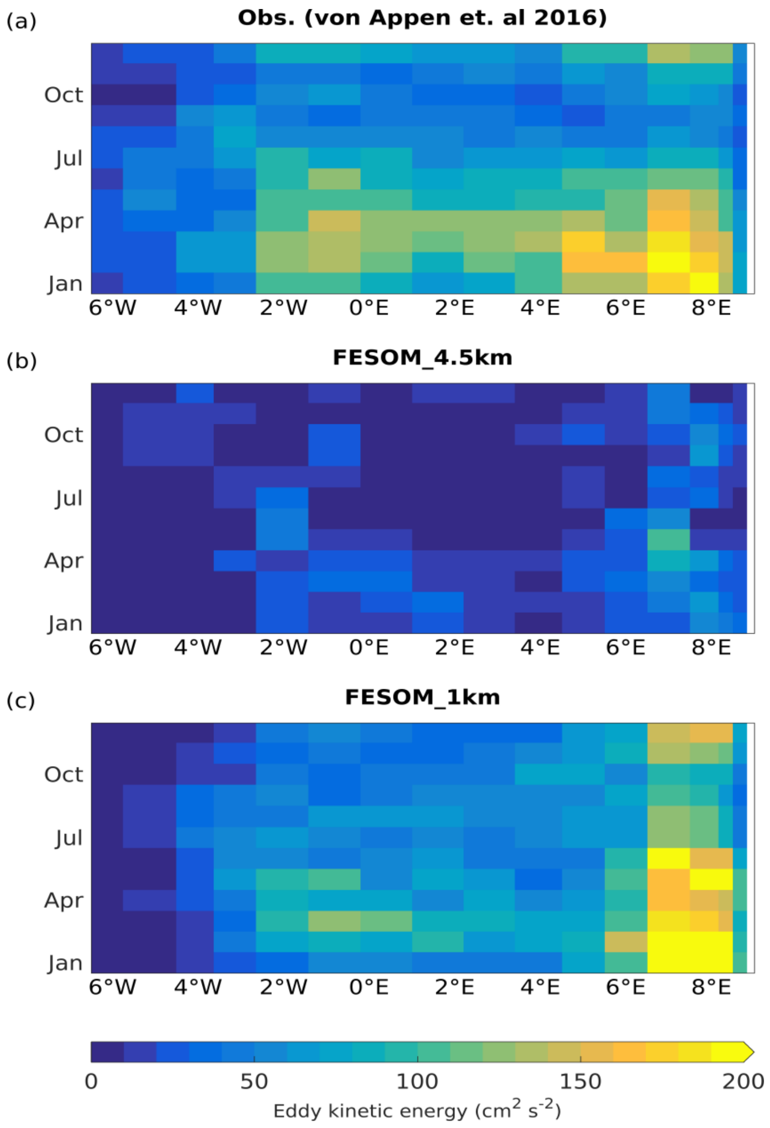
Potential temperature section at 15W

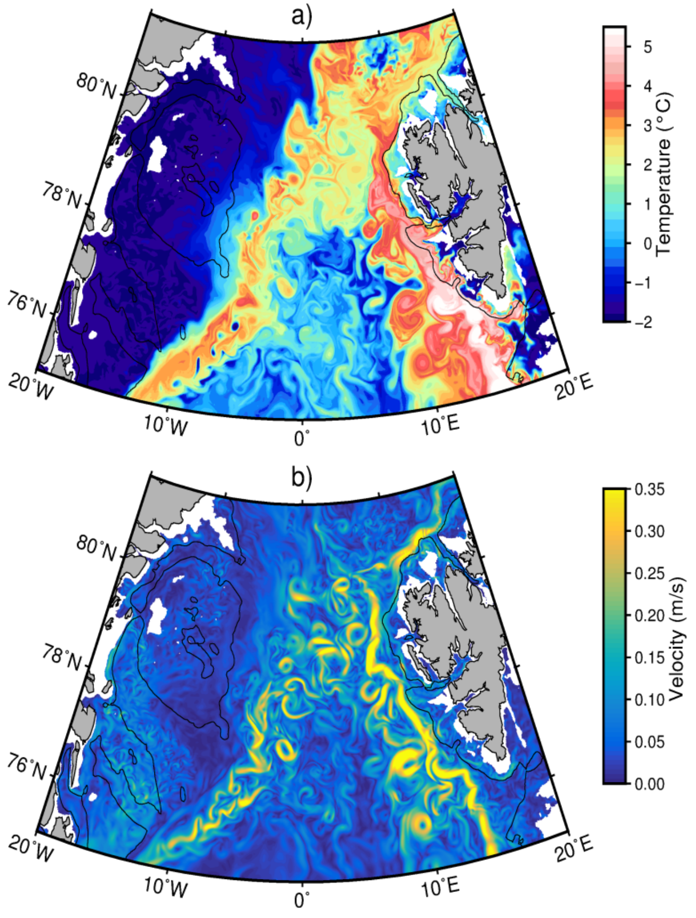
Eddy resolving in the Fram Strait



