Multiresolution ocean simulations on unstructured meshes

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(with contributions from Q.Wang, C. Wekerle, V. Haid, R. Timmermann,
X. Wang, D. Sidorenko, T. Rackow, ...)

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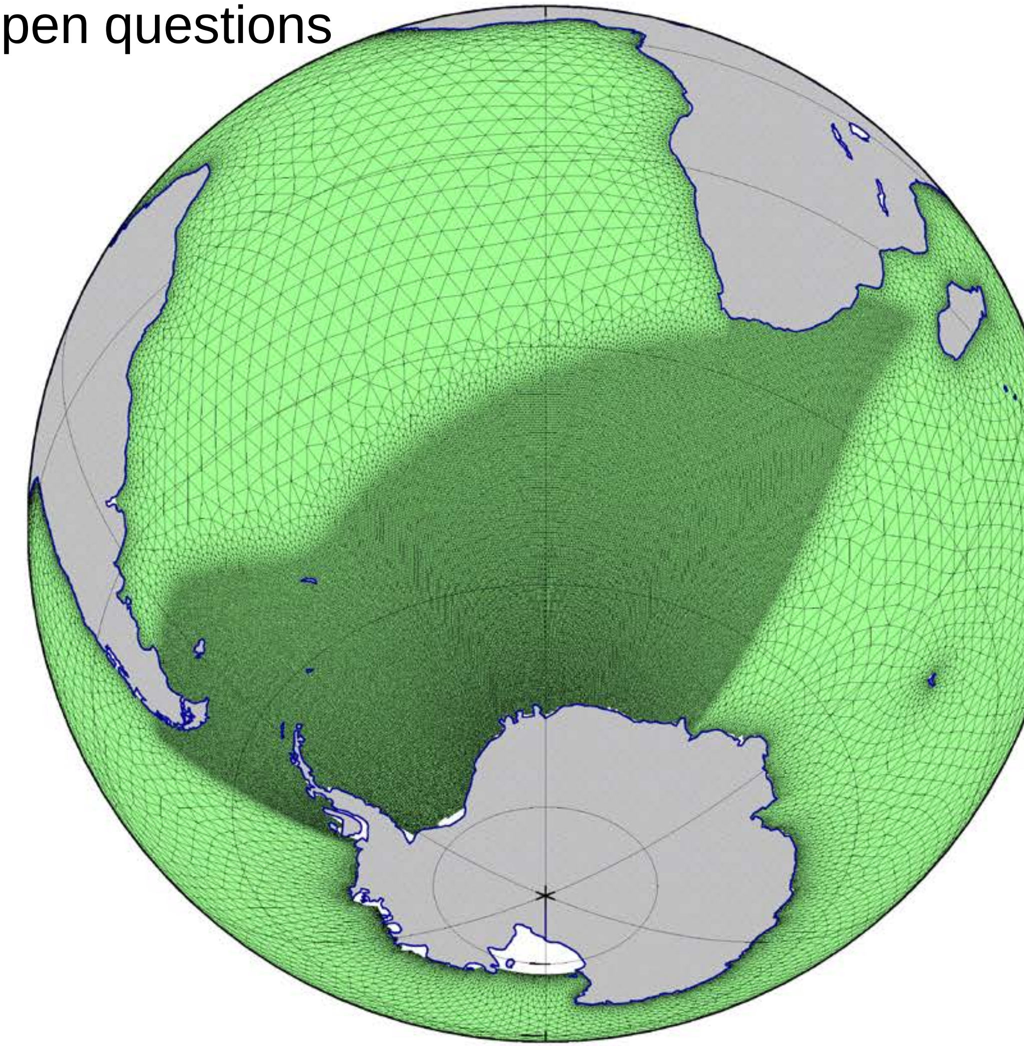
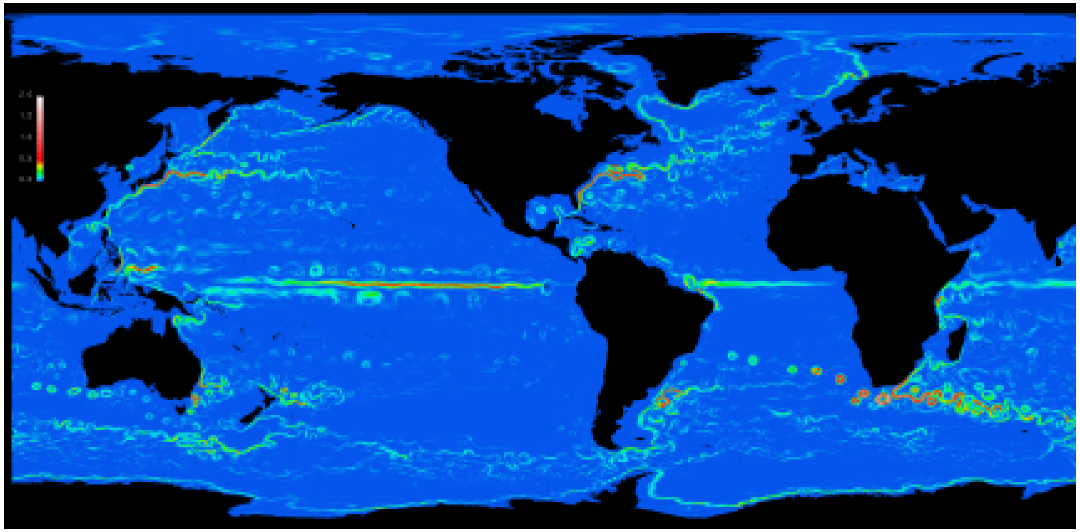
Outline:

1. Why unstructured meshes can be useful?
2. FESOM (Finite-Element Sea-ice Ocean circulation Model)
3. Examples
4. New developments, and open questions
5. Conclusions

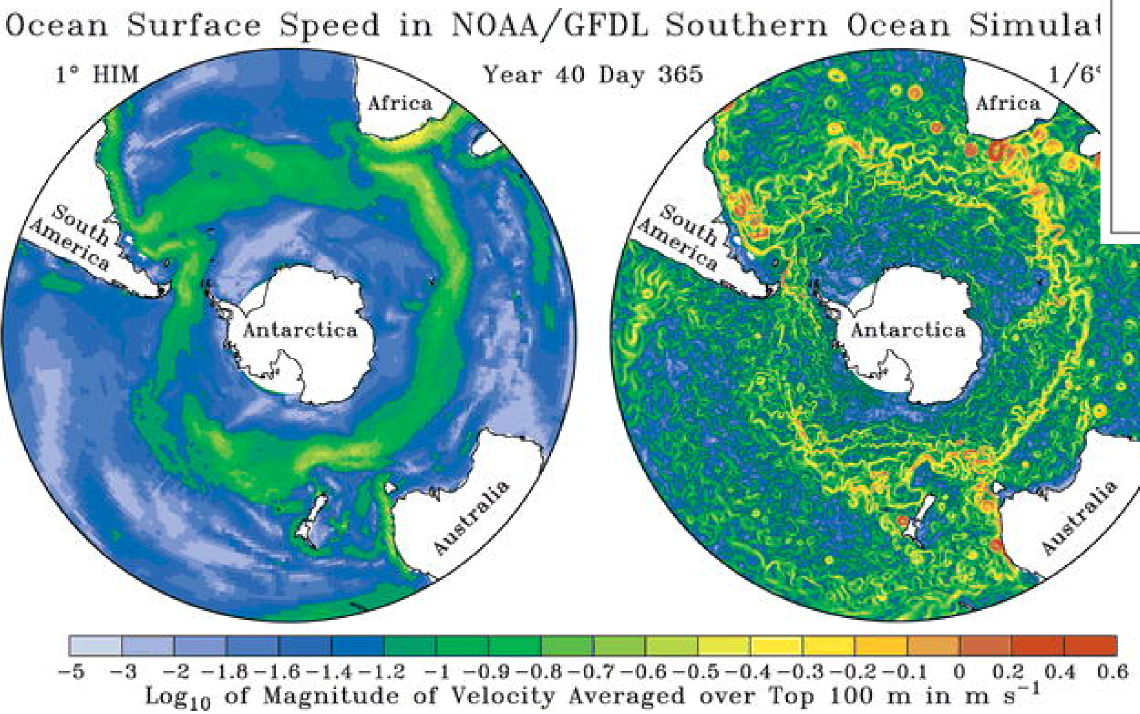


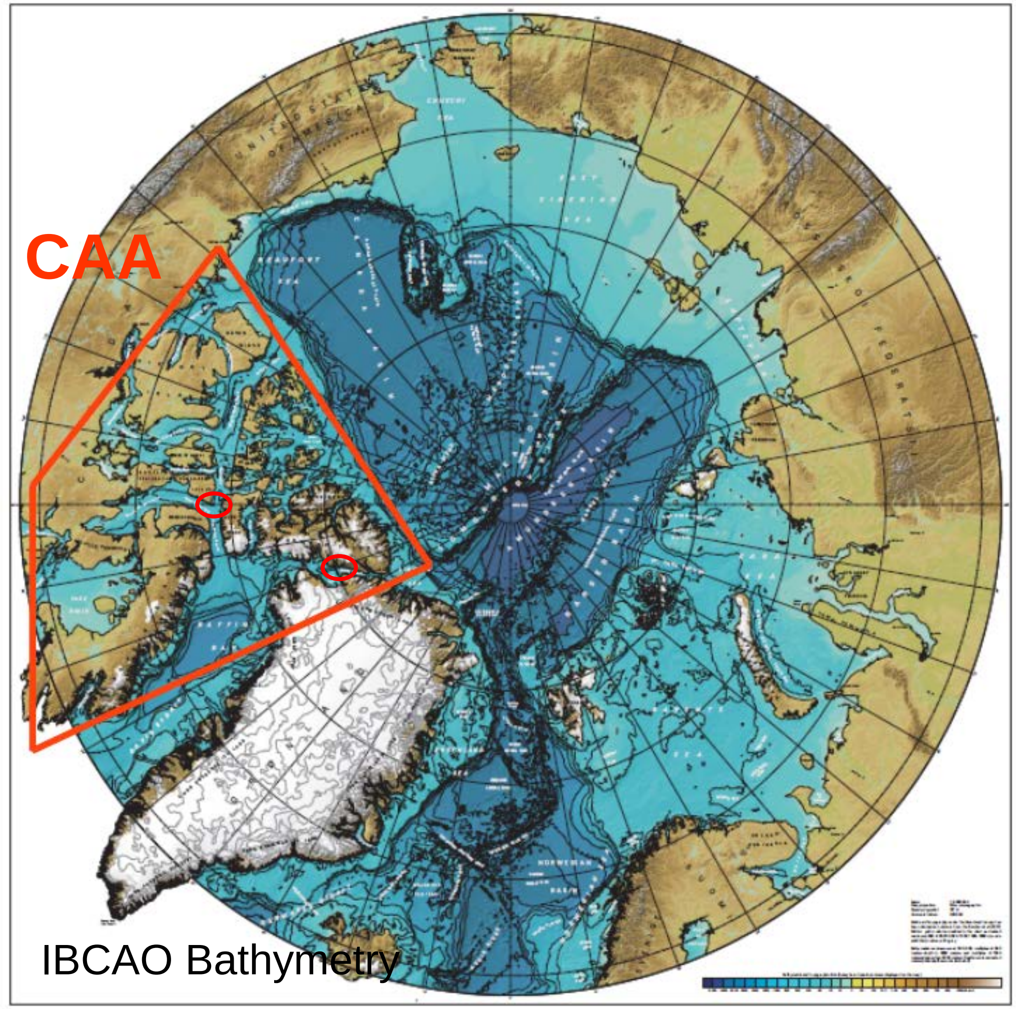
Multiresolution approach is of interest for:

Ringler et al., 2013



Halberg and Gnanadesikan, 2006



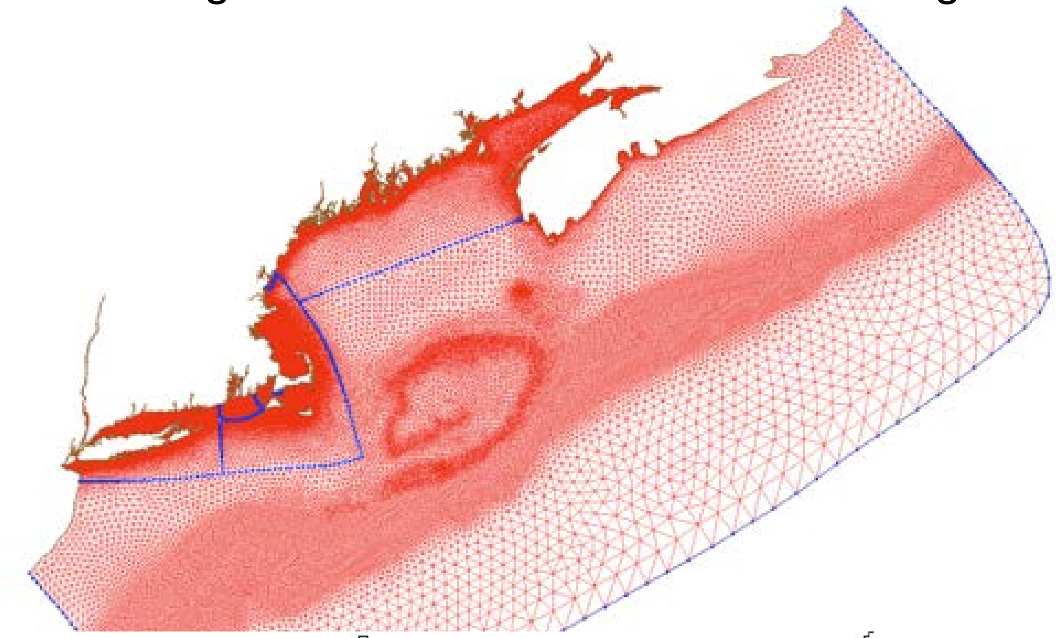


- resolving boundary currents or regional dynamics
- resolving coastlines, continental break and passages
- resolving outflows or sides of deep water formation

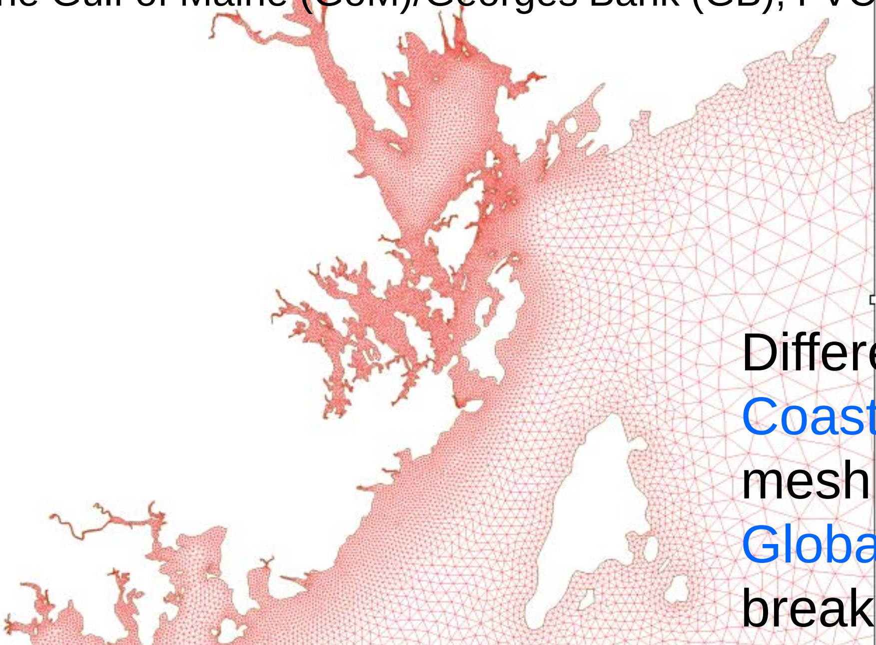
Coastal vs. large-scale ocean: The difference is subtle, but dynamics and integration times are different

Coastal: Dominated by tidal dynamics
Short integration time

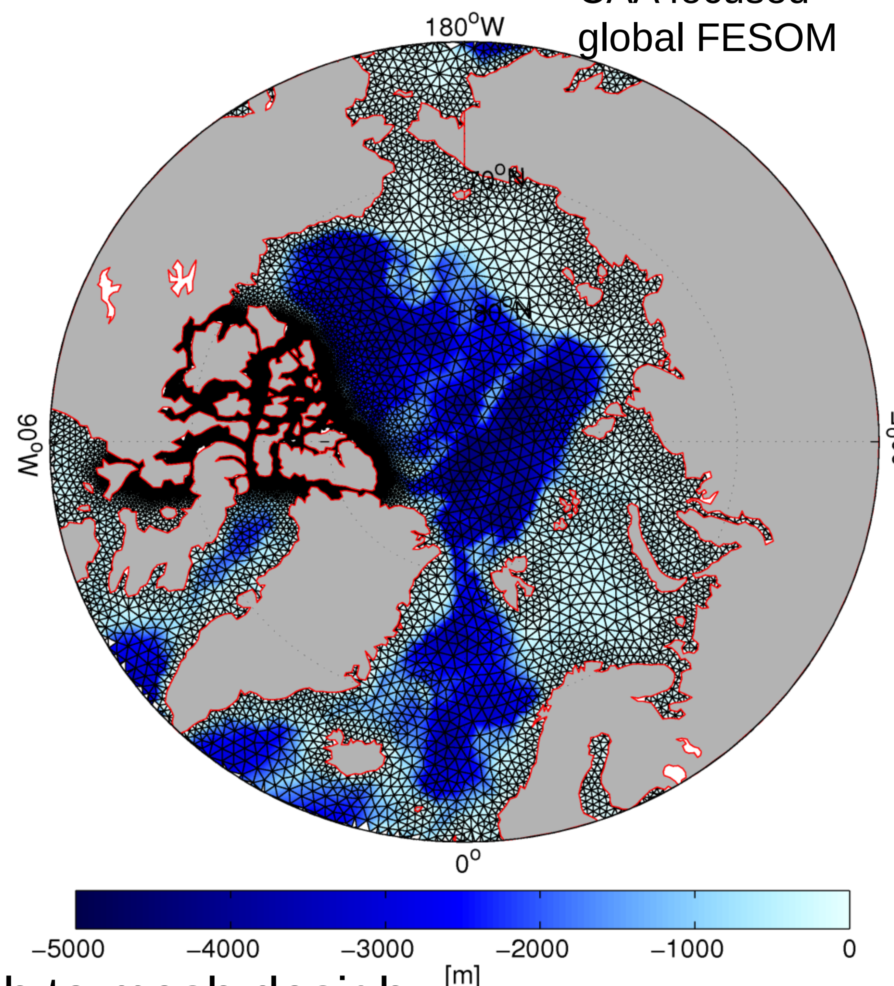
Large-scale: Driven by exchange with the atmosphere
Integration times – from tens to hundreds of years



The Gulf of Maine (GoM)/Georges Bank (GB), FVCOM web site



CAA focused global FESOM



Different approach to mesh desigh:

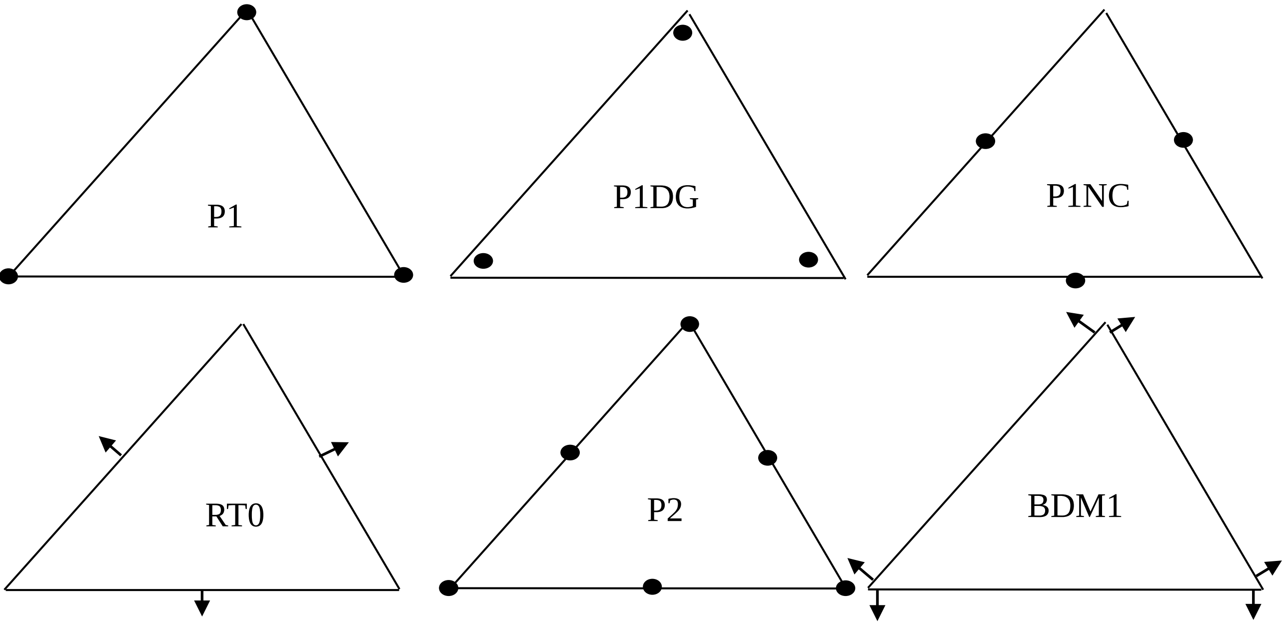
Coastal: Resolve coastlines and provide a uniform mesh in phase speed metrics.