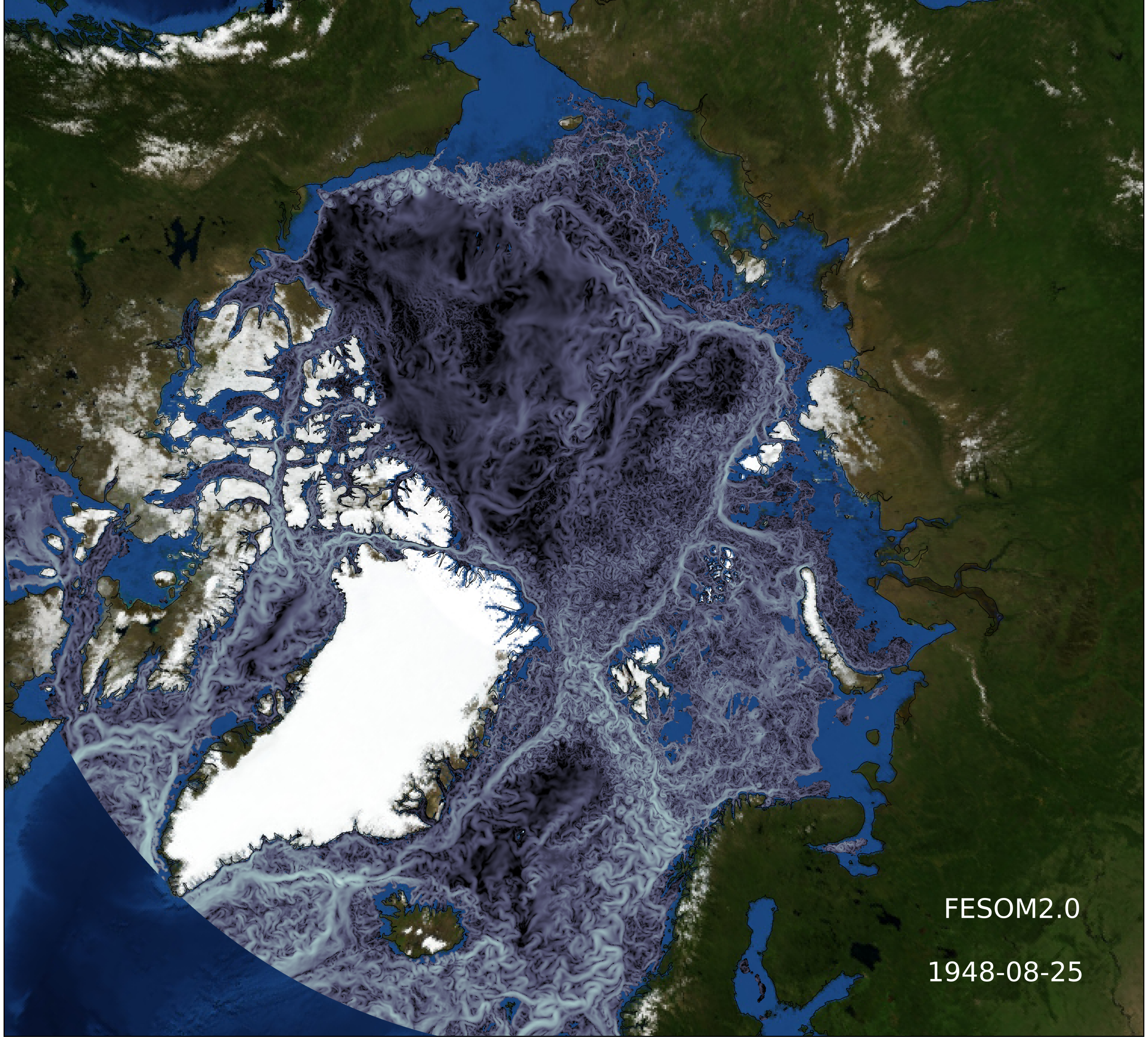
Wekerle et al., 2017

Eddy resolving in the Fram Strait



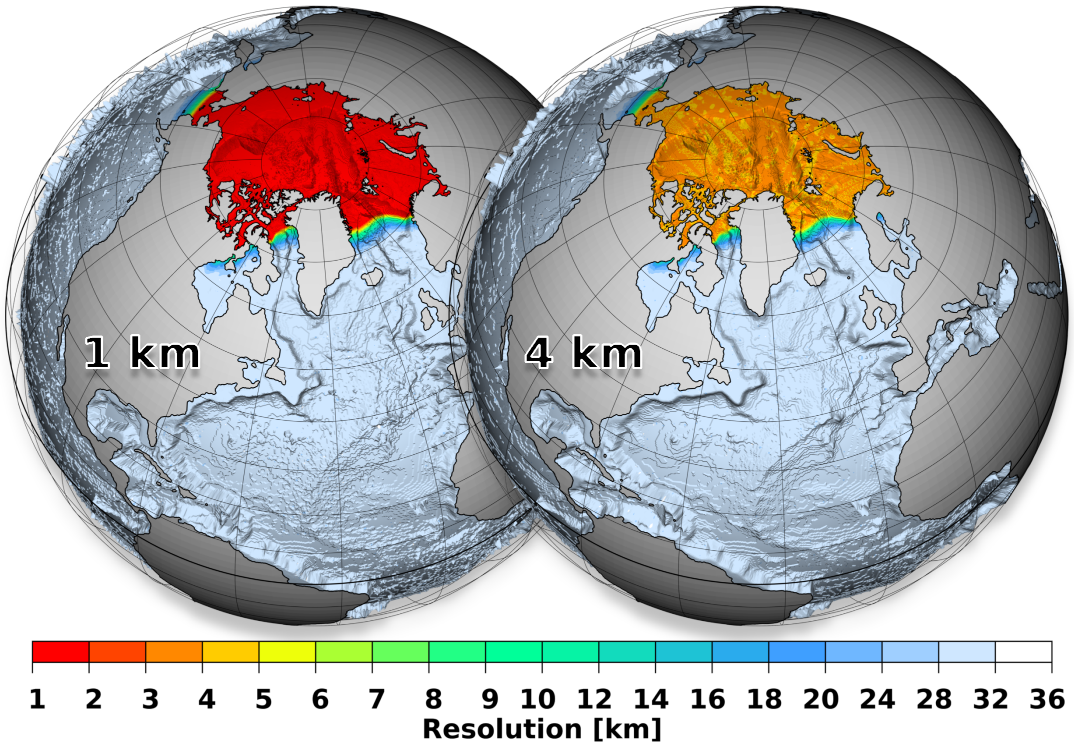


Wekerle et al., 2017



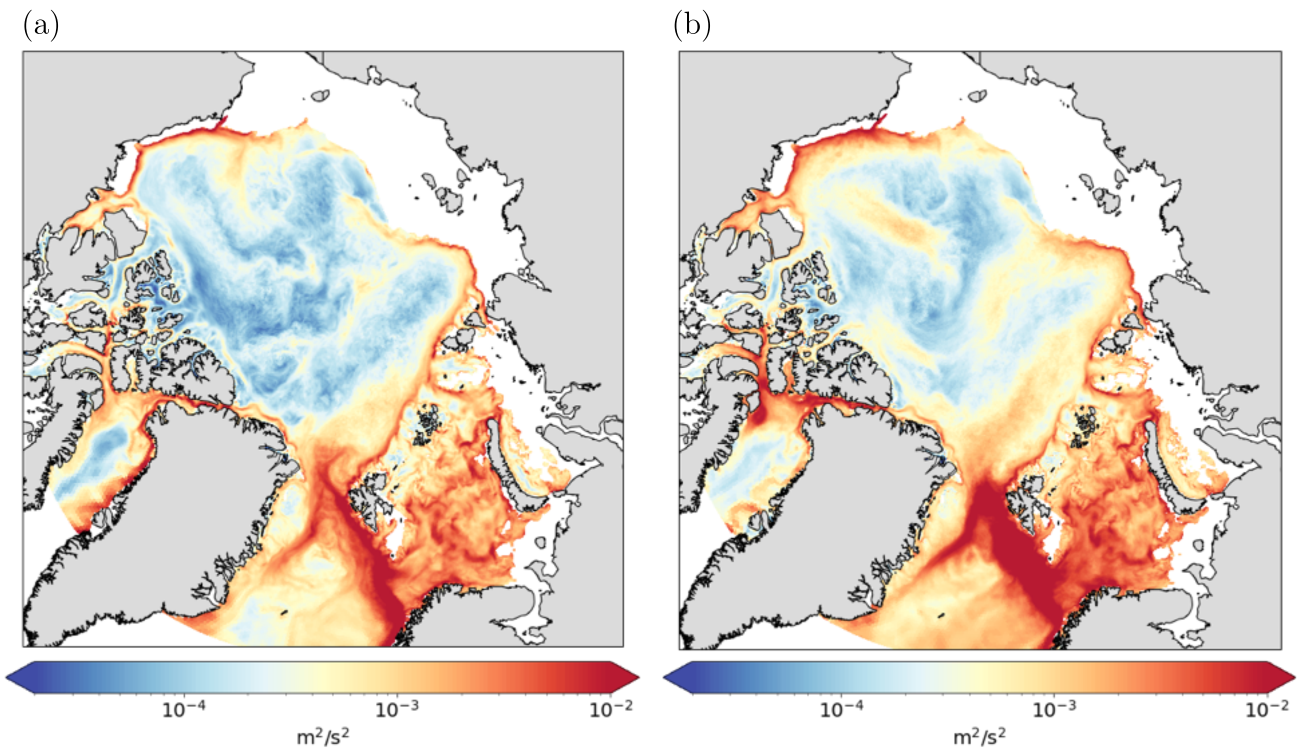
A snapshot of log10(|u|) @100 m in 1 km Arctic in FESOM2 Mesh with 11M surface vertices (N. Koldunov)