Global: Do nesting, resolve passages and continental break where needed,coastlines are less important

Main low-order discretizations:

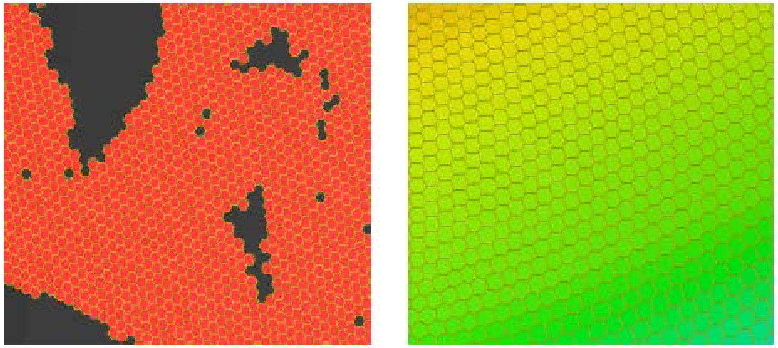
Triangular meshes

(i) continuous and discontinuous FE



Voronoi (quasi-hexagonal) meshes,

C-grid approach

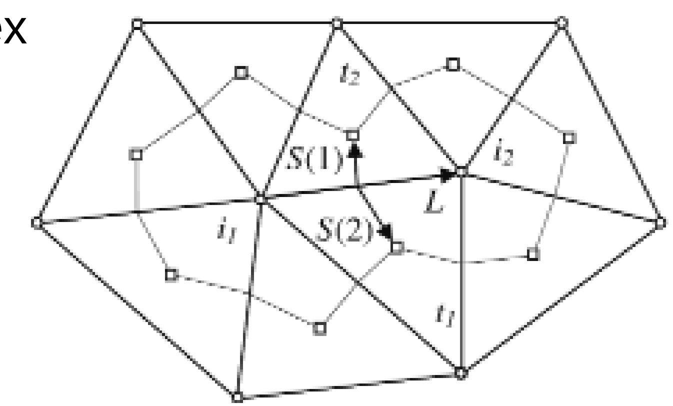


Ringler et.al, 2013

For a review, see
Danilov, 2013, *Ocean Modelling*

Main velocity-pressure pairs: P1-P1, P1NC-P1, P1DG-P1DG
RT0-P0 (triangular C-grid)

(ii) Finite-volume methods
vertex-vertex
cell-vertex
cell-cell



Analogs of A-grid
P1-P1~ triangular vertex-vertex~ hexagonal cell-cell
triangular cell-cell
Analogs of B-grid (staggering)
cell-vertex~P0-P1~ZM hex
P1nc-P1

Scalar parts of triangular cell-vertex and hex-C-grid are similar

Unstructured meshes == multiresolution meshes

•Enable one to resolve complex geometry or small features (straits, passages)

•Enable one to refine resolution in dynamically important regions
(plays the same role as nesting, but does it in a dynamically consistent way)

It is believed that by resolving dynamics local dynamics in key regions we can improve the skill of our models.

Other advantages: (i) can be more economical
(ii) require less storage compared to regular fine-resolution models

Models available now:

FESOM (P1-P1)

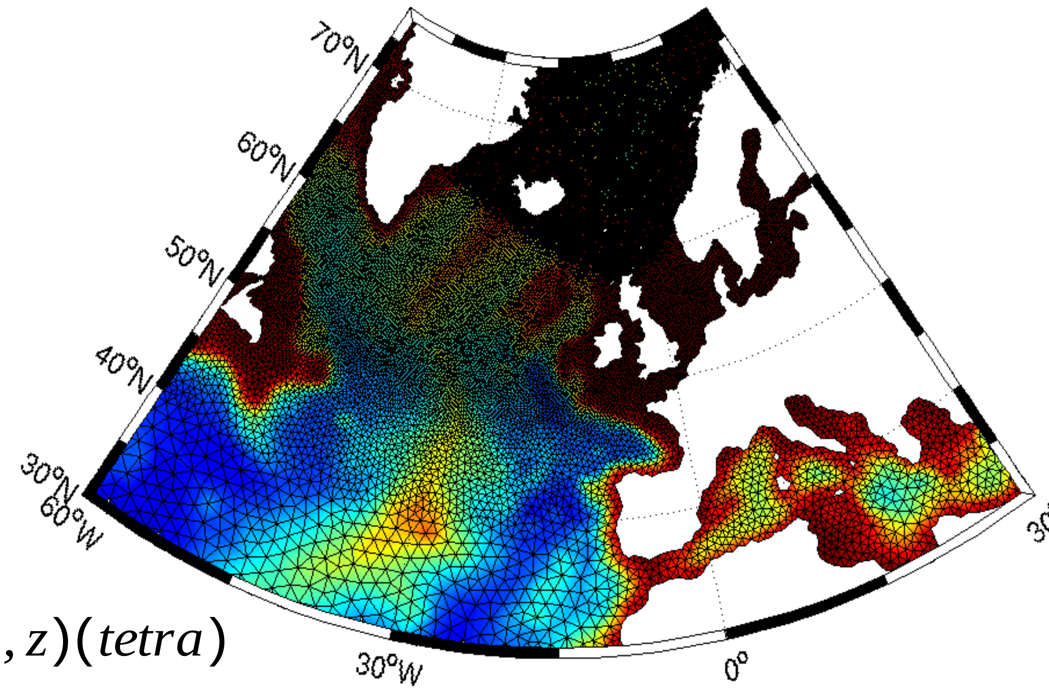
Models to be available soon:

MPAS-ocean (Los-Alamos) (hex-C-grid)
ICON (MPI-DWD) (tri-C-grid)
New dynamical core for FESOM (end 2013) (cell-vertex FV)

FESOM (*Finite Element Sea-ice Ocean Model*)

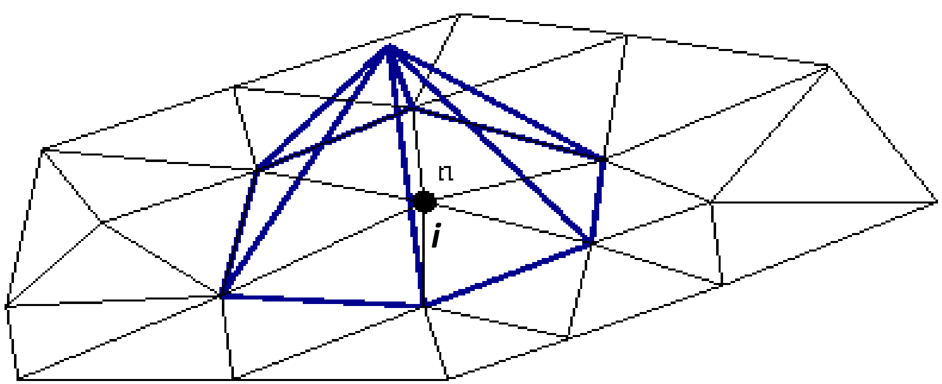
Ocean General Circulation Model

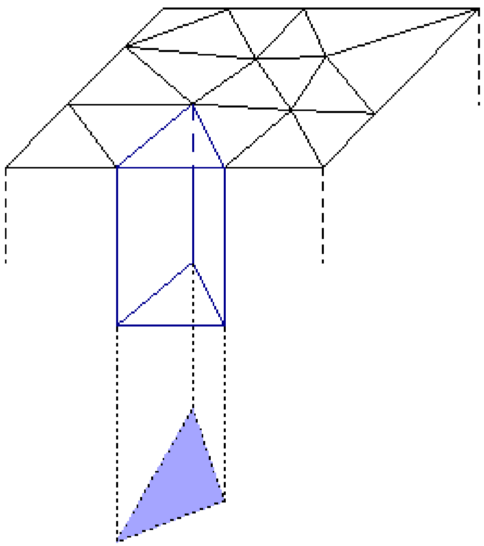
Hydrostatic primitive equations
FE method:
Continuous linear basis functions
Triangles on the surface
Tetrahedra (or prisms) in 3D

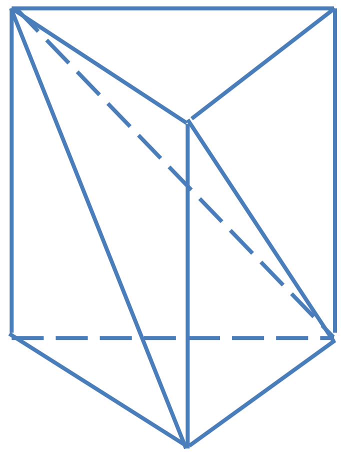


$$T=\sum T_i(t)N_i(x,y,z)$$

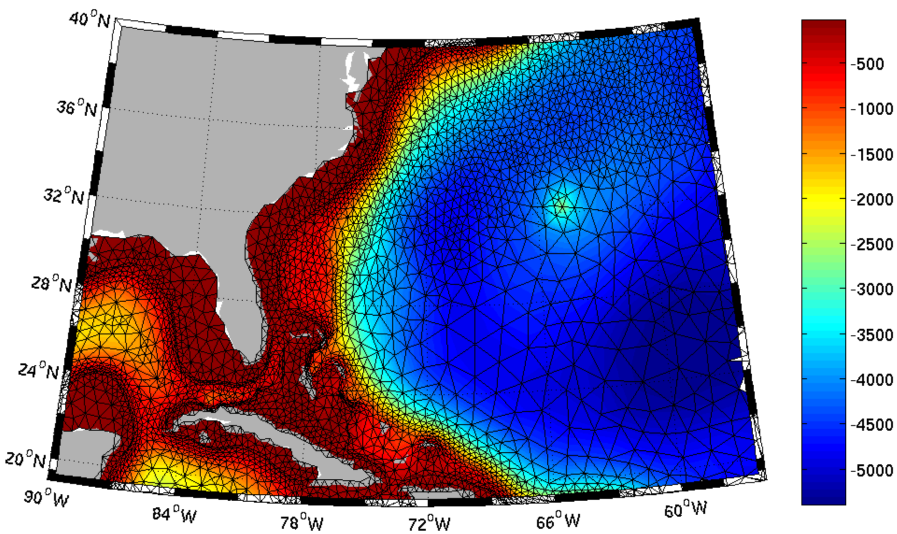
$$N_i=P_1(x,y)P_1(z)\ \ (prisms)\ \ N_i=P_1(x,y,z)(tetra)$$



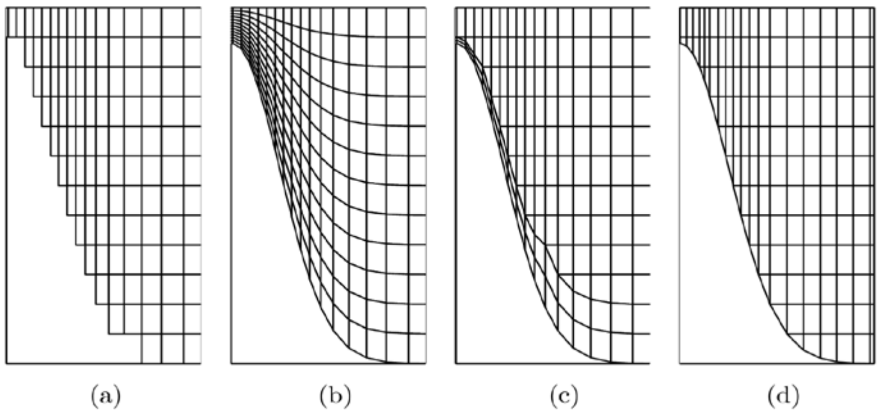


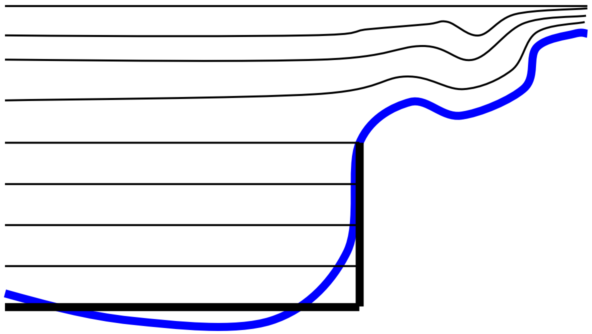


Bottom representation



Available in FESOM:





Models formulated on unstructured meshes can benefit from their ability to align mesh with topography.

Ingredients of FESOM:

Advection schemes: Taylor-Galerkin (TG) Formally second order
TG-FCT (Lohner 1984)
Galerkin-Least-Squares

Mixed-layer schemes: PP, KPP, Mellor-Yamada, + modifications

Options: Nonliner free surface, nonhydrostatic solver
GM, Redi rotated diffusivity tensor

Coupled to Finite-Element Ice model (0-layer thermodynamics, EVP and VP solvers; future plans are to add CICE and LIM3 as options)

Coupled to ECHAM6

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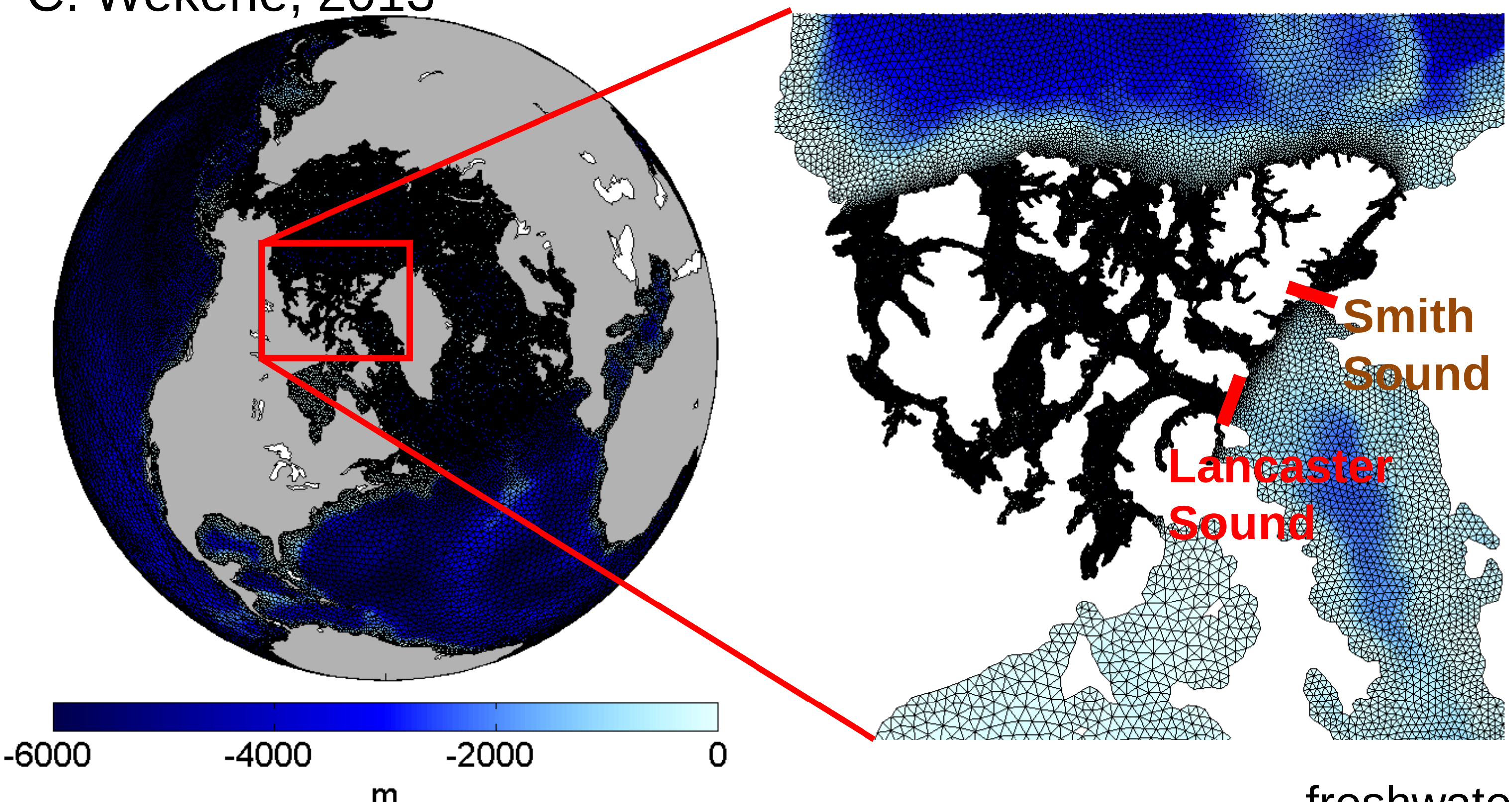
We will discuss further:

- The freshwater transport through CAA and its variability (C. Wekerle)
- Impact of tides on overflows in the Ross Sea (Q. Wang)
- Arctic modeling (Q. Wang, X. Wang)
- Greenland Ice Sheet (GIS) melting studies (X. Wang)
- Weddell Sea polynias and their role in deep water production
- Antarctic ice cavities (R. Timmermann, H. Helmer)
- Coupled simulations ECAM6-FESOM

FESOM *(Finite Element Sea-ice Ocean Model)*

Freshwater transport through Canadian Arctic Archipelago

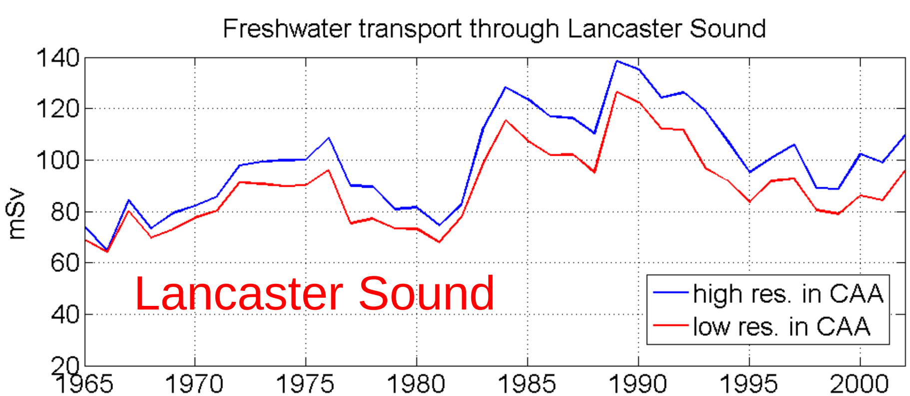
C. Wekerle, 2013

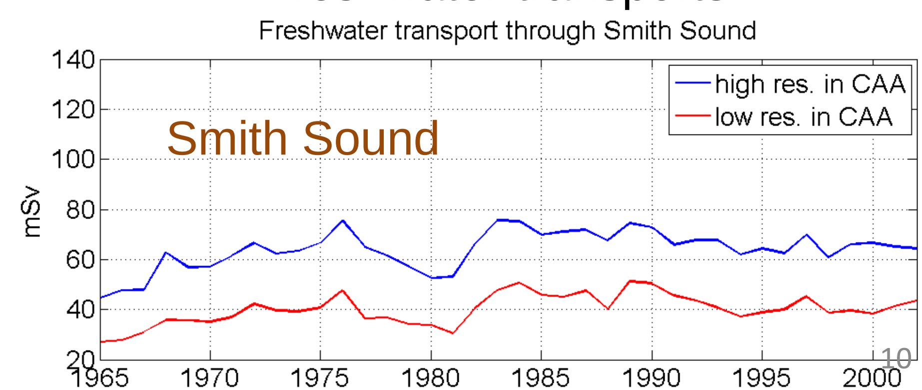


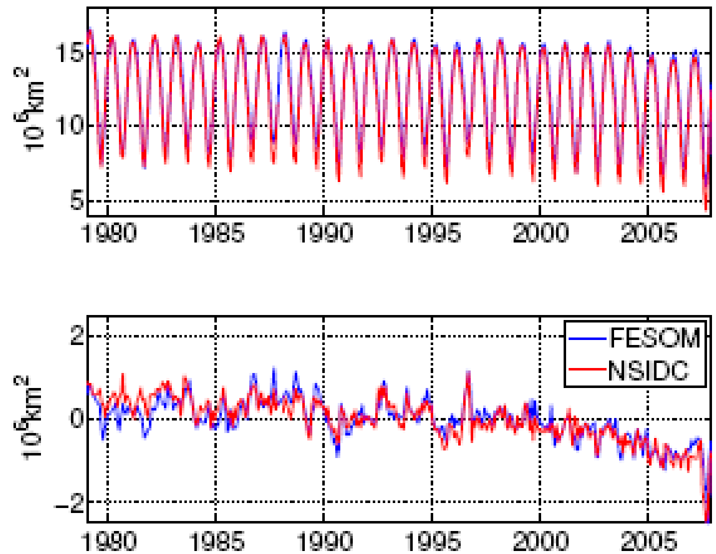
1.5°→5km
Arctic Ocean 24 km
1958-2007
CORE forcing

Two res. for CAA
5 km (Fine, blue)
24 km (Coarse,red)

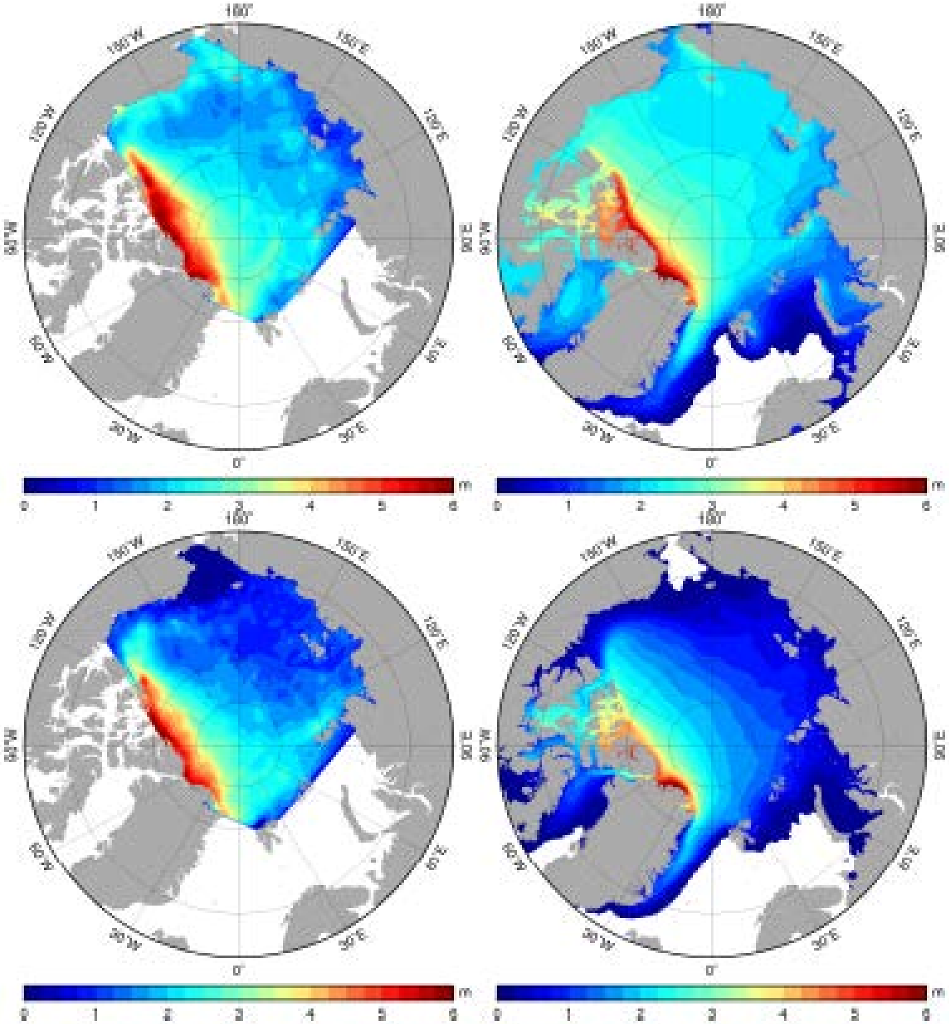
freshwater transports





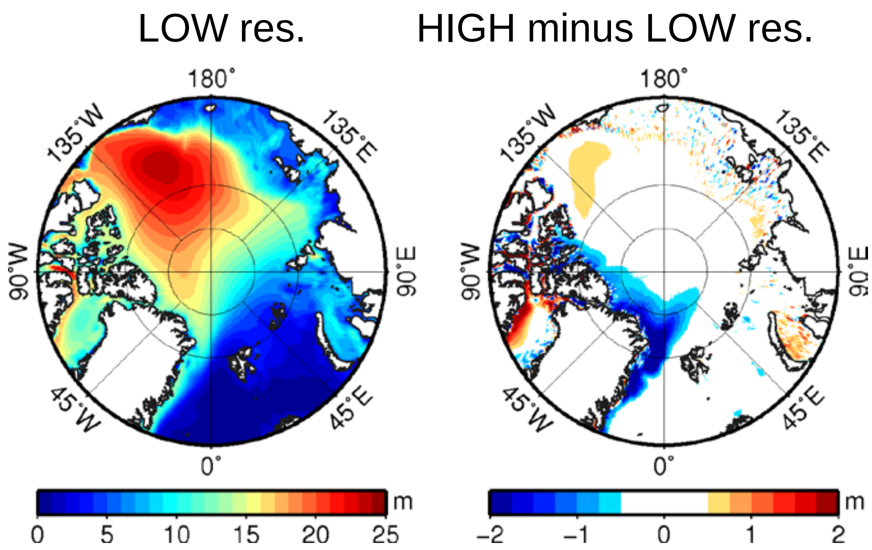


Sea ice extent (top) and its anomaly (bottom)
FESOM (blue) and satellite observation
(Fetterer et al., 2009, red).