EKE in the Arctic Ocean

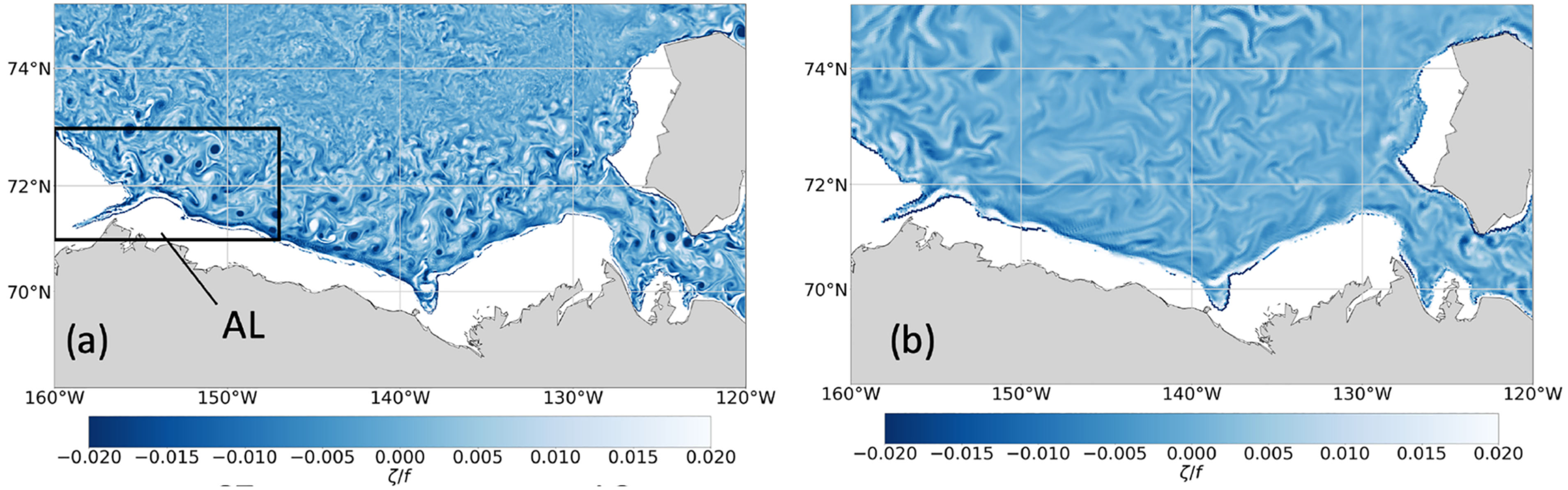


Wang et al. 2020

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

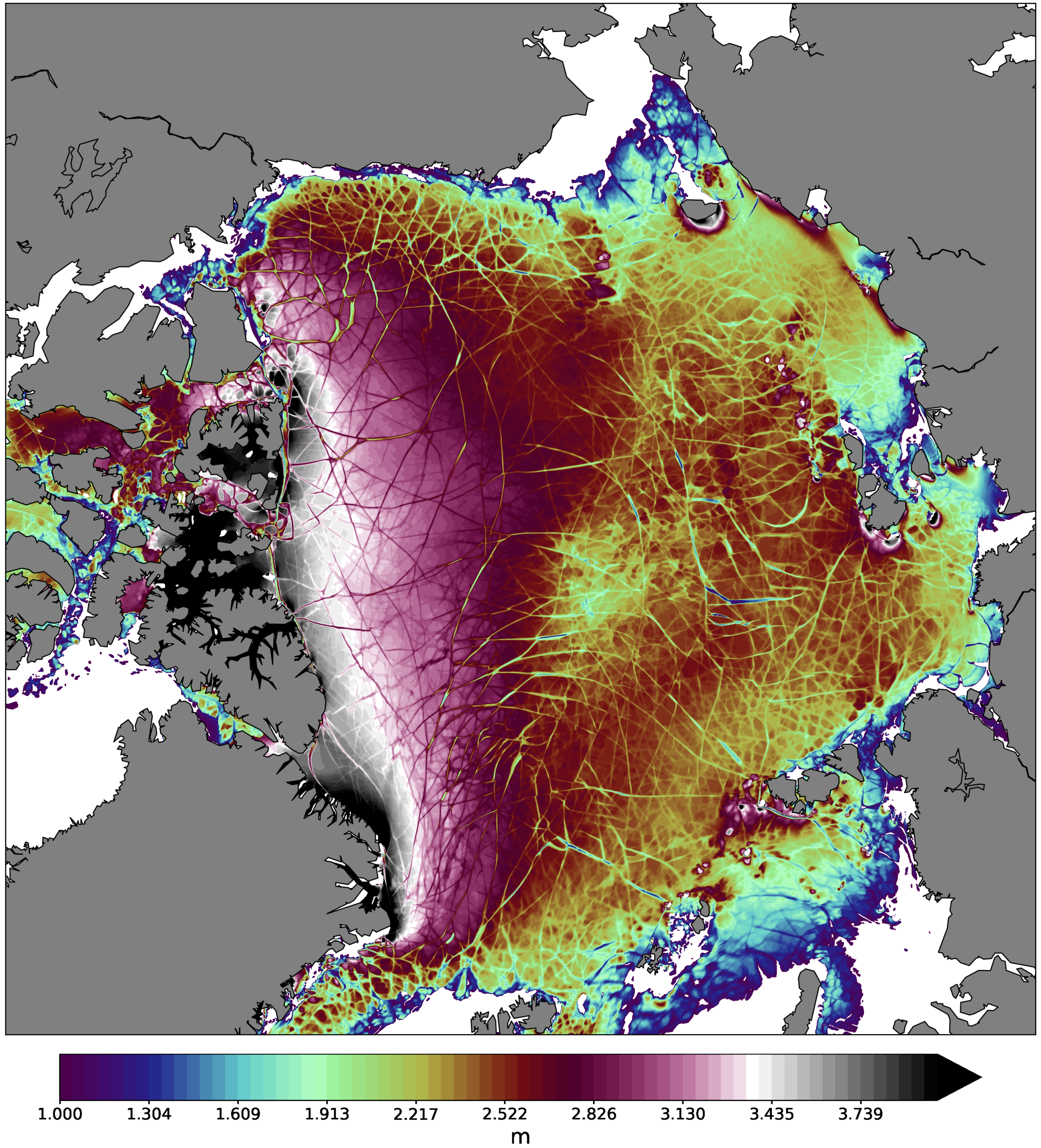


Relative vorticity in runs on 1 km and 4 km meshes



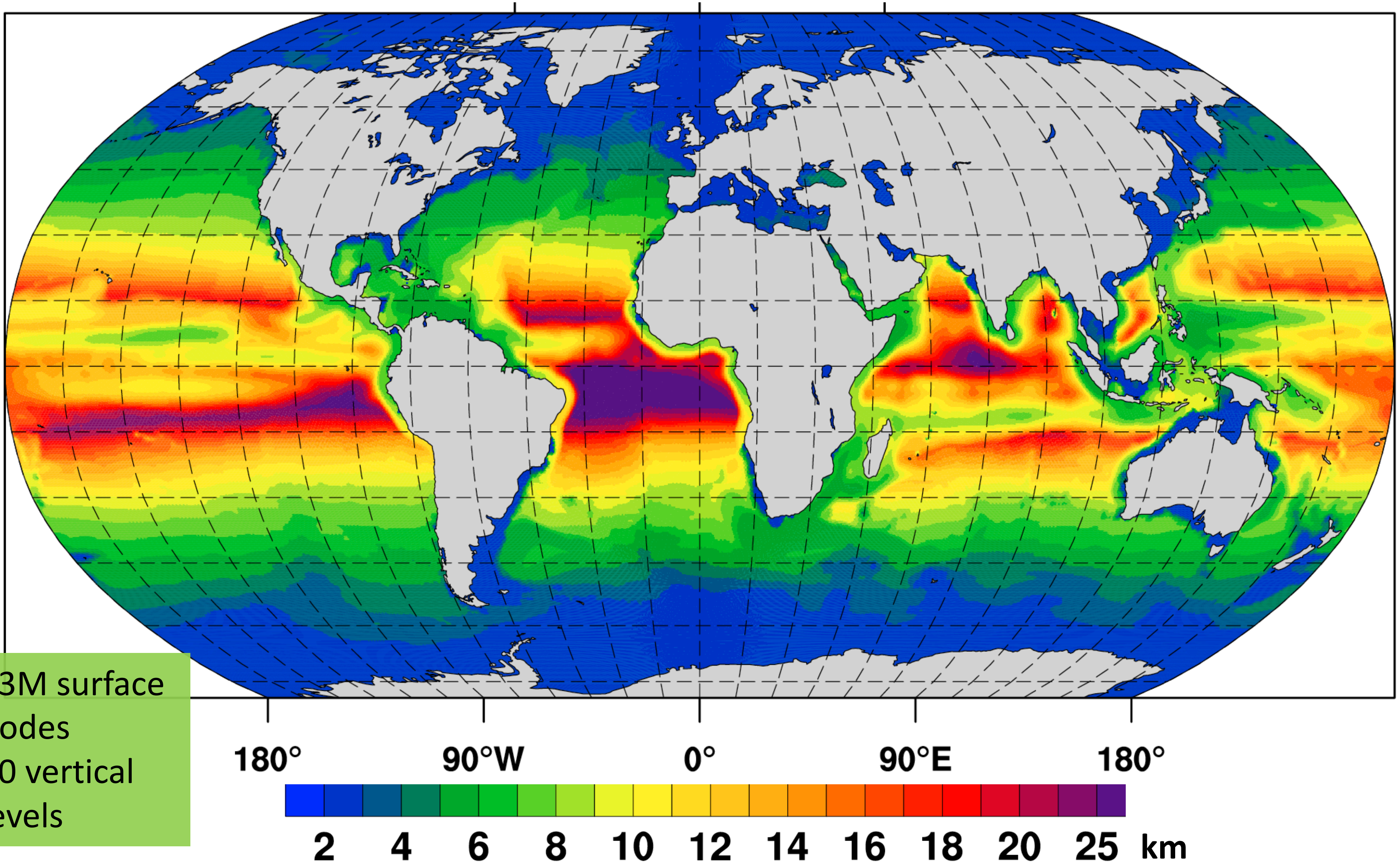
Resolution much finer than L_d (about 8-10 km) is needed in the Arctic Ocean (Wang et al. 2020)