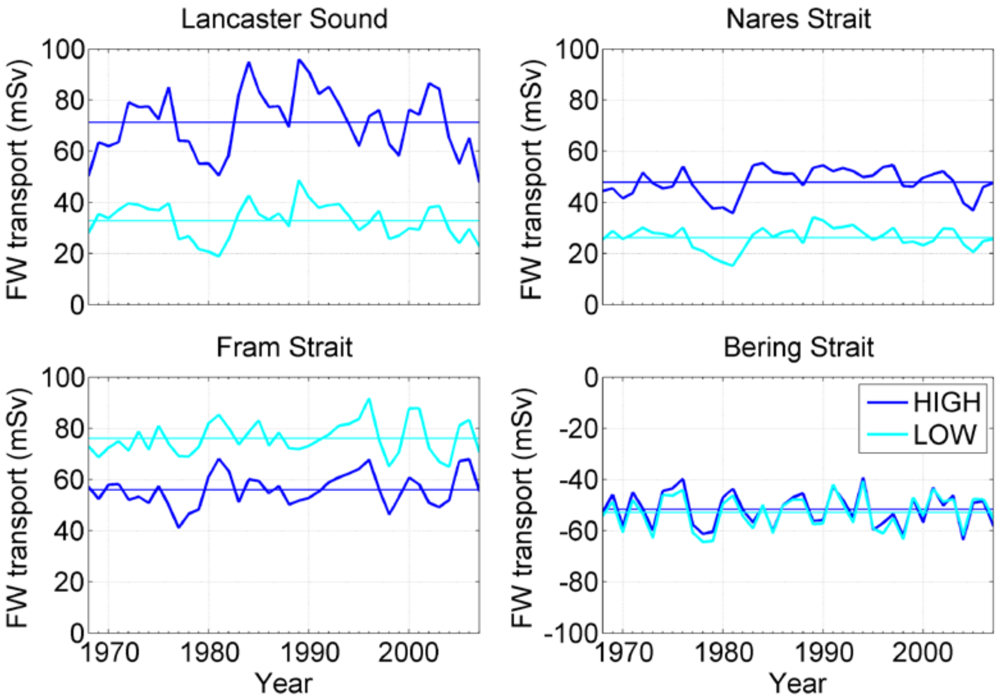


Mean sea ice thickness (2003-2007) in spring (top) and fall (bottom)
Left: ICESat measurements (Kwok and Cunningham (2008))
Right: FESOM simulations.

Arctic Ocean FW content and exports



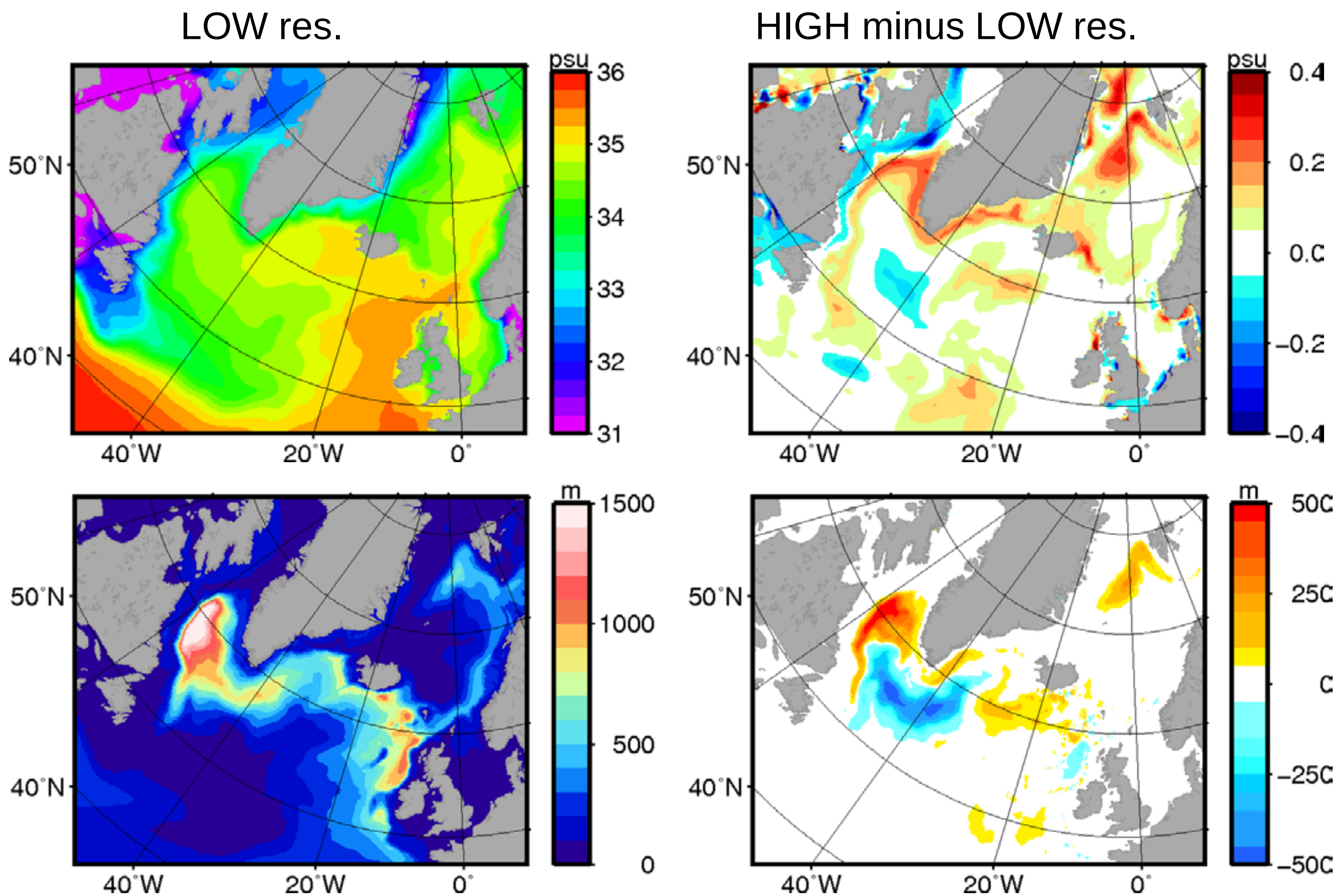
Mean FW content from 500 m depth to the surface relative to 34.8 psu for 1968-2007



Annual mean FW transports (with a reference salinity of 34.8 psu)

- *"Redirection"* of FW transports: higher CAA mesh resolution
  → increase of FW transports west of Greenland, decrease east of Greenland

Changes in the North Atlantic



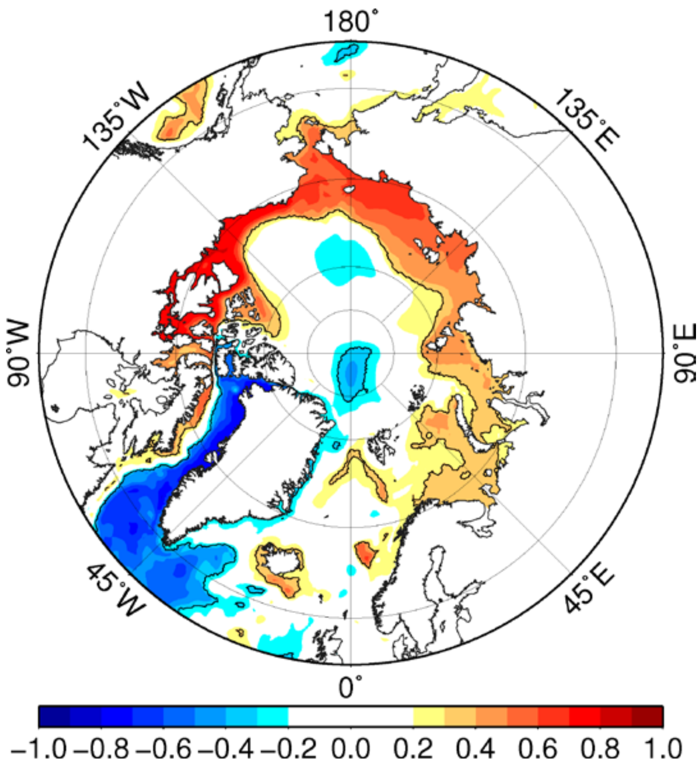
Mean salinity of the top 50 m for 1968-2007

Mean winter mixed layer depth for 1968-2007

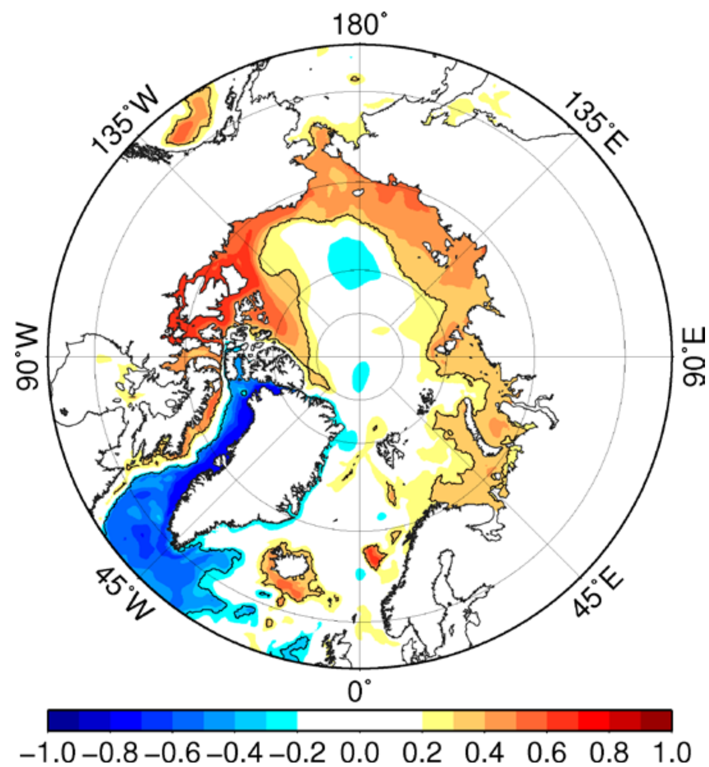
increased CAA mesh resolution leads to:
→ fresher Baffin Island Current, saltier East and West Greenland Current
→ deeper mixed layer in northern Labrador Sea, shallower mixed layer south of Greenland

The role of sea surface height II

Lancaster Sound



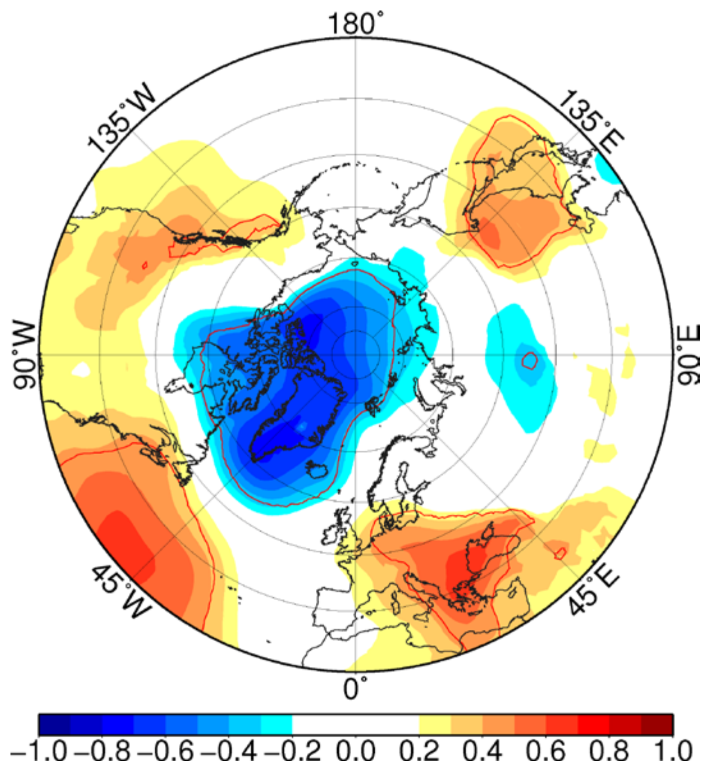
Nares Strait



Correlation of annual mean SSH with volume transport through the CAA

What drives sea level - along the Beaufort Sea coast?
- in Baffin Bay / Labrador Sea?

Large scale atmospheric forcing



Correlation of annual mean sea level pressure with volume transport through Lancaster Sound

Correlation of NAO index with volume transport:
- Lancaster Sound: r=0.68
- Nares Strait: r=0.49

Large scale forcing simultaneously leads to SSH changes up- and downstream of the CAA:

- Arctic Ocean:

Low pressure anomaly

High SSH along the Beaufort Sea coast

Higher transport through Lancaster Sound

- Labrador Sea:

Strong pressure difference

Strong winds and cooling of the ocean surface layer

Lower SSH

Higher transport through the CAA

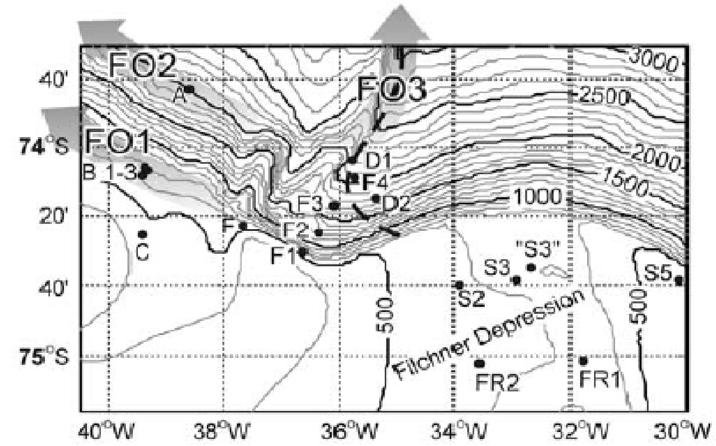
Process studies of Antarctic Bottom Water (AABW) formation

Tasks:

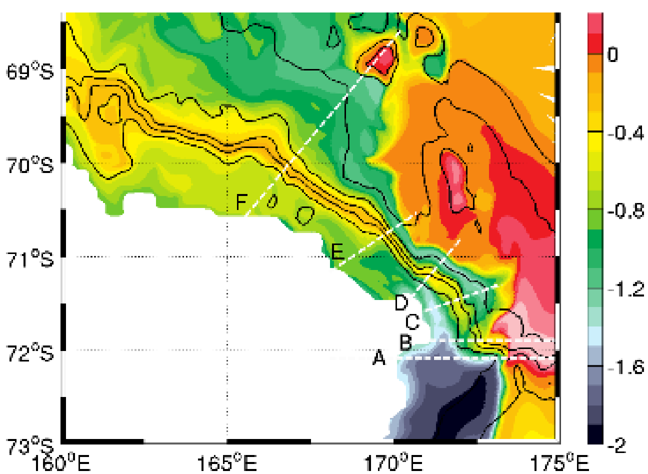
(i) the role of topographic steering

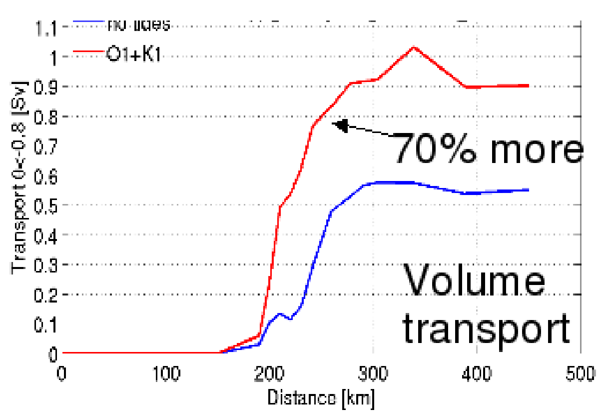
(ii) the impact of tides

Resolution: from 30 to 0.5 km on slope
(see Wang et al., JGR, 2010)



Foldvik et al. 2004



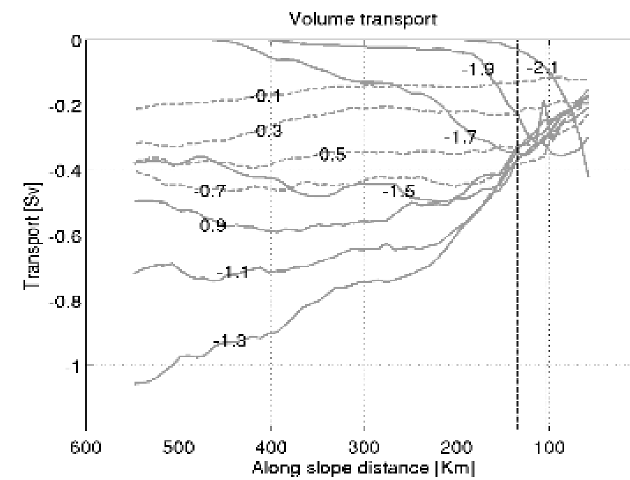


Western Ross Sea

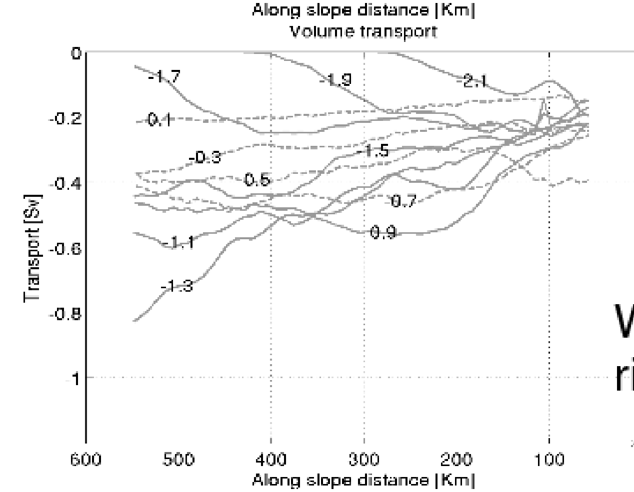
Impact of tides

Southern Weddell Sea

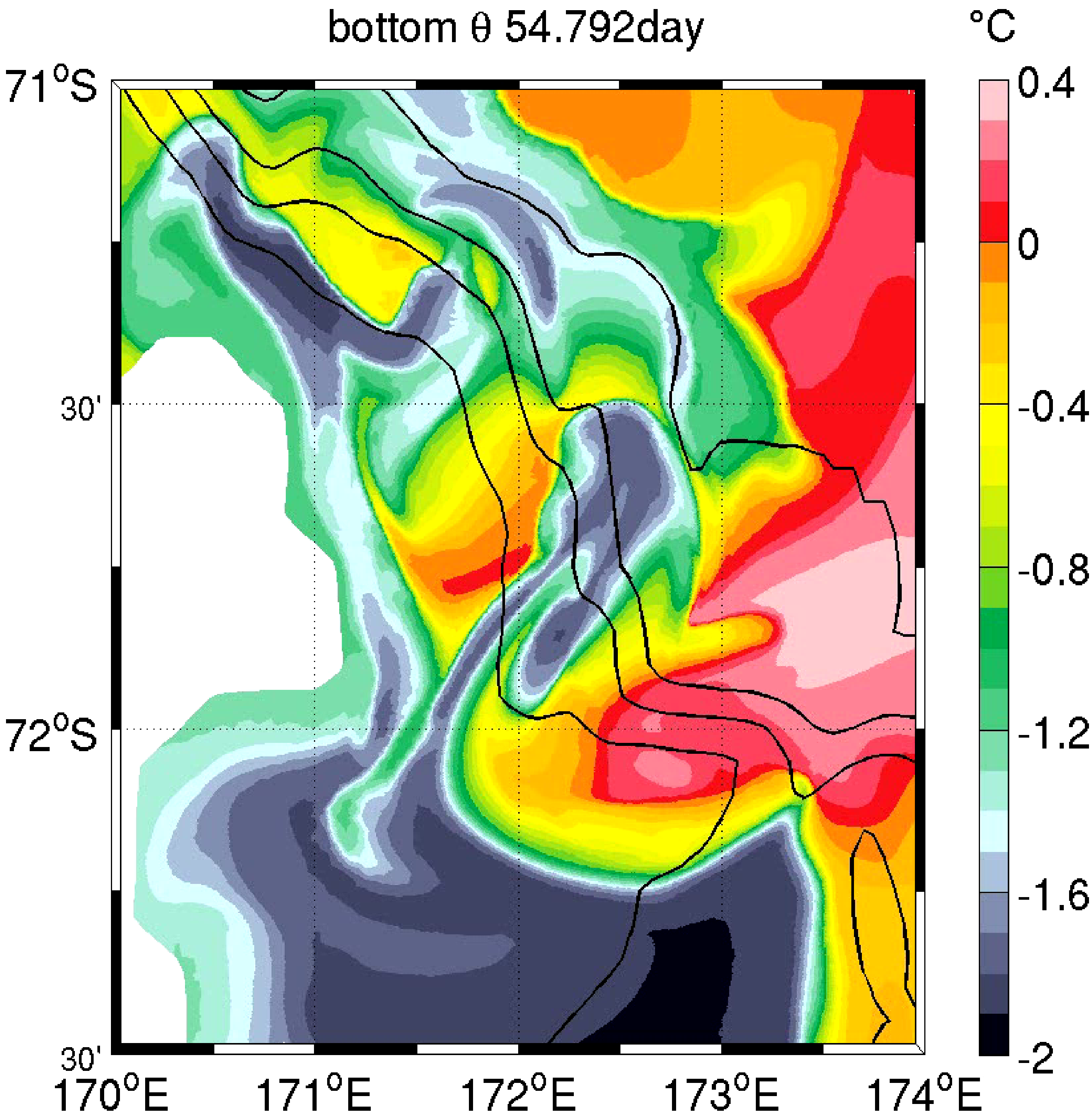
Topographic effects on mixing and steering