FESOM2 1 km Arctic simulations

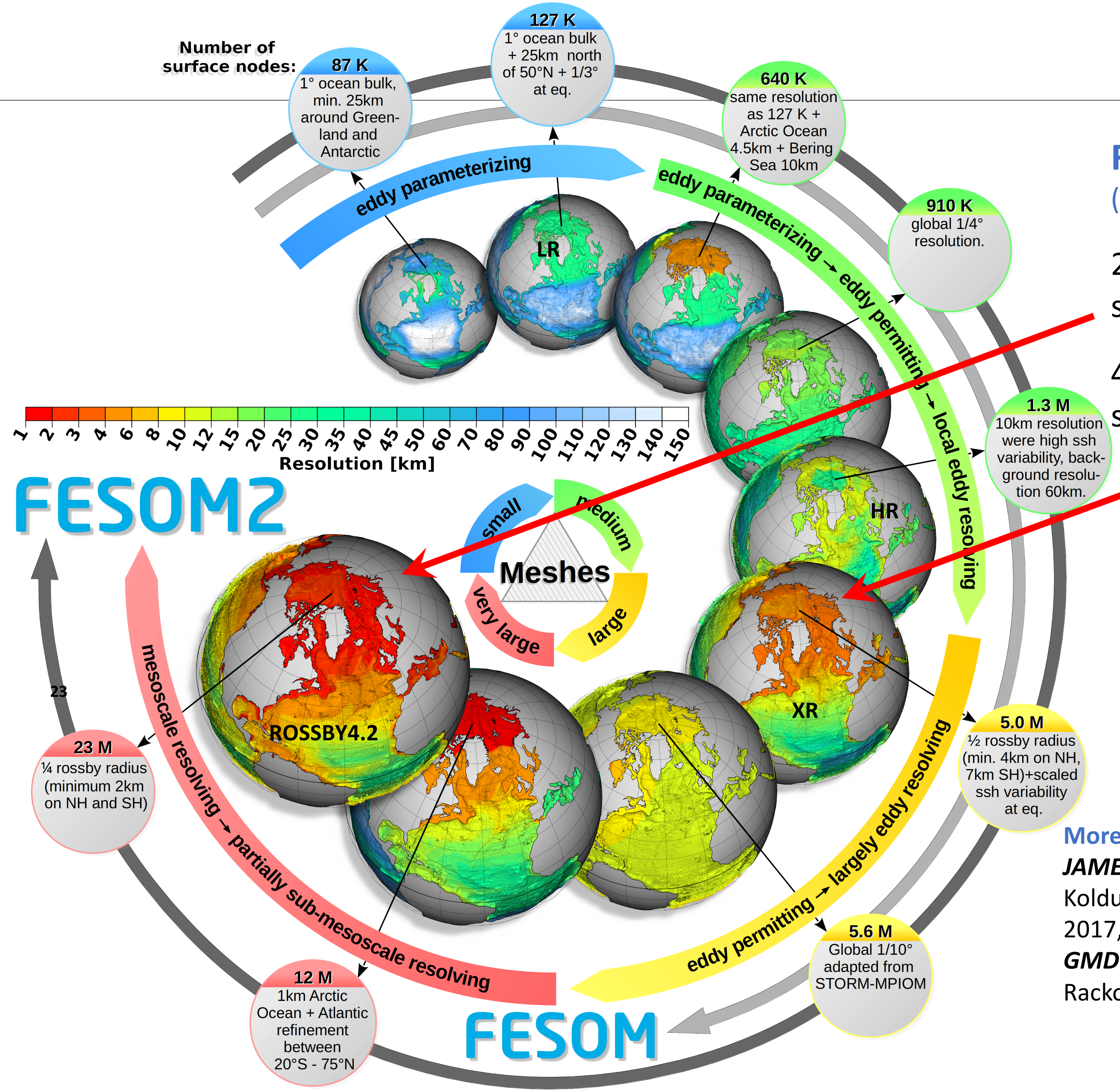


Ice thickness,
snapshot, mEVP solver

ROSSBY 4.2 resolution: $\max\{L_d/4, 2km\}$



23M surface nodes
80 vertical levels



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:

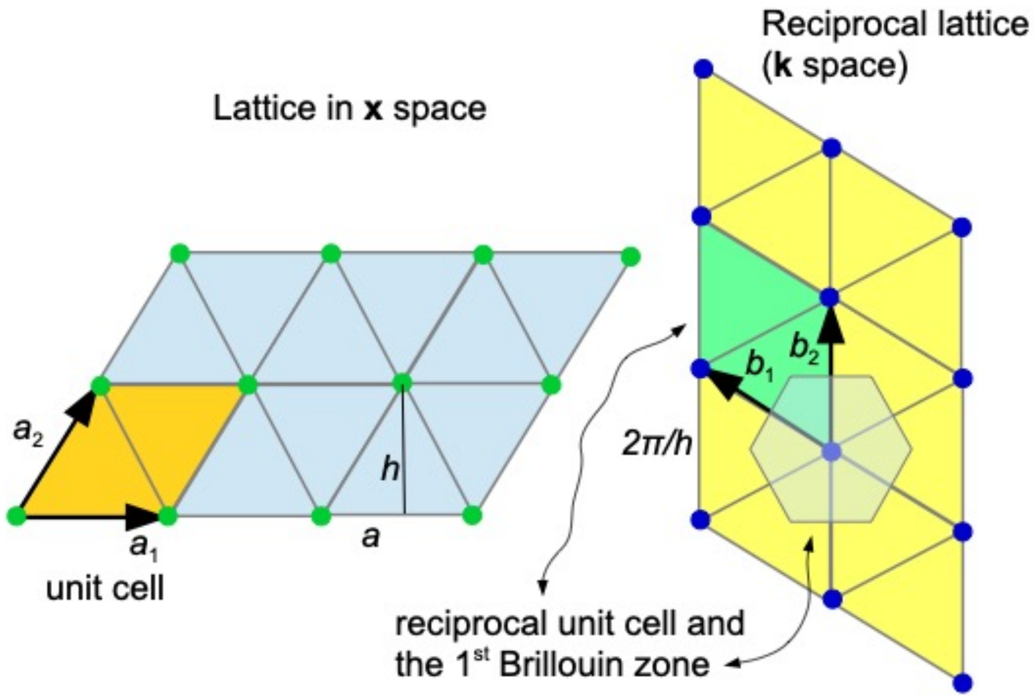
JAMES:

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

GMD:

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

Wave vectors resolvable on triangular and hexagonal meshes



TRIANGULAR LATTICE: Vertices of equilateral triangular lattice are invariant to translations

$$\mathbf{x} \rightarrow \mathbf{x} + \mathbf{z}, \quad \mathbf{z} = n_1\mathbf{a}_1 + n_2\mathbf{a}_2,$$

where

$$\mathbf{a}_1 = (1, 0)a, \quad \mathbf{a}_2 = (1/2, \sqrt{3}/2)a = (a/2, h)$$

a and h the triangle side and height, and n_1 and n_2 integer numbers.
A rhombus formed by $\mathbf{a}_1$ and $\mathbf{a}_2$ is the unit cell of triangular lattice. The unit cell is not unique, but the set of translations $\mathbf{z}$ is.

RECIPROCAL LATTICE in the wave-number space is given by translations

$$\mathbf{q} = m_1\mathbf{b}_1 + m_2\mathbf{b}_2,$$

where m_1 and m_2 are integers, and the reciprocal vectors are

$$\mathbf{a}_i \cdot \mathbf{b}_j = 2\pi\delta_{ij}, \Rightarrow \mathbf{b}_1 = (2\pi/a)(-1, 1/\sqrt{3}), \quad \mathbf{b}_2 = (2\pi/a)(0, 2/\sqrt{3}).$$

A unit cell of the reciprocal lattice is a rhombus formed by $\mathbf{b}_1$ and $\mathbf{b}_2$.

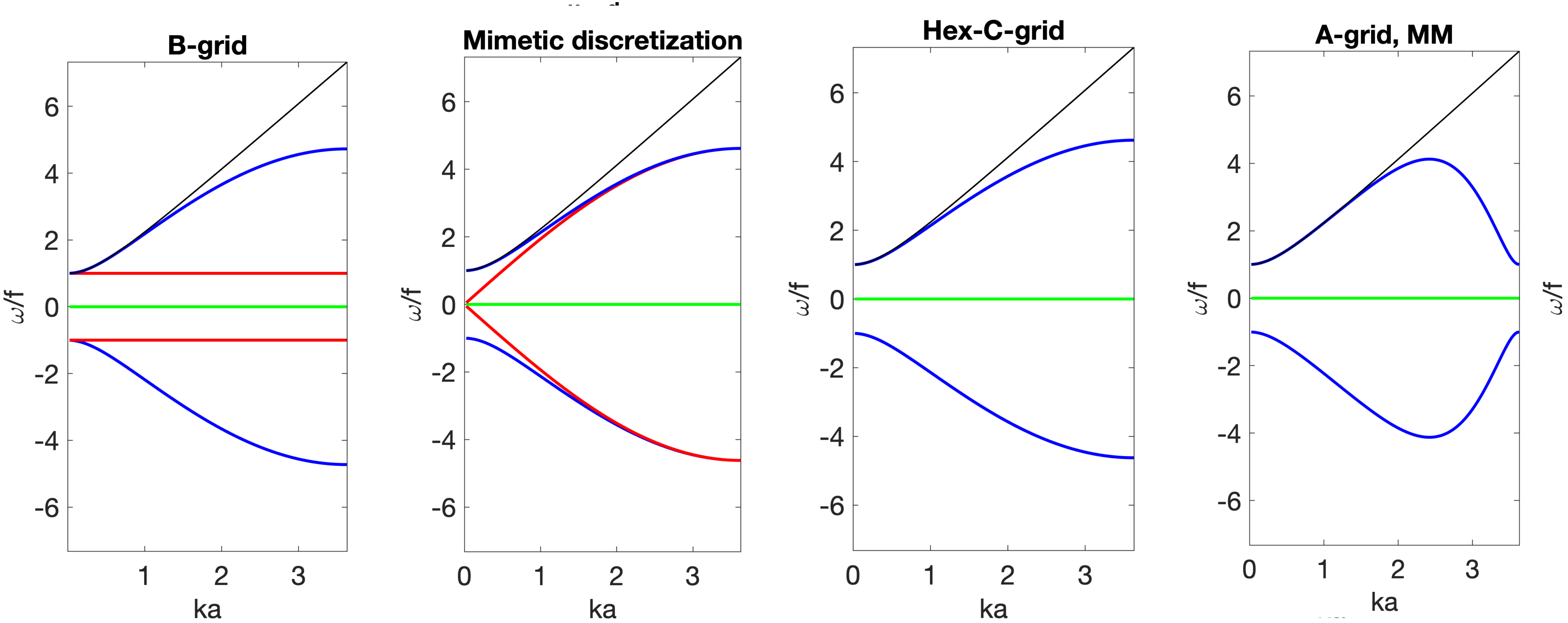
Because of the invariance with respect to translations **q** in **k** space, it is sufficient to consider **k** within the unit reciprocal cell. More commonly, we consider **k** within the first Brillouin zone, which is the Voronoi cell of the reciprocal lattice.

- The representable wave numbers are those within the first Brillouin zone.
- The amplitude of representable wave number depends on direction. In the worst case

  $$|\mathbf{k}|_{max} = 2\pi/(\sqrt{3}a) = \pi/h,$$

  i.e., the geometrical resolution is given by the height of triangles. It is 15% better than the resolution of quadrilateral mesh with the same side a.

Linearized SWE dispersion for $L_d/a=0.5$ (a the side)



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 optimal choice is still a subject of research.

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