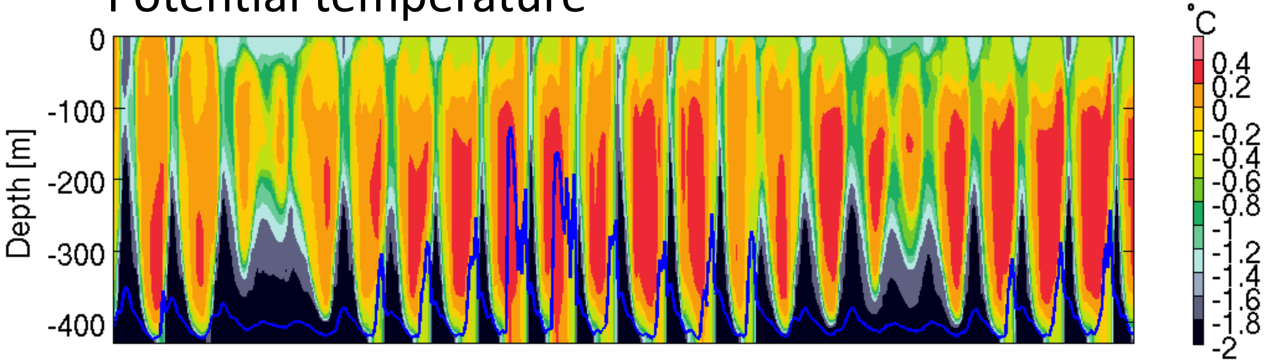
With ridges



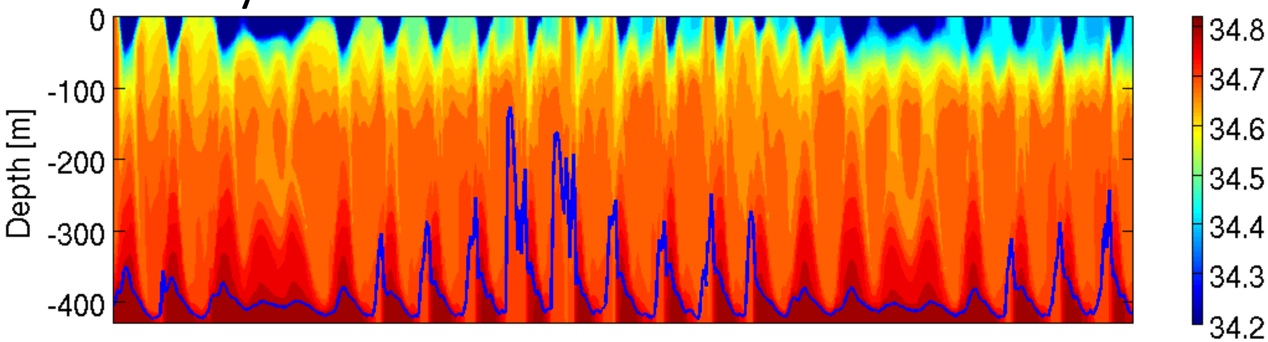
Without ridges


bottom θ 54.792day
°C
0.4
0
-0.4
-0.8
-1.2
-1.6
-2
71°S
30'
72°S
30'
170°E
171°E
172°E
173°E
174°E

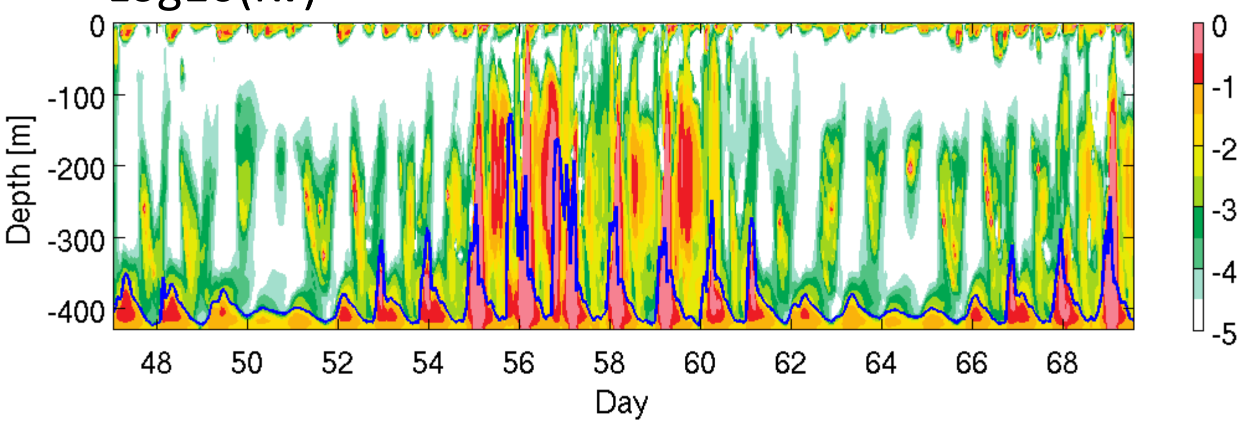
Potential temperature

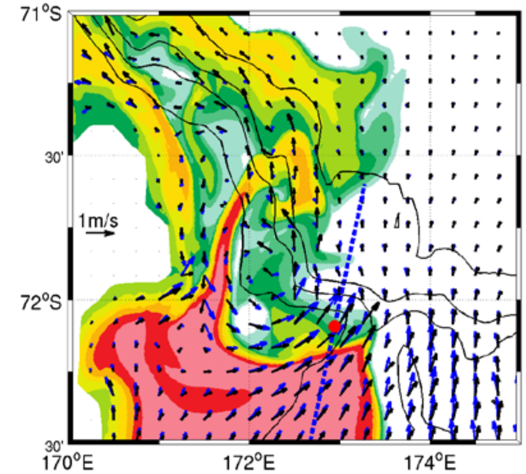


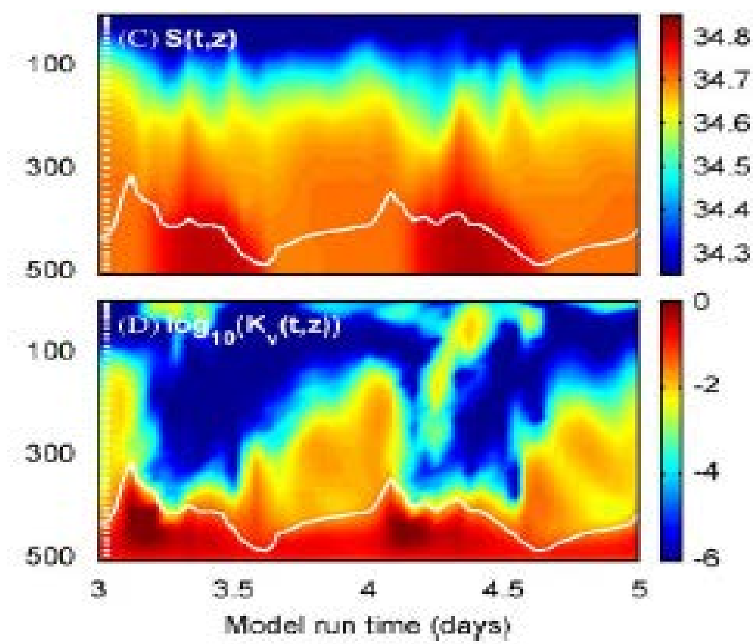
salinity



Log10(Kv)



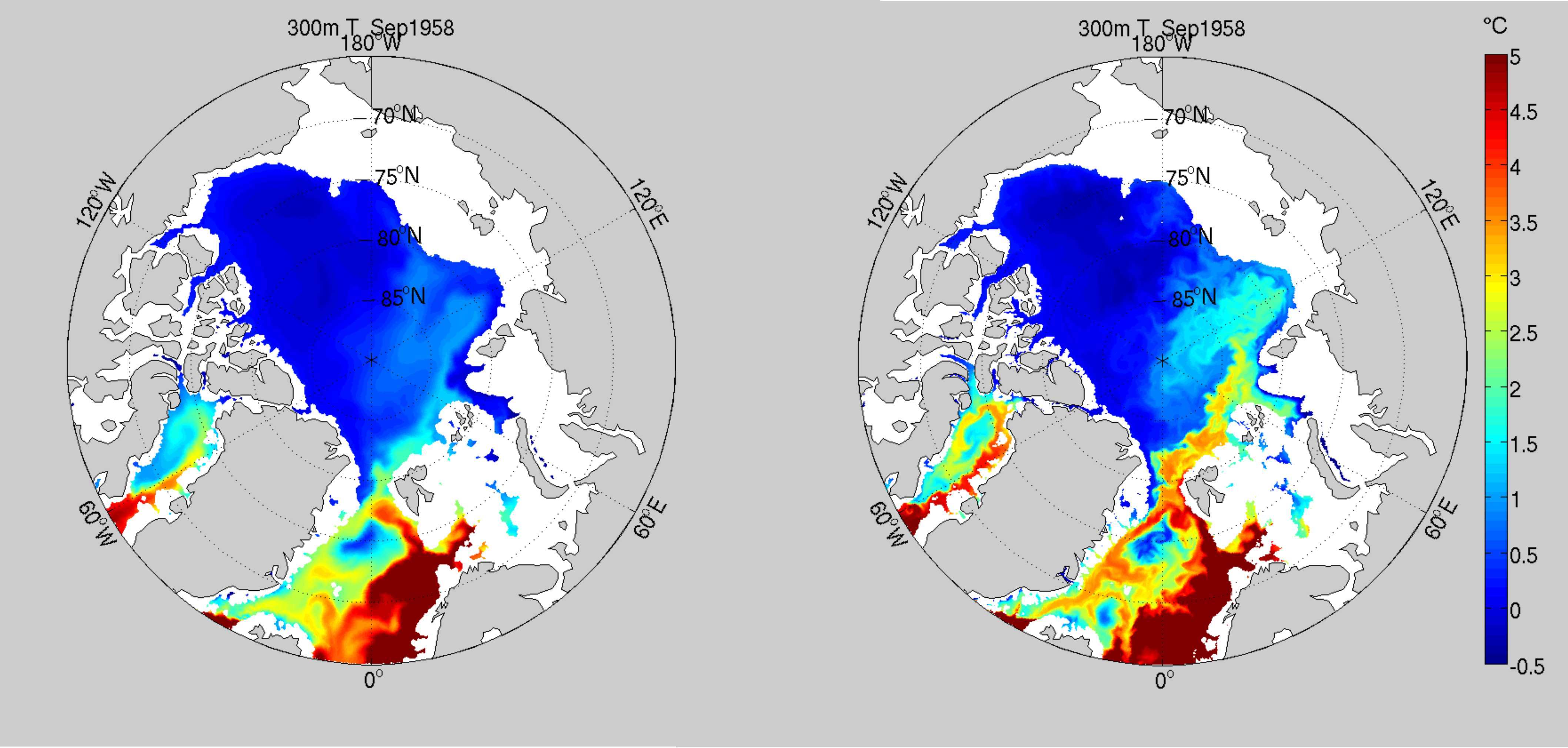




Padman et al., 2009

Arctic Ocean modeling with global FESOM

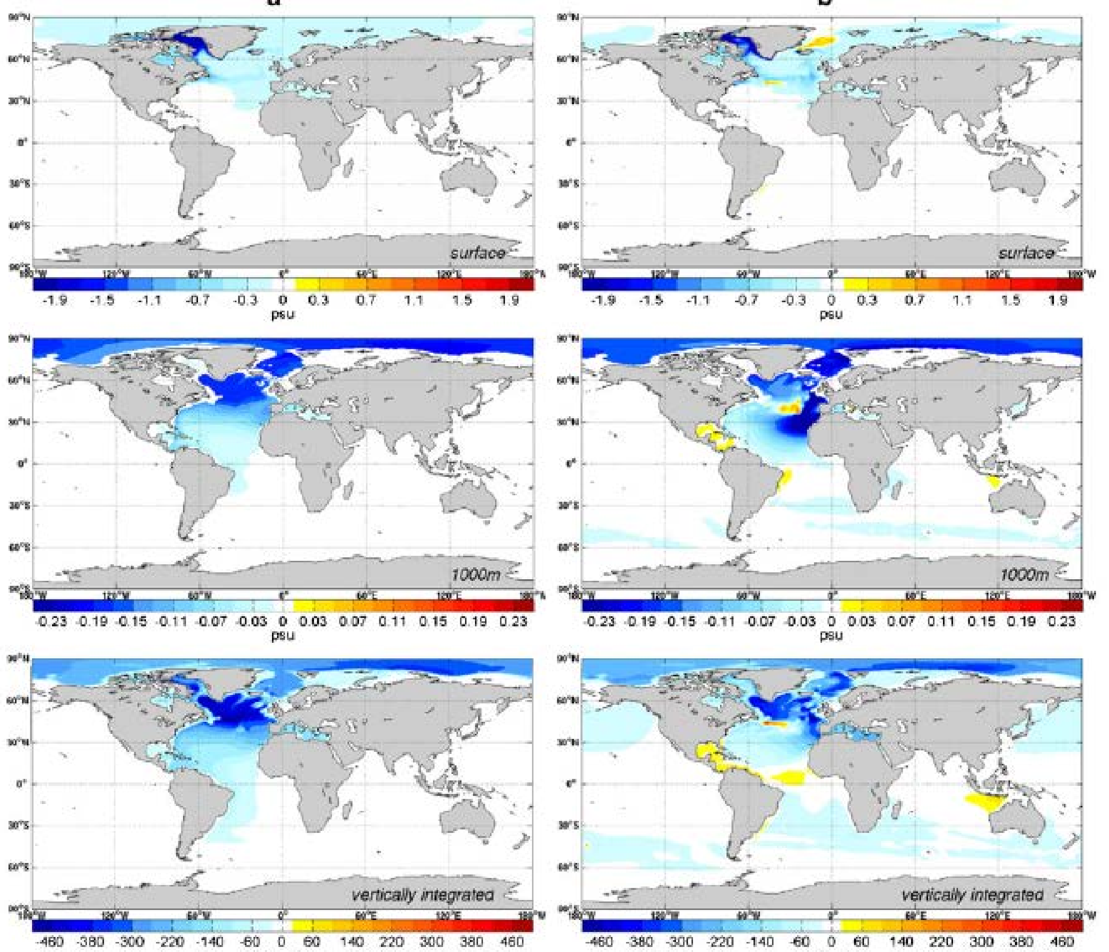
24 km Arctic mesh **9 km Arctic mesh**



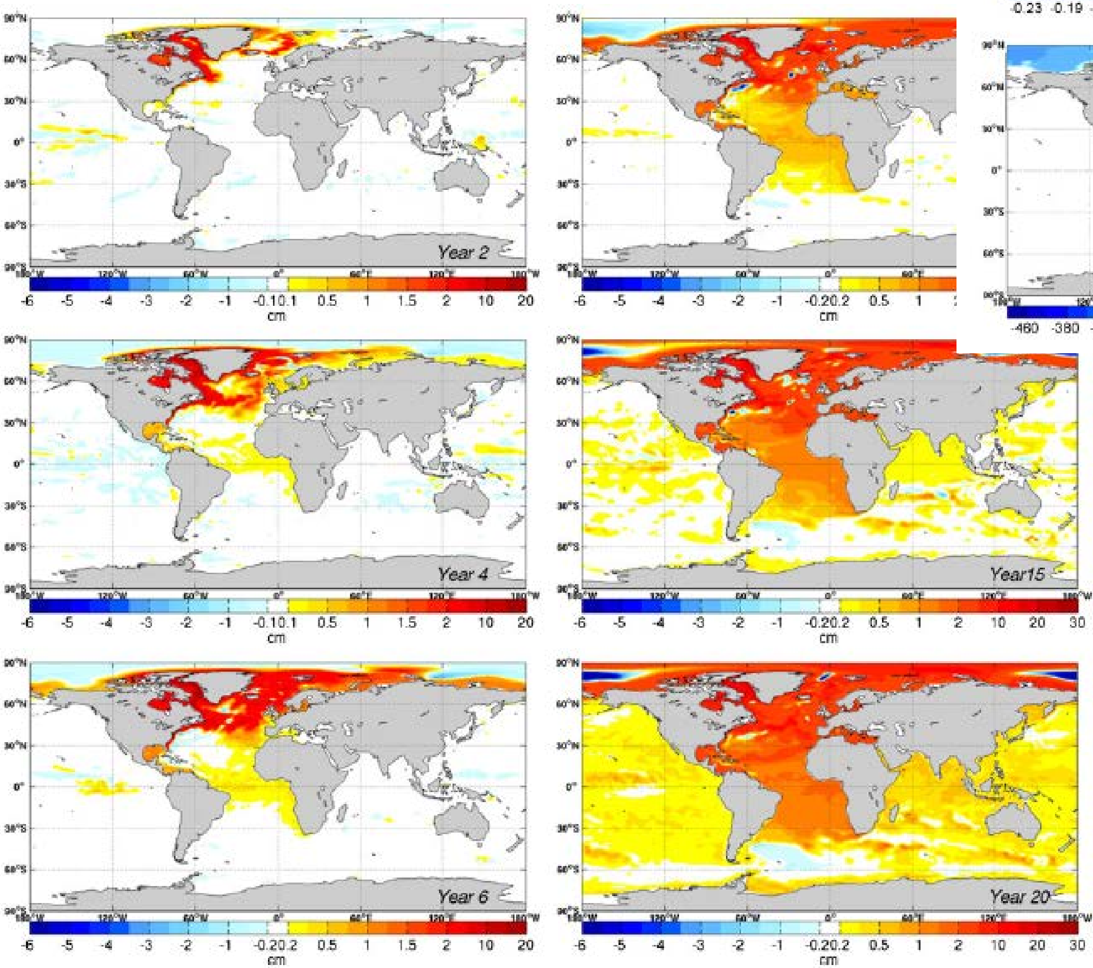
Shown is temperature at 300 m.
Questions: the role of different gates and lateral eddy mixing
X. Wang, Ph.D thesis

Impact of Greenland Ice Sheet Melting
(X. Wang et al., 2012)

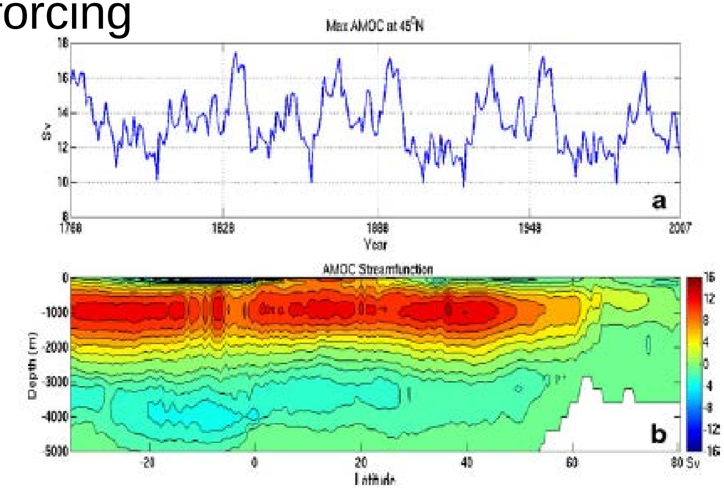
Salinity (right column) and passive tracer anomalies(GIS melting-control)=>



The development of ssh anomaly with time (GIS melting-control)



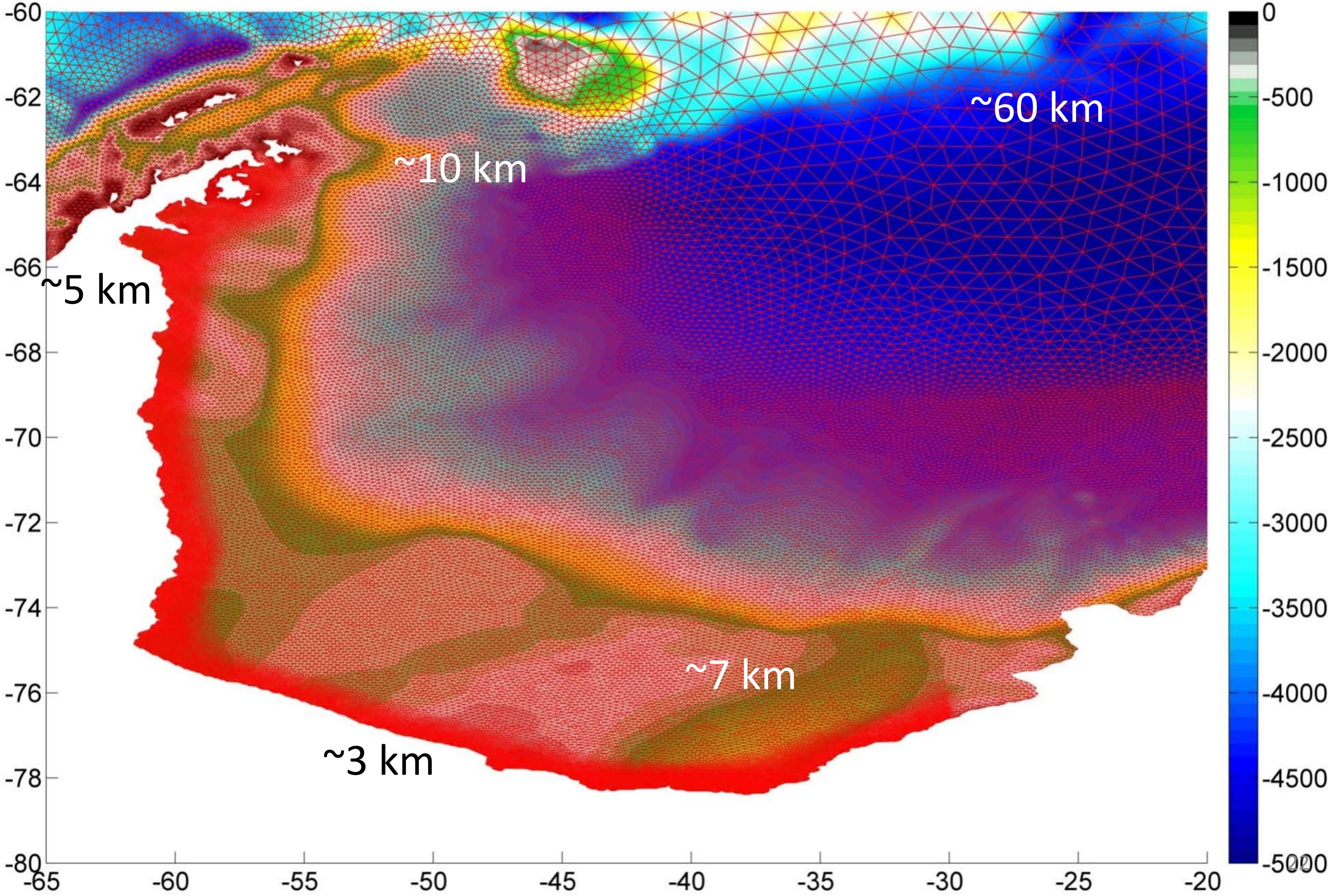
Control run: 4 cycles of 60-year CORE forcing



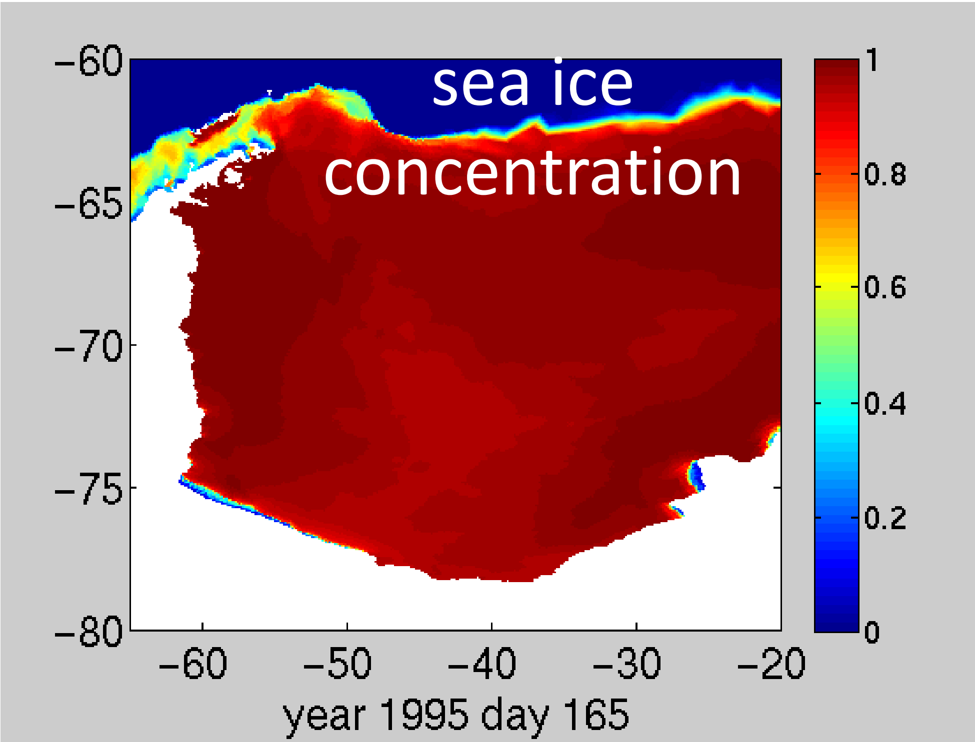
FESOM (*Finite Element Sea-ice Ocean Model*)

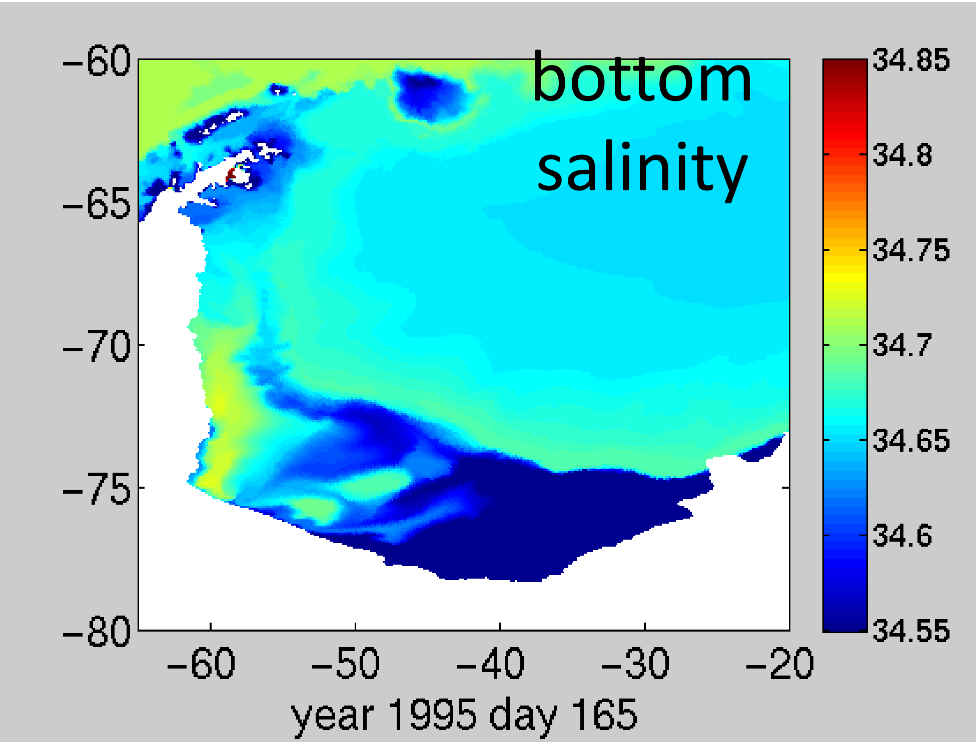
Weddell Sea Polynya

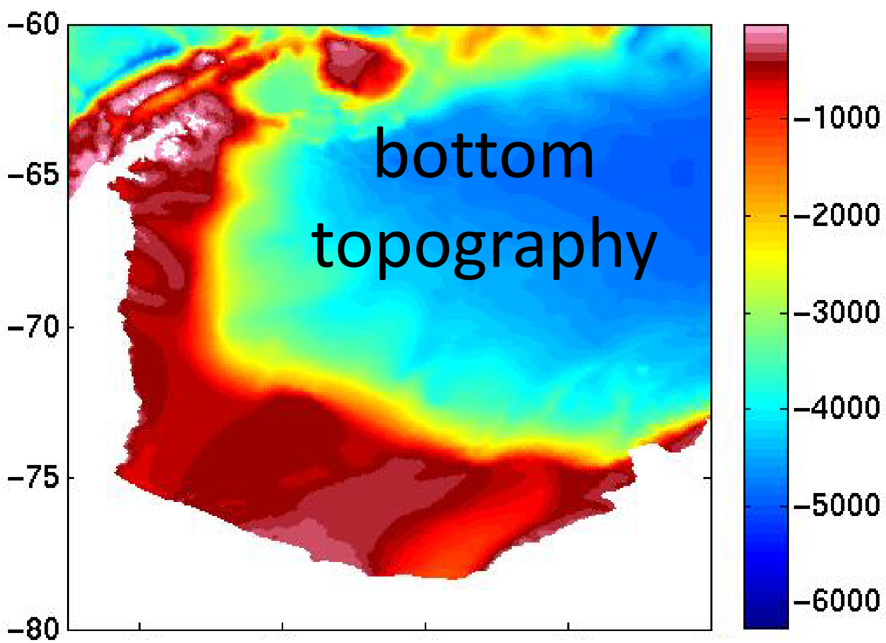
PhD thesis, V. Haid; V. Haid et al. 2013



FESOM *(Finite Element Sea-ice Ocean Model)*



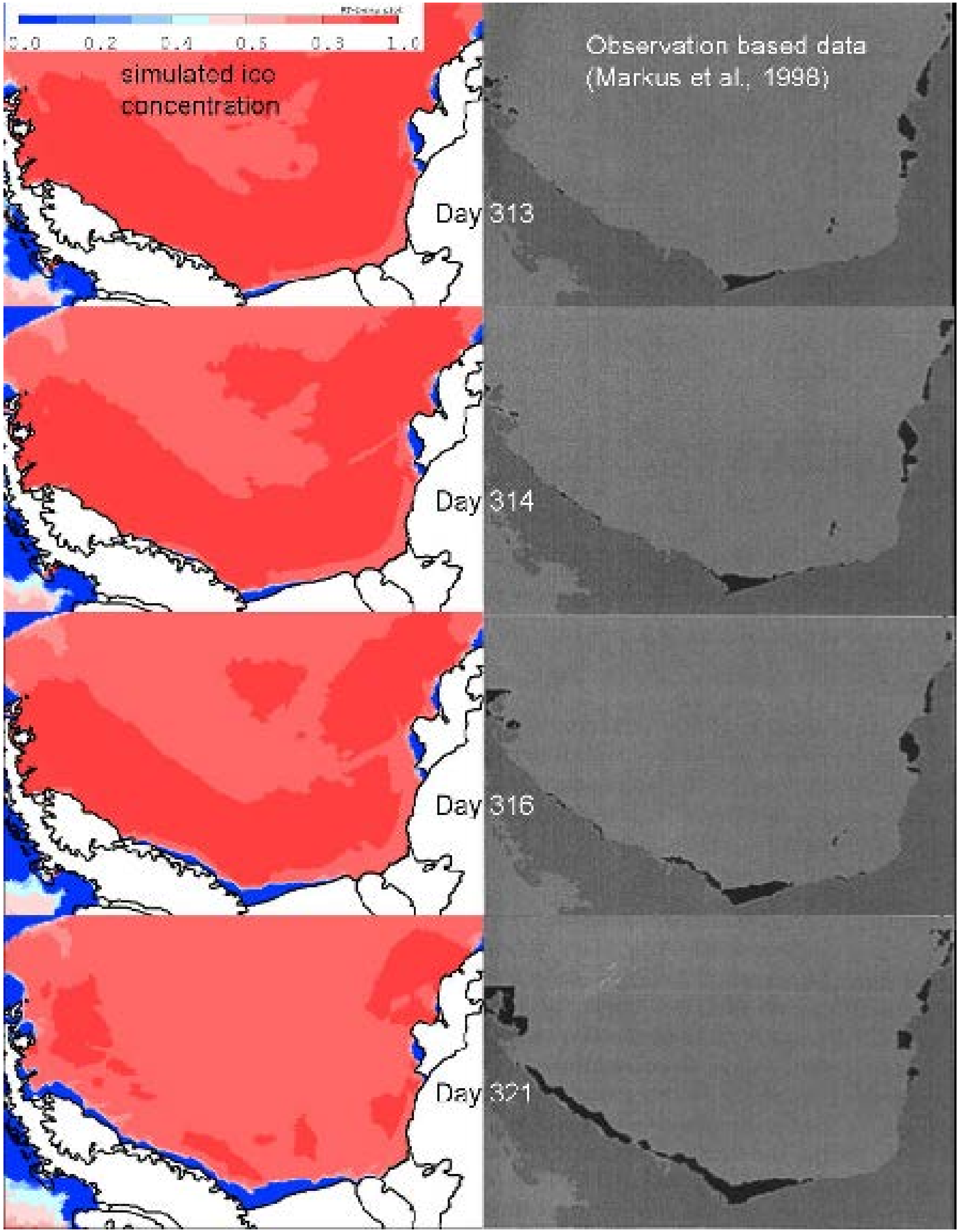




Increased ice production in polynias leads to salt rejection and deep water formation.

Covering 0.6% of the area polynias contribute 11% to ice volume

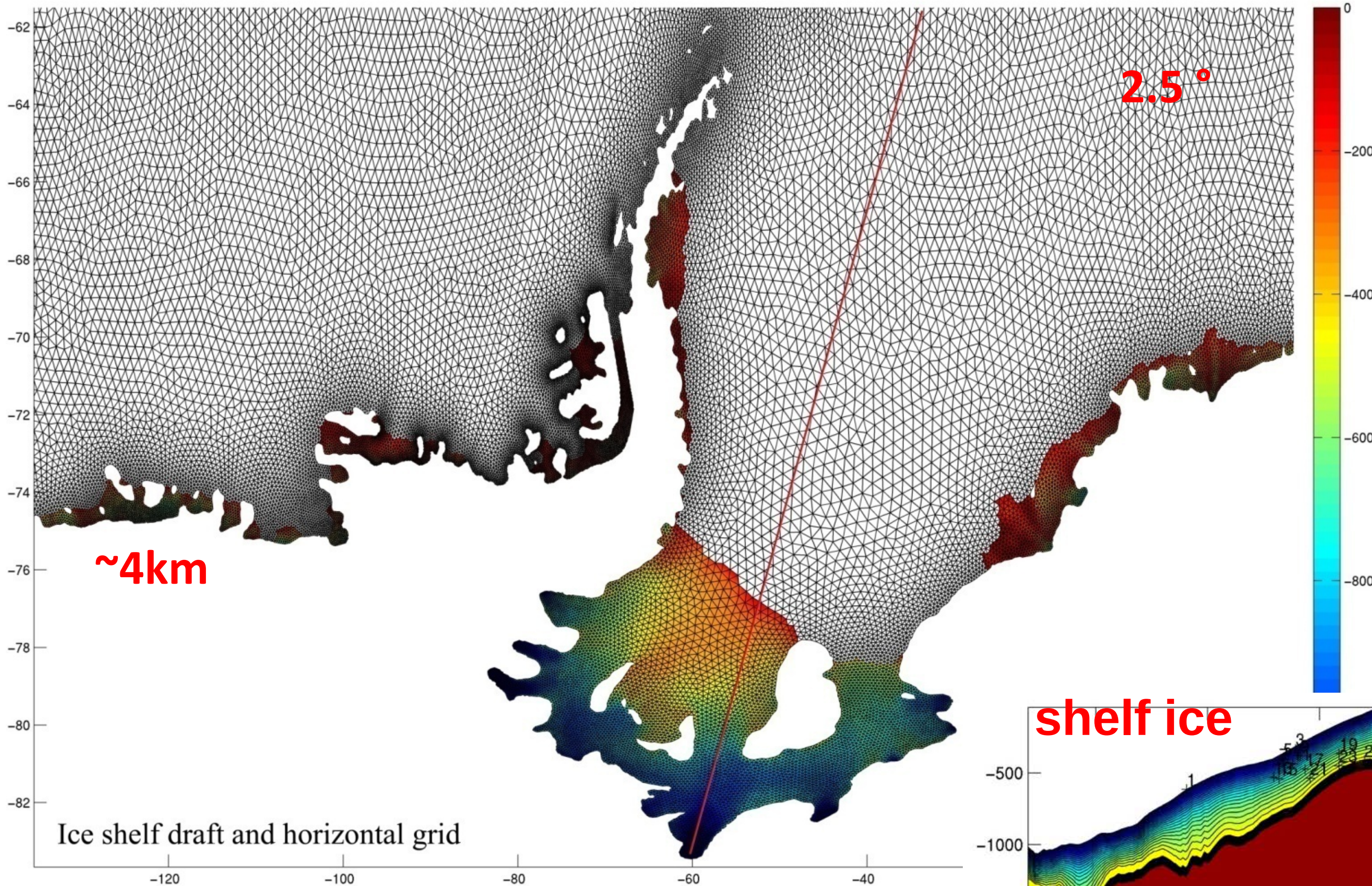
FESOM (*Finite Element Sea-ice Ocean Model*)



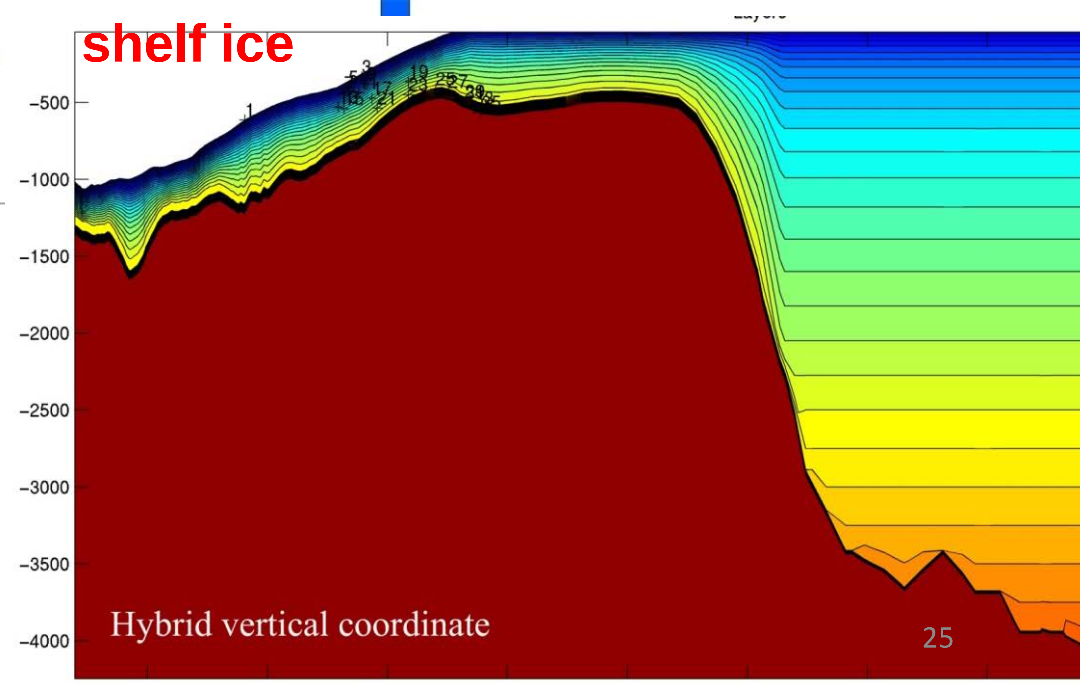
Ice concentration:

simulations vs. observations

Ice Shelf Modeling



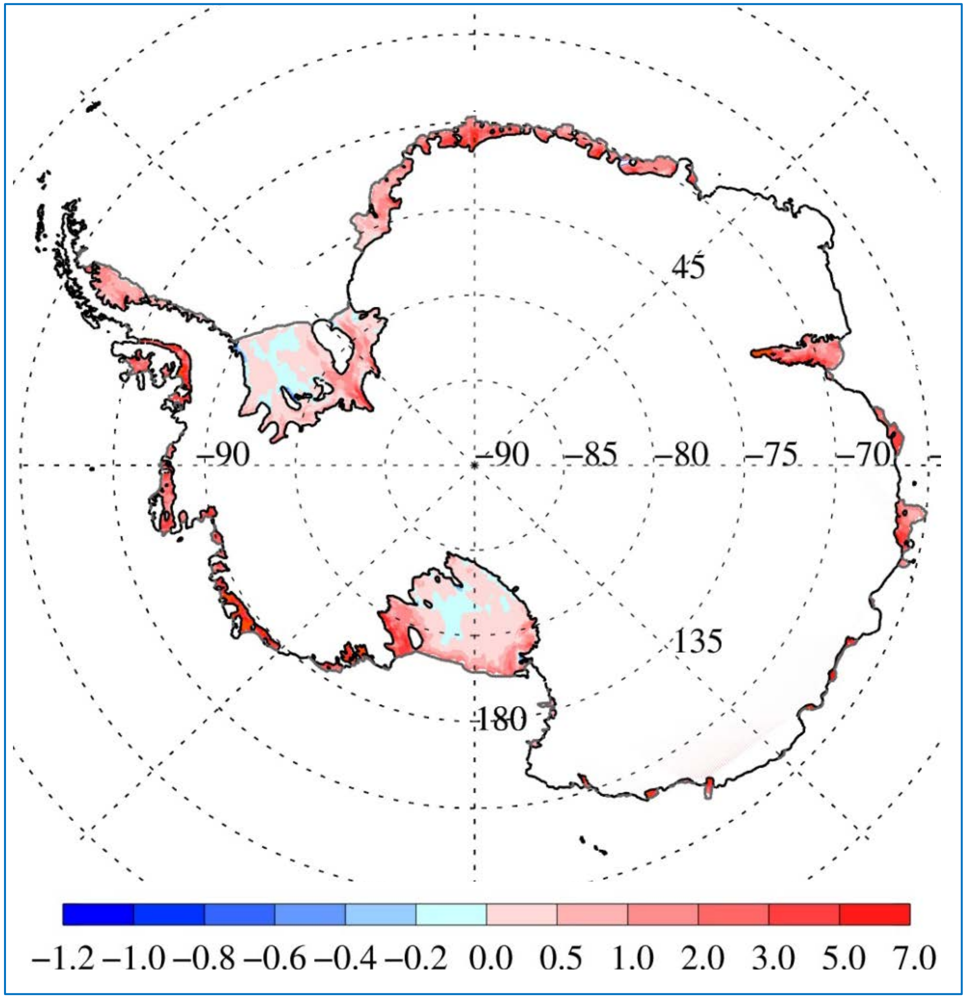
Goals:
- rate of ice mass loss
- under ice-shelf processes
- improve projections of the contribution of ice to future sea-level rise (Ice2sea EU project)



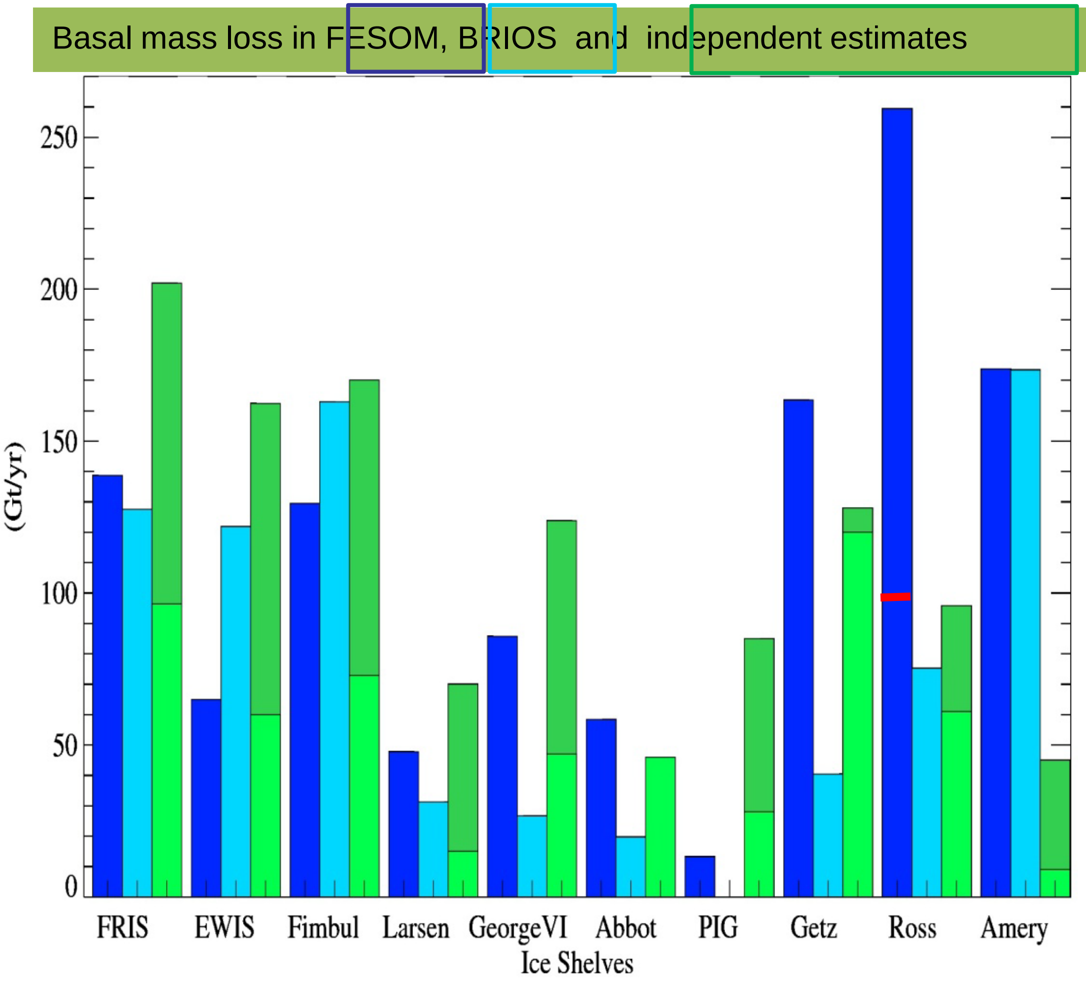
Timmermann et al. 2012 Ann.Glaciol.
Hellmer et al., 2012, Nature

Ice shelf-ocean interaction: Today

Validation“ simulations forced with NCEP data: average 1990-1999

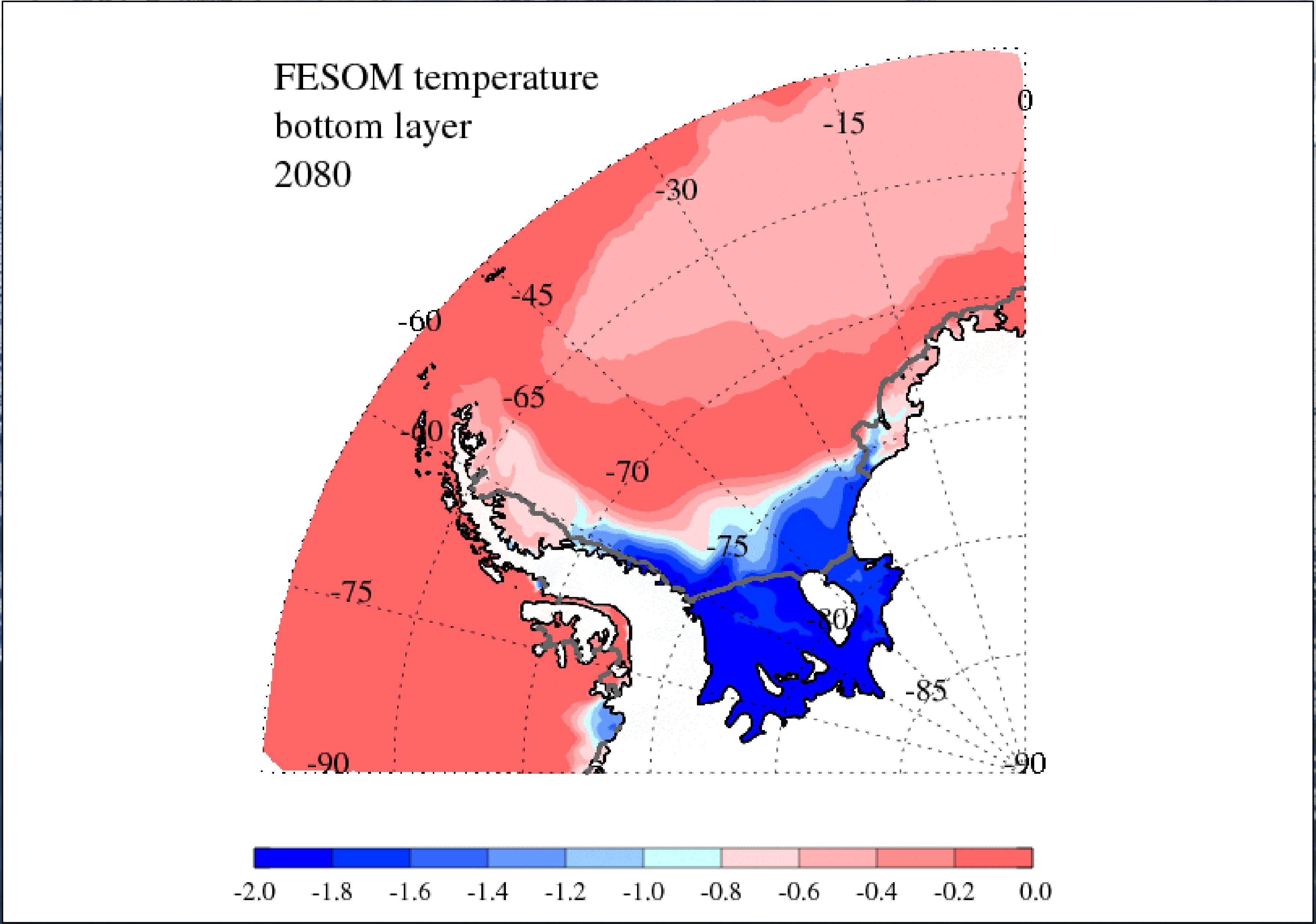


FESOM Sub-ice shelf basal melt rate (10-yr mean)

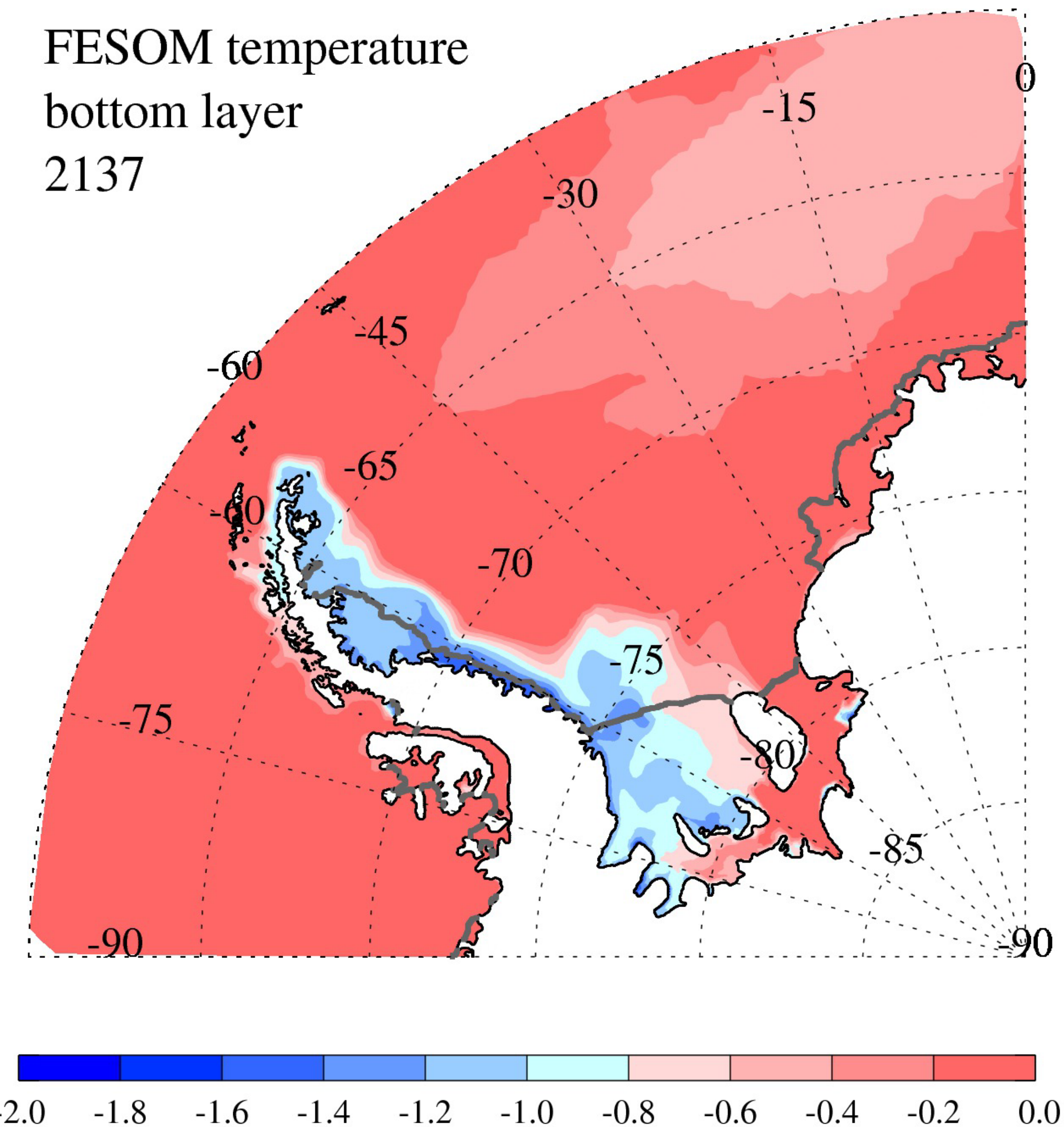


Basal mass loss for ten larger ice shelves

WDW in FRIS cavity

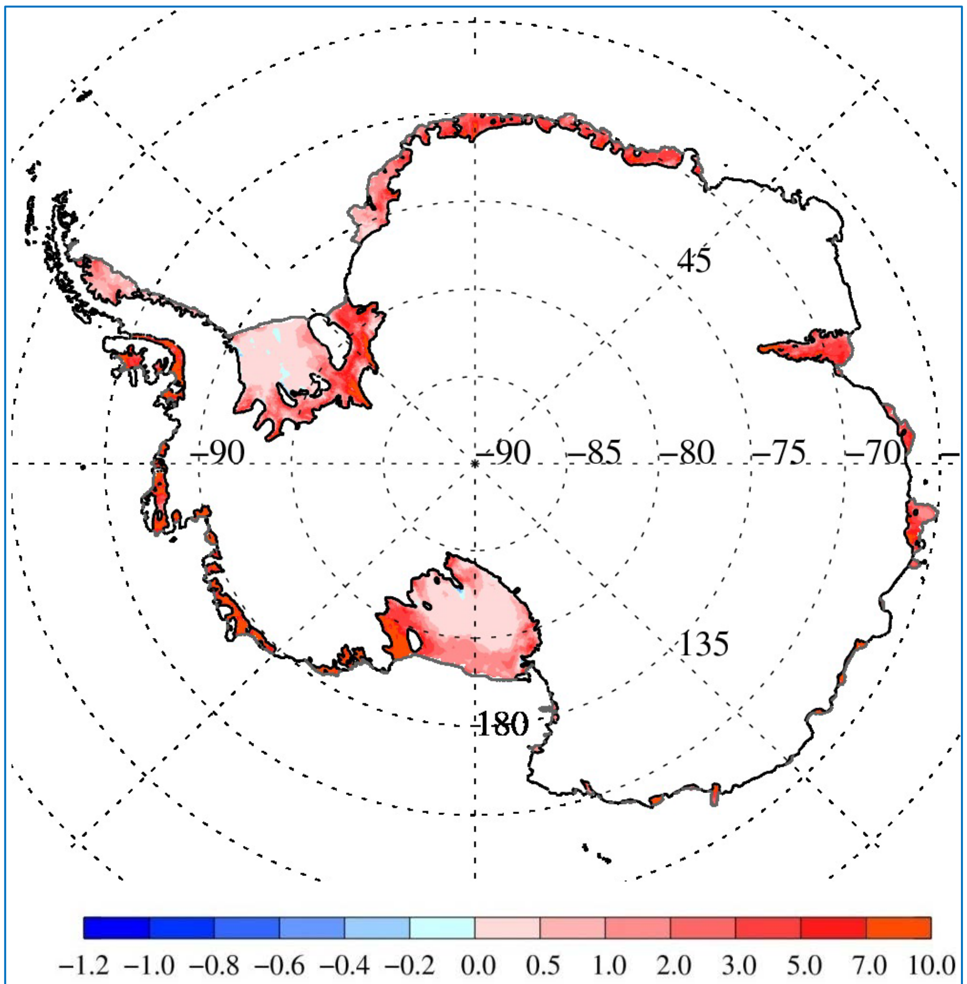


WDW in FRIS cavity

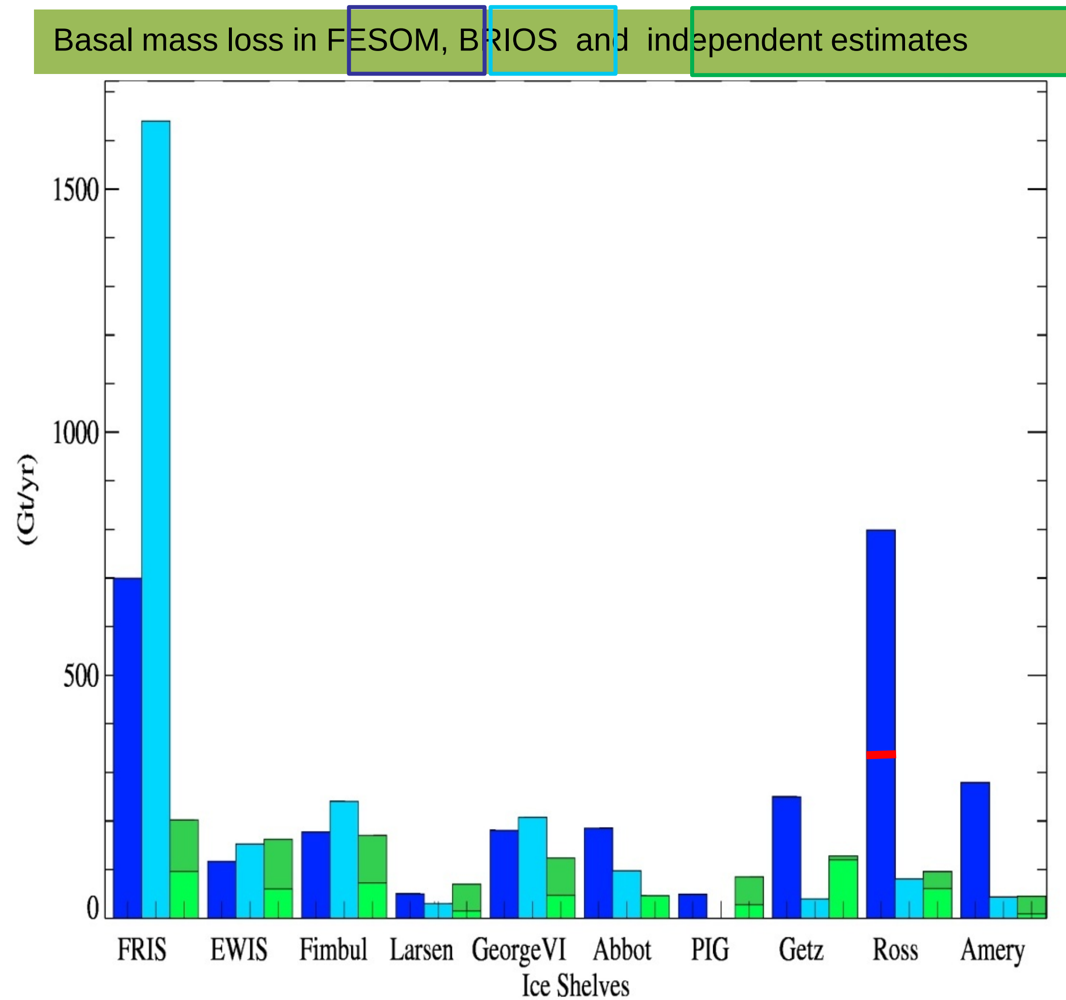


Ice shelf-ocean interaction: Projection

Simulations forced with HadCM3 A1B data: average 2121-2130

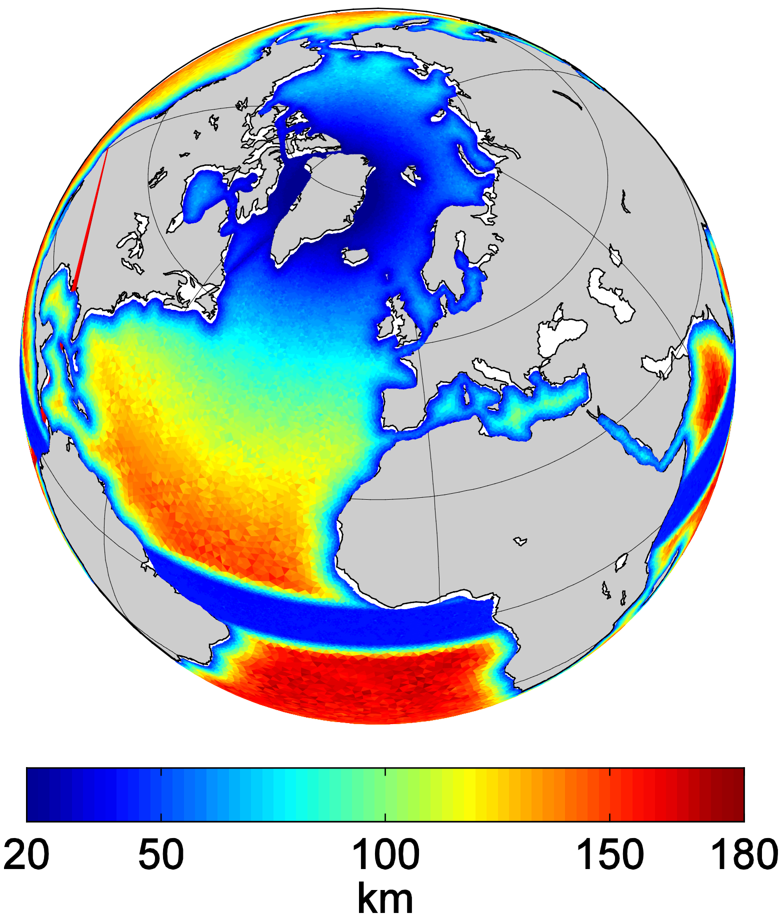


FESOM Sub-ice shelf basal melt rate (20-yr mean)



Basal mass loss for ten larger ice shelves

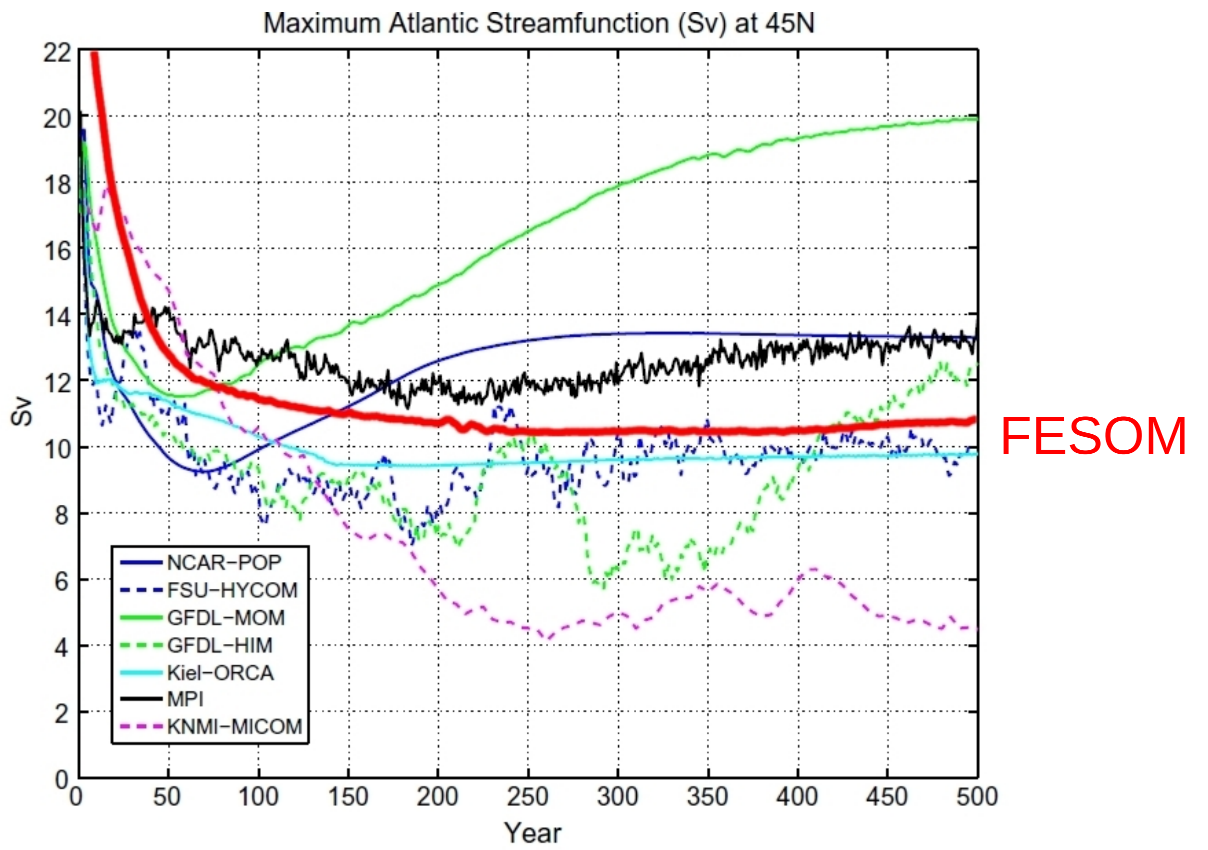
CORE-1 intercomparison (Griffies et al. 2009)
FESOM under 500 years of CORE-1 forcing (Sidorenko et al, 2011)



FESOM CORE mesh resolution

Goal: To demonstrate that FESOM reproduces an ocean state that is similar to other models used in climate research (NCAR-POP, MPI-OM, FSU-HYCOM, GFDL-MOM, GFDL-HIM, Kiel-ORCA, KNMI-MICOM)

AMOC at 45N

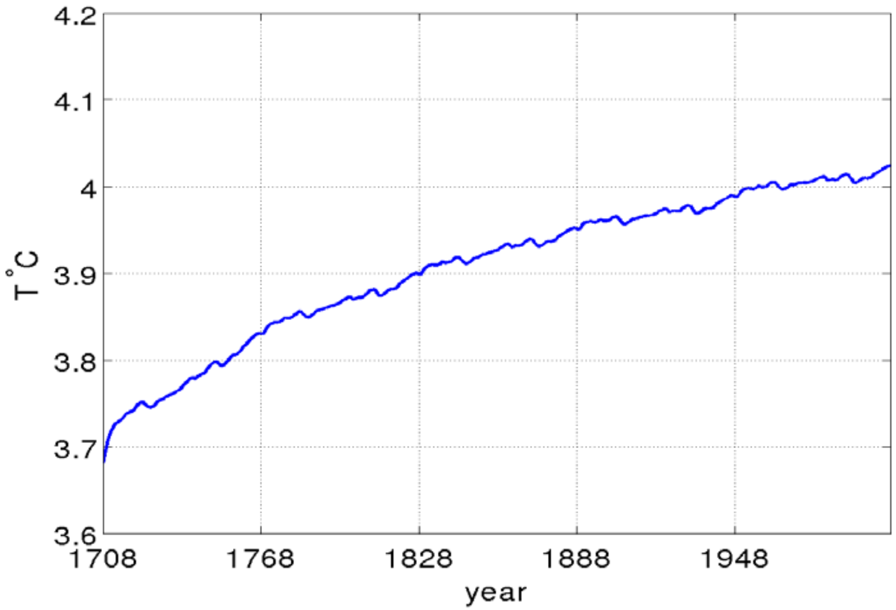


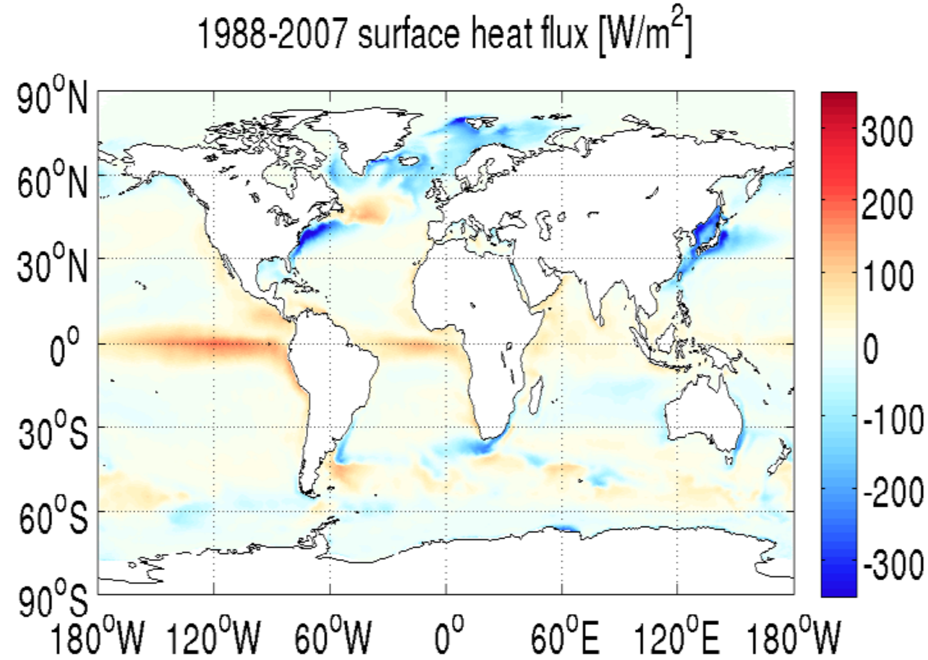
FESOM participates in CORE-II intercomparison project

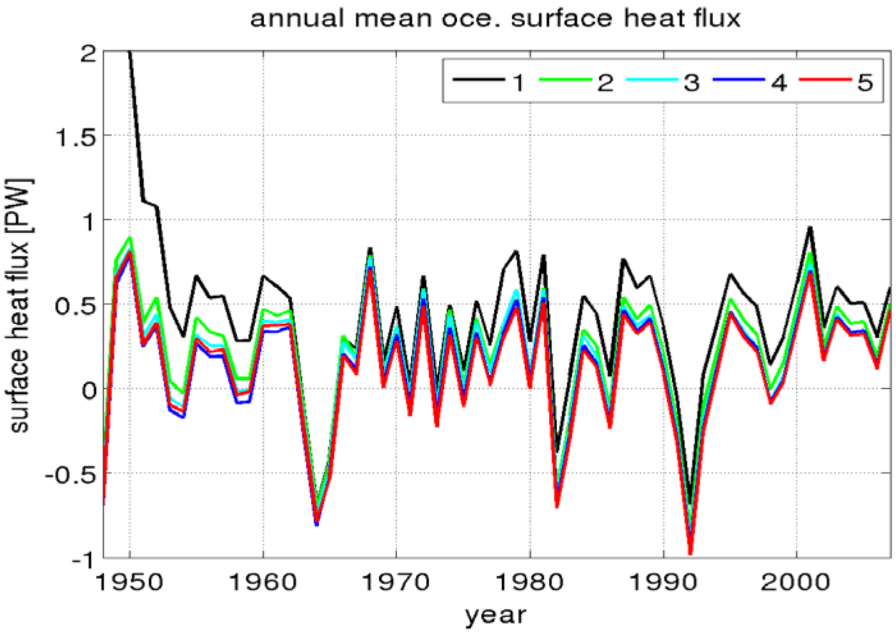
Protokol: 5 cycles of CORE-II forcing (1948-2007),

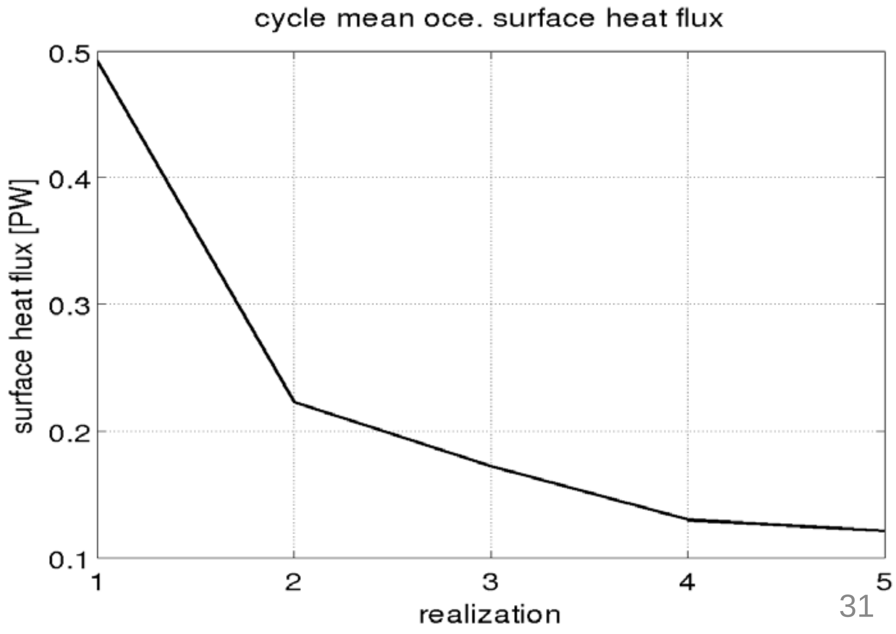
The goal: Learn how models reproduce variability

Global mean T

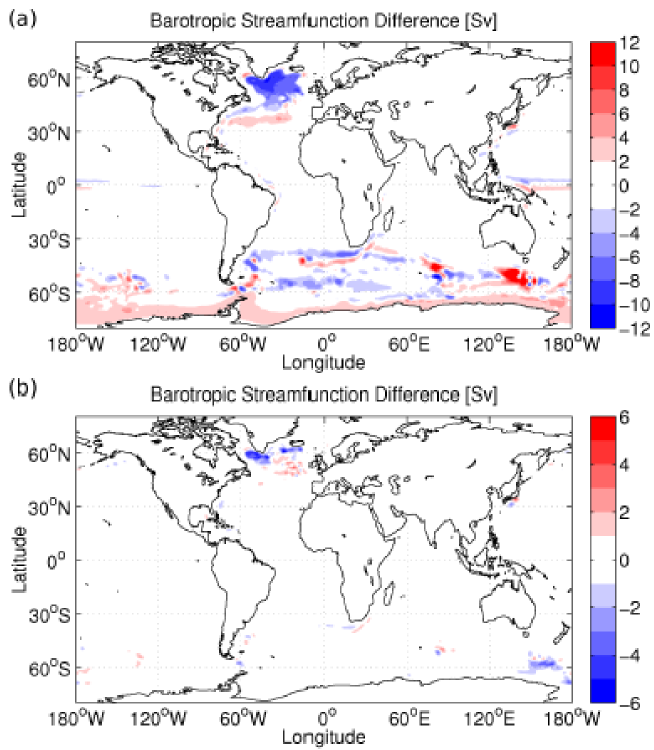








Systematic study of the effects of parameterizations, geometry, etc. Q. Wang, 2013



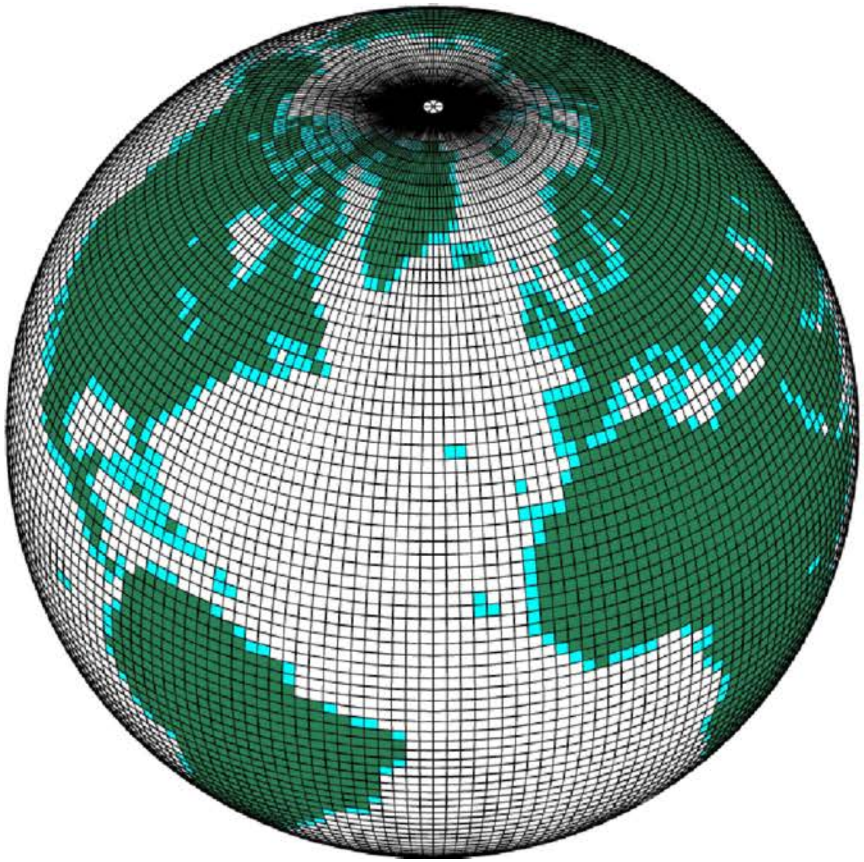
Question: How to parameterize subgrid processes on unstructured meshes?

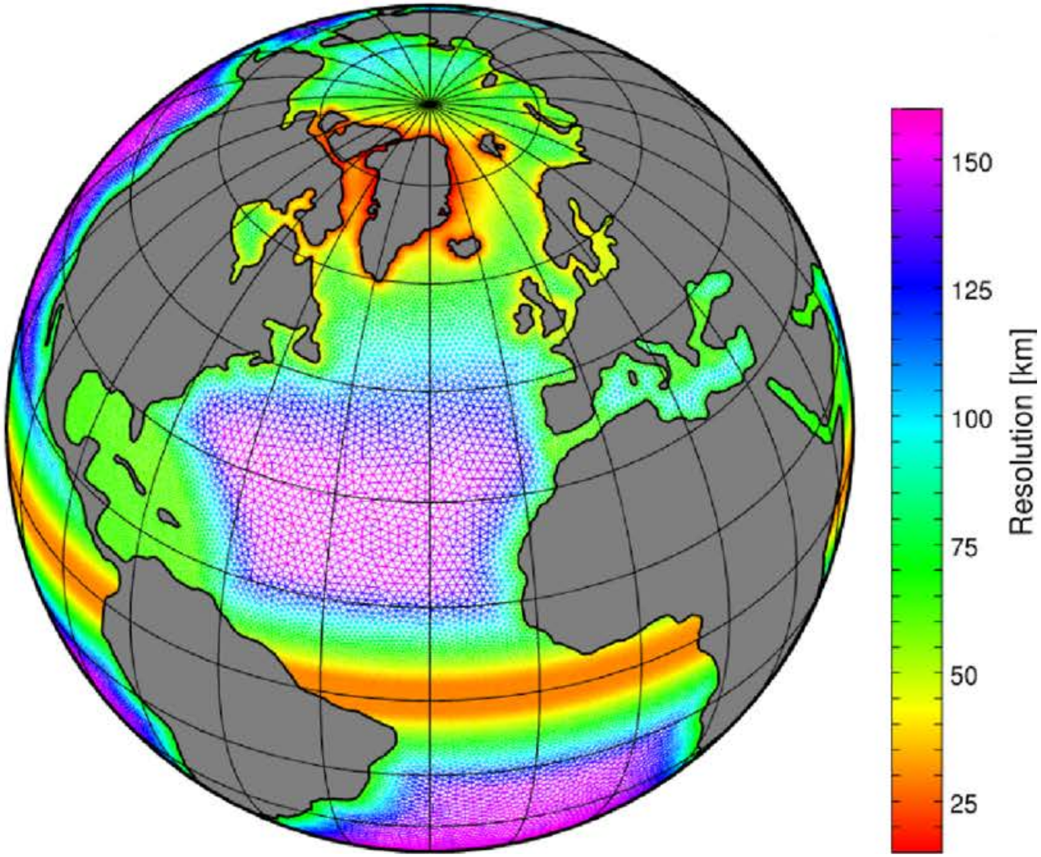
We are learning about consequences, but systematic studies are required.

top: Biharmonic Smagorinsky-Laplacian
bottom: Bih.Smag. – Bih. cubic-scaled

FESOM / ECHAM6 coupled system

Sidorenko et al. 2013





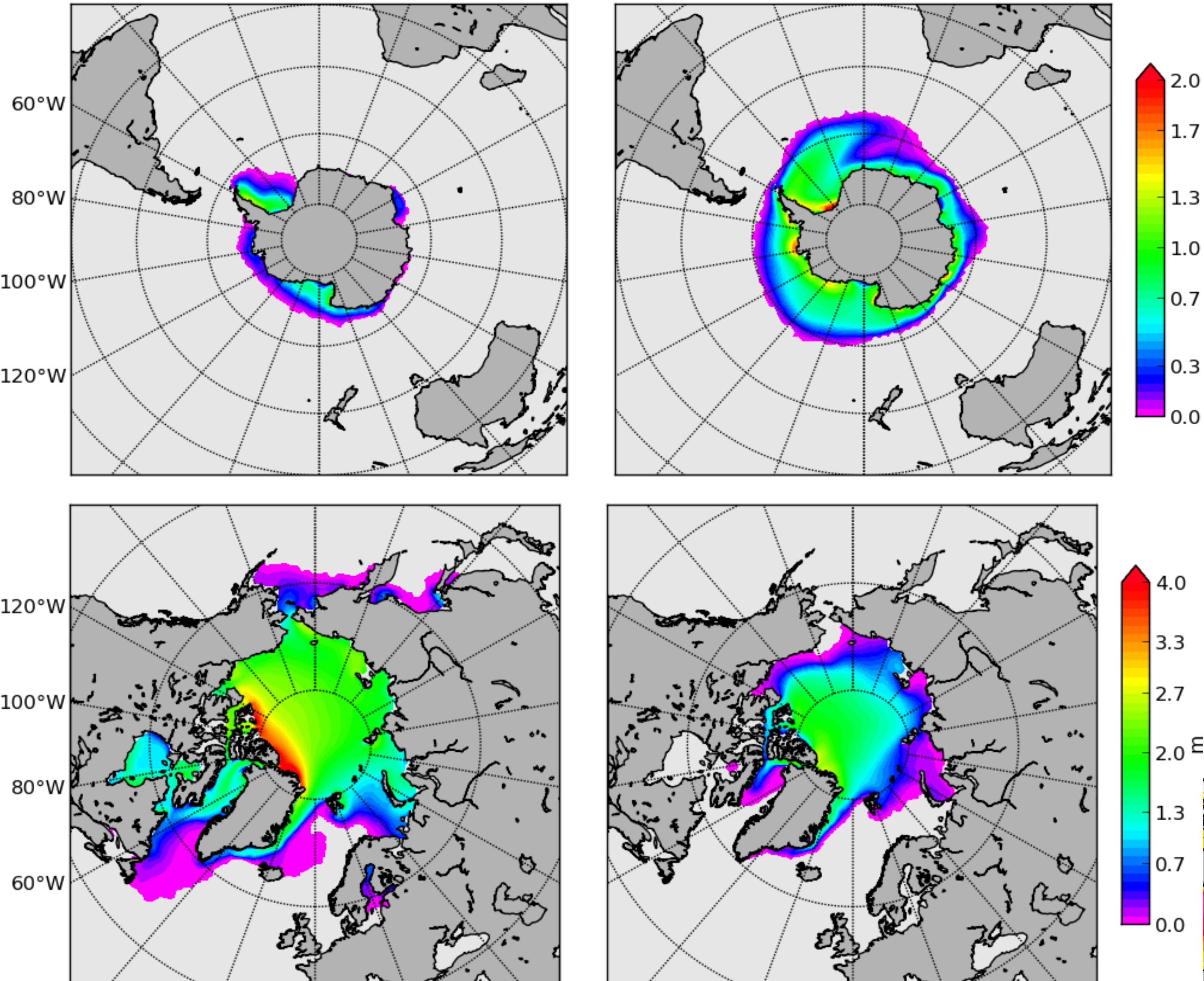
exchange grid

ECHAM6 → **FESOM**

Coupling is via OASIS3 MCT and auxiliary regular mesh

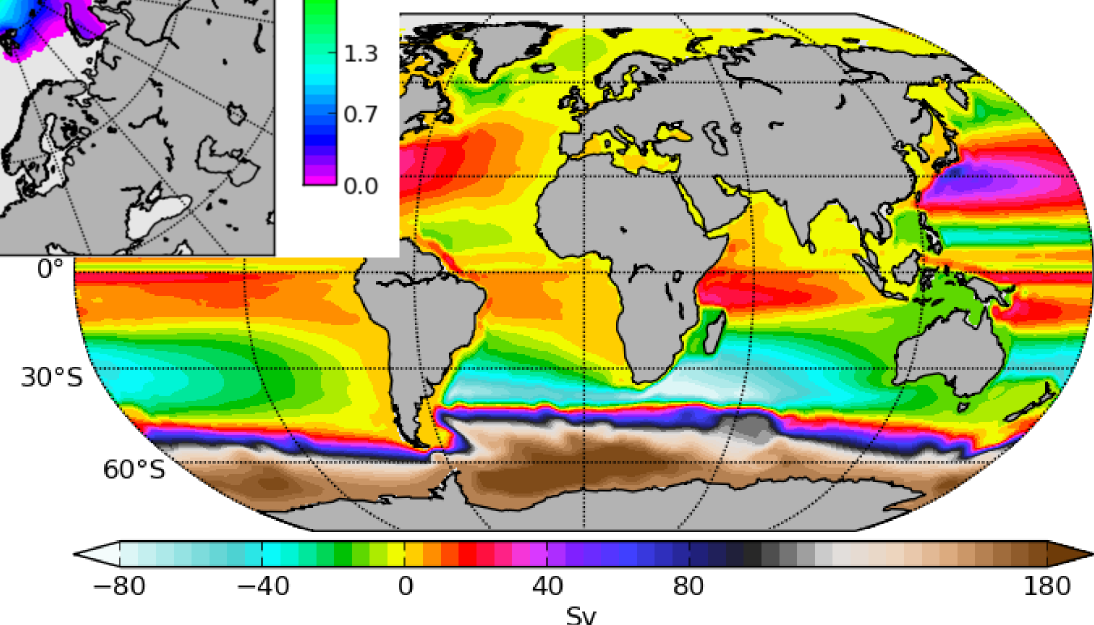
Coupled ECHAM6-FESOM simulations

Ice thickness in Southern and Northern Hemispheres, after 400 years of integration



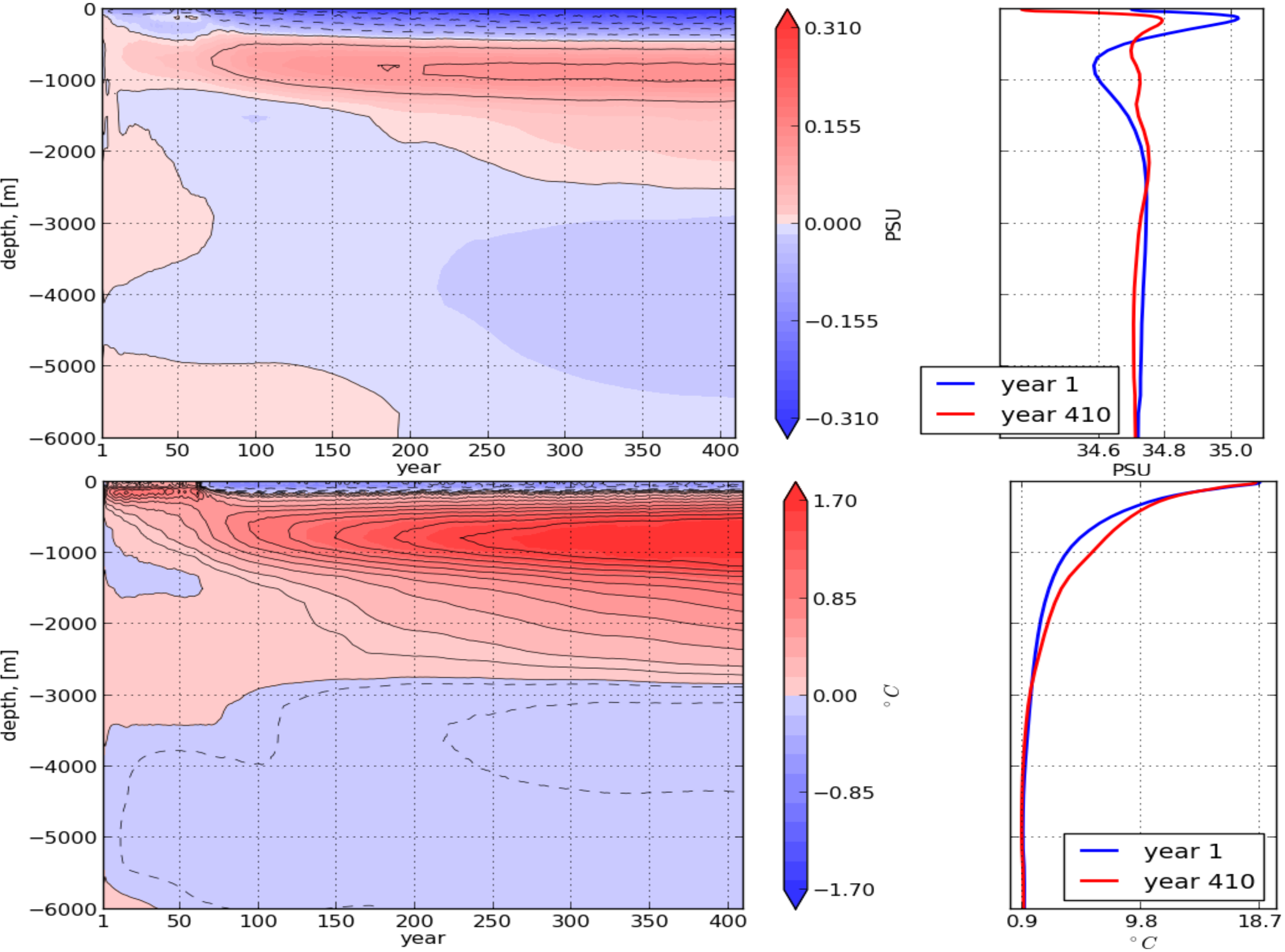
March | September

Mean barotropic streamfunction

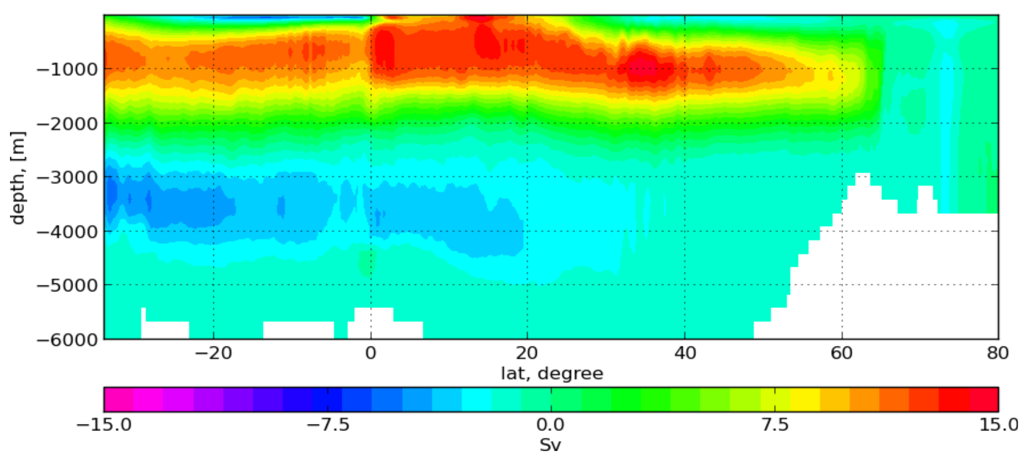


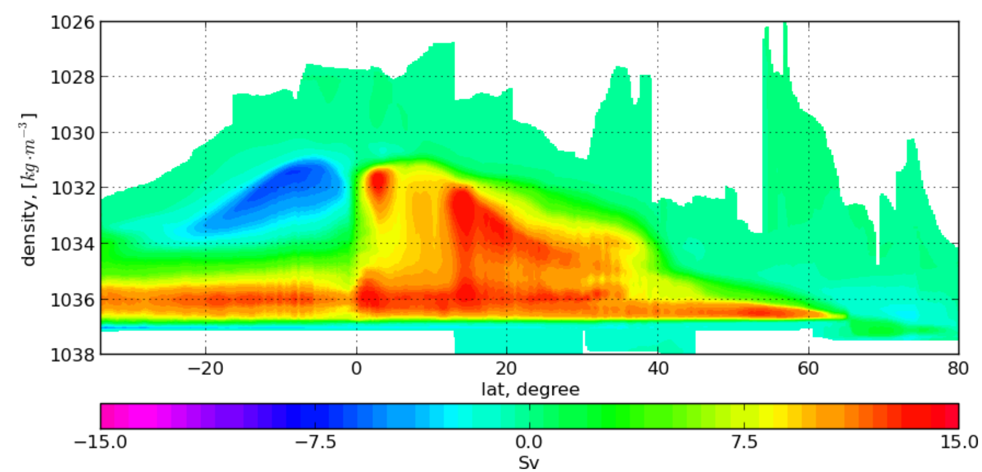
Coupled ECHAM6-FESOM simulations

Mean salinity and temperature drift



Atlantic MOC in z and density coordinates





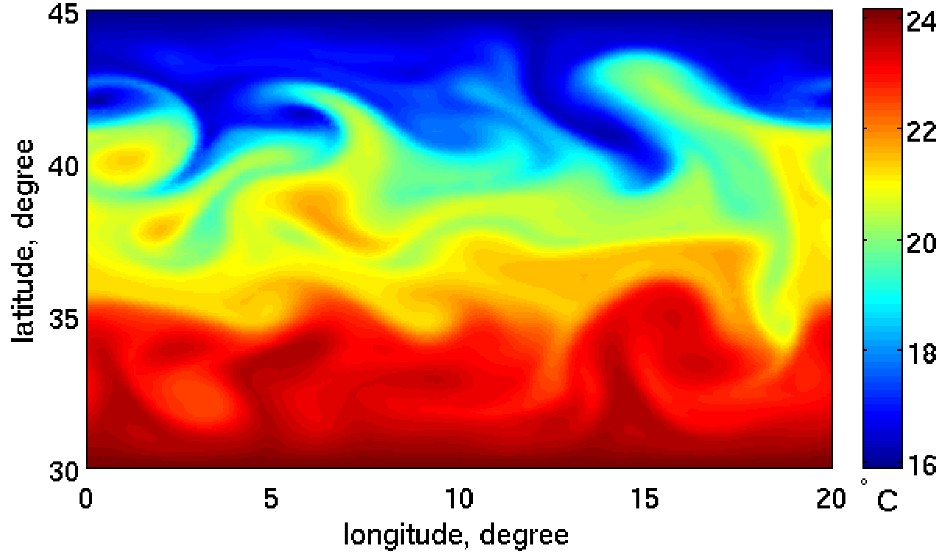
Challenges:

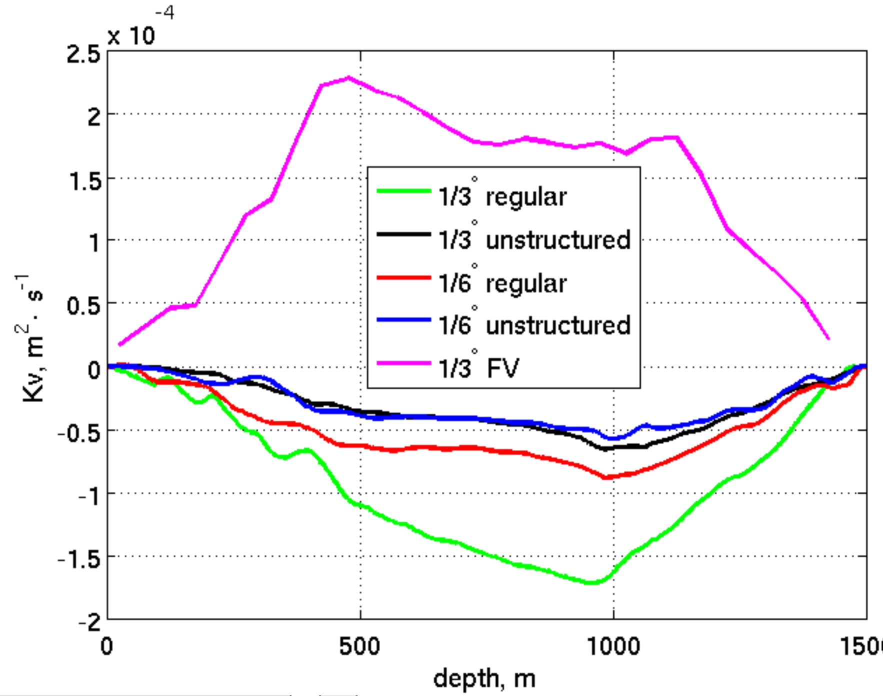
1. High-accuracy advection schemes, the analysis of spurious diapycnal numerical mixing associated with them on unstructured meshes. It is tightly linked to the behavior of velocities on the mesh scale.

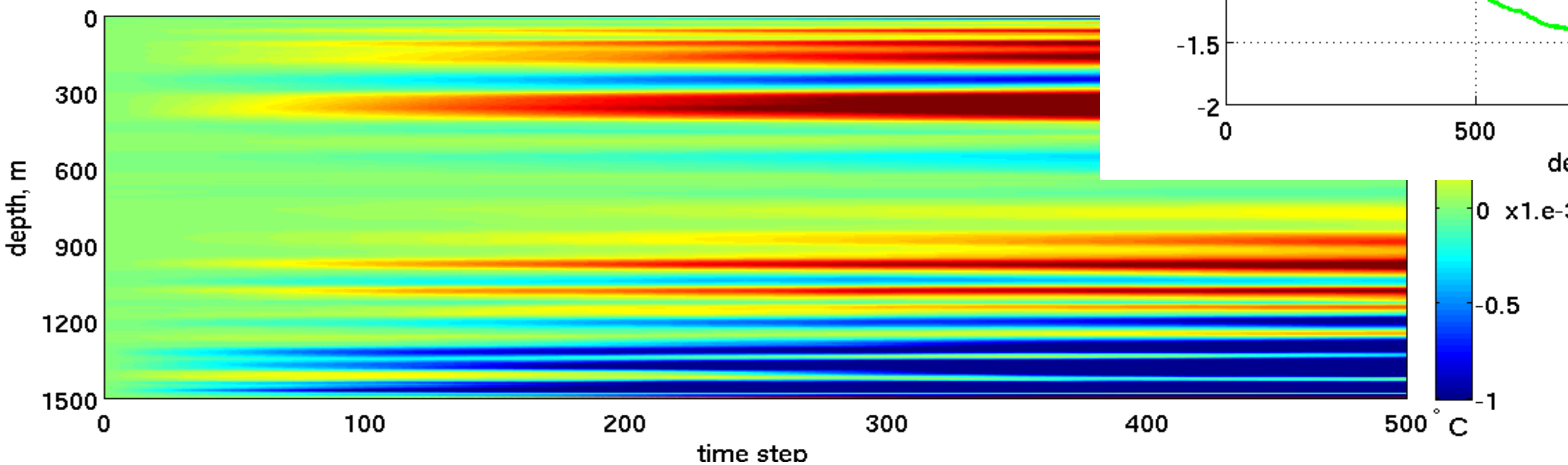
2. Numerical efficiency --- Finite volumes vs. Finite elements

3. Physical aspects of coupling to (as a rule) coarser and regular atmosphere

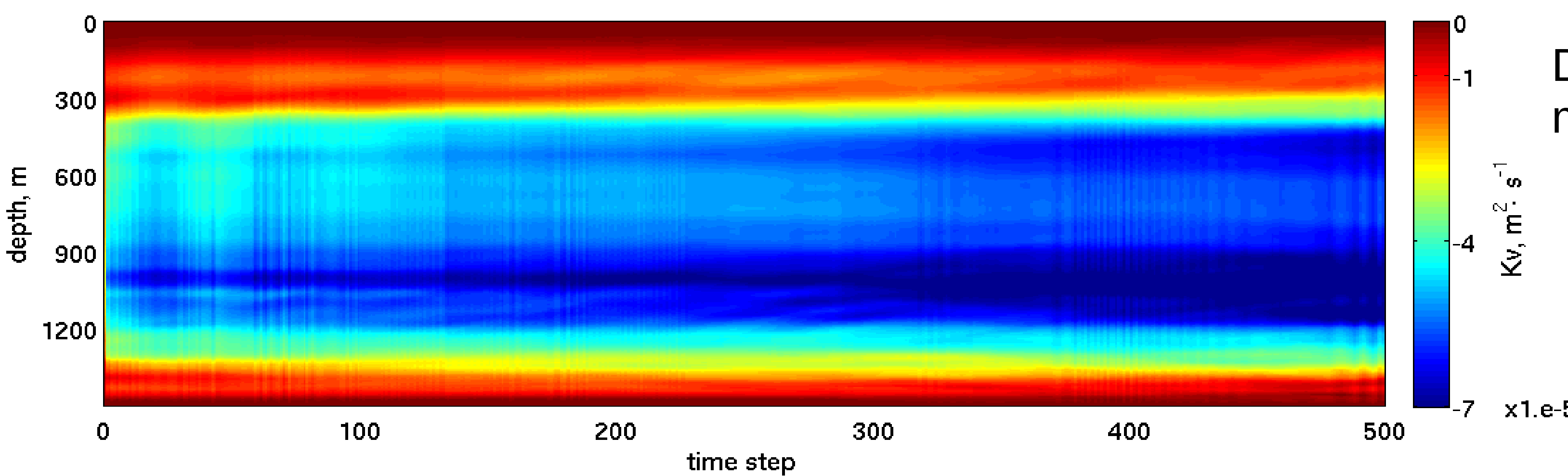
Spurious diapycnal mixing of FESOM FCT







Sorted temperature anomaly

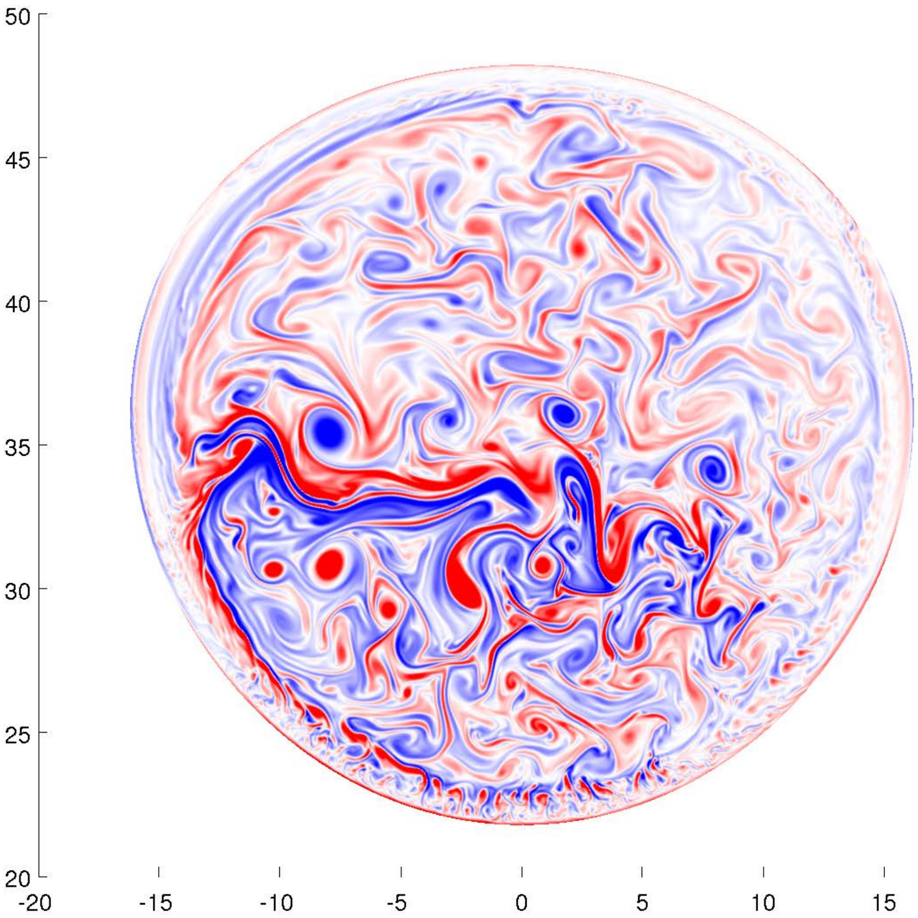


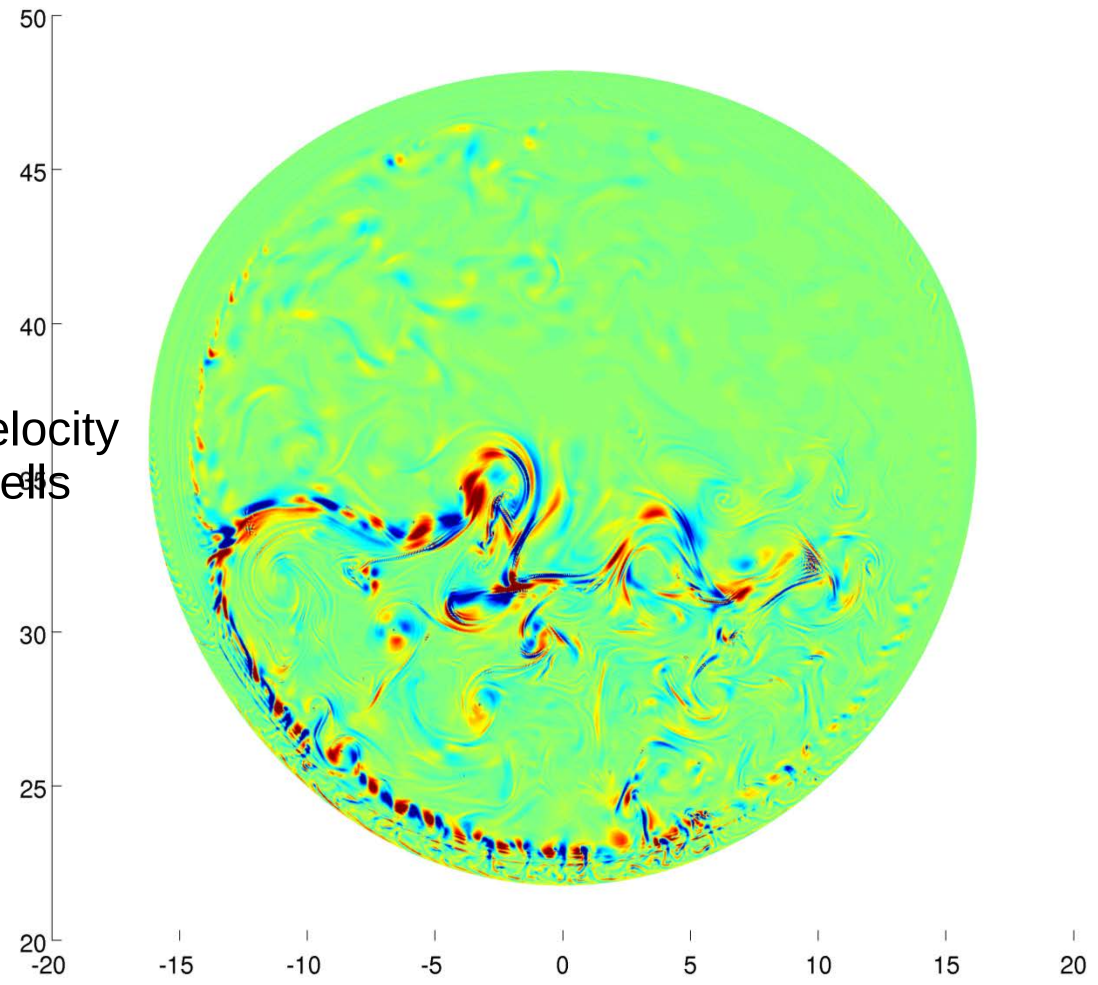
Diagnosed diapycnal mixing

SOMA test case (together with MPAS)
hex-C-grid MPAS
cell-vertex FV code AWI

Wind-driven circulation in a stratified
fluid, resolution 32:16:8:4 km, 40 layers,
in a basin of approx. 2500 km in diameter

Snapshots of relative vorticity and vertical velocity
after 10 years, 4 km resolution, about 40M cells





Conclusions

Nesting offered by multiresolution methods is valuable for large-scale ocean modeling.

Numerical efficiency of unstructured-mesh codes matters, but one can already use them rather efficiently. New FV codes (new core at AWI and MPAS) promise to make multiresolution models even more relevant.

Many questions still remain on the physical side, such as parameterizations or bottom representation. Coupling to a typically coarser atmosphere is an issue too (up and downscaling, stochastic parameterization?)