Ocean Modeling with Adaptive REsolution (OMARE) – A New Multi-Scale Ocean Modeling Framework

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Virtual Presentation

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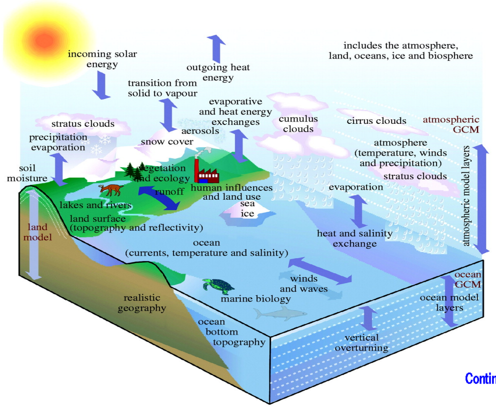
Status Quo:

- High-res. models simulates turbulent & (arguably) more realistic ocean dynamics
- Ocean & climate research frontiers calls for multi-scale capable & flexible models:
  - Sub-mesoscale, energy cycle & cascading, key regions (ice shelf, coastal, etc.), multi-physics
- Challenges to multiple disciplines: parameterization (scale-awareness), computatbility, etc.

Key Points:

- Adaptive mesh refinement (AMR) to support long-term model devel. & key scientific problems/applications
- **OMARE**: refactor **NEMO** with software middleware of **JASMIN**, with support for: ***AMR***, parallelization, I/O, etc.
- Laminar – eddy-rich – submesoscale-capable simulations w/ OMARE



Geofluid Dynamics

Mathematical Modeling & Numerics

Continuity: $\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0$

X – Momentum: $\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = -\frac{\partial p}{\partial x} + \frac{1}{Re_r}\left[\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z}\right]$

Y – Momentum: $\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho v^2)}{\partial y} + \frac{\partial(\rho vw)}{\partial z} = -\frac{\partial p}{\partial y} + \frac{1}{Re_r}\left[\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z}\right]$

Z – Momentum: $\frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho uw)}{\partial x} + \frac{\partial(\rho vw)}{\partial y} + \frac{\partial(\rho w^2)}{\partial z} = -\frac{\partial p}{\partial z} + \frac{1}{Re_r}\left[\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z}\right]$

Energy:

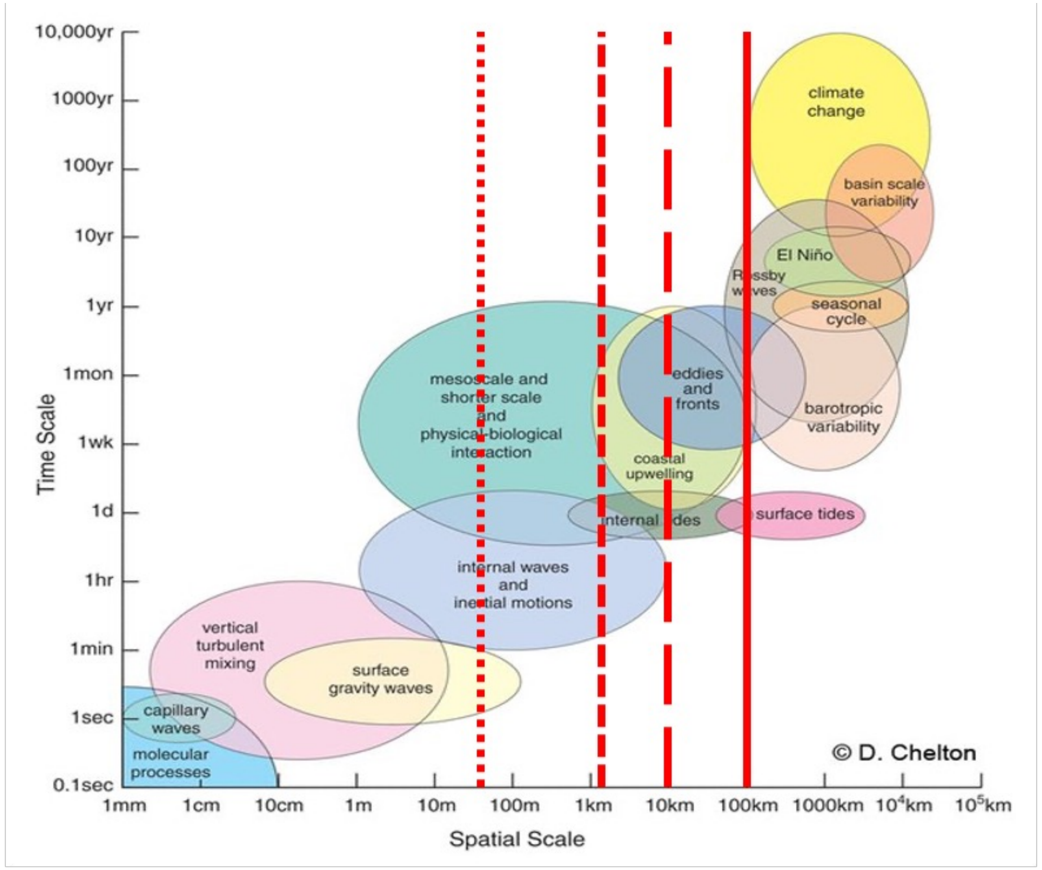
$$\frac{\partial(E_T)}{\partial t} + \frac{\partial(uE_T)}{\partial x} + \frac{\partial(vE_T)}{\partial y} + \frac{\partial(wE_T)}{\partial z} = -\frac{\partial(up)}{\partial x} - \frac{\partial(vp)}{\partial y} - \frac{\partial(wp)}{\partial z} - \frac{1}{Re_r Pr_r}\left[\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z}\right] + \frac{1}{Re_r}\left[\frac{\partial}{\partial x}(u\tau_{xx} + v\tau_{xy} + w\tau_{xz}) + \frac{\partial}{\partial y}(u\tau_{xy} + v\tau_{yy} + w\tau_{yz}) + \frac{\partial}{\partial z}(u\tau_{xz} + v\tau_{yz} + w\tau_{zz})\right]$$

Code Implementation & HPC

Multi-Scale Ocean Dynamic Processes

Challenges to High-Res. Models:

- Upscaling of small-scale processes, oceanic energy cycle & forward/backward cascading
- Scale-aware parameterization
- Looming future of multi-physics (non-hydrostatic, LES, etc.)
- High computational overhead, low time-to-solution



100km: climate models (i.e., CMIP)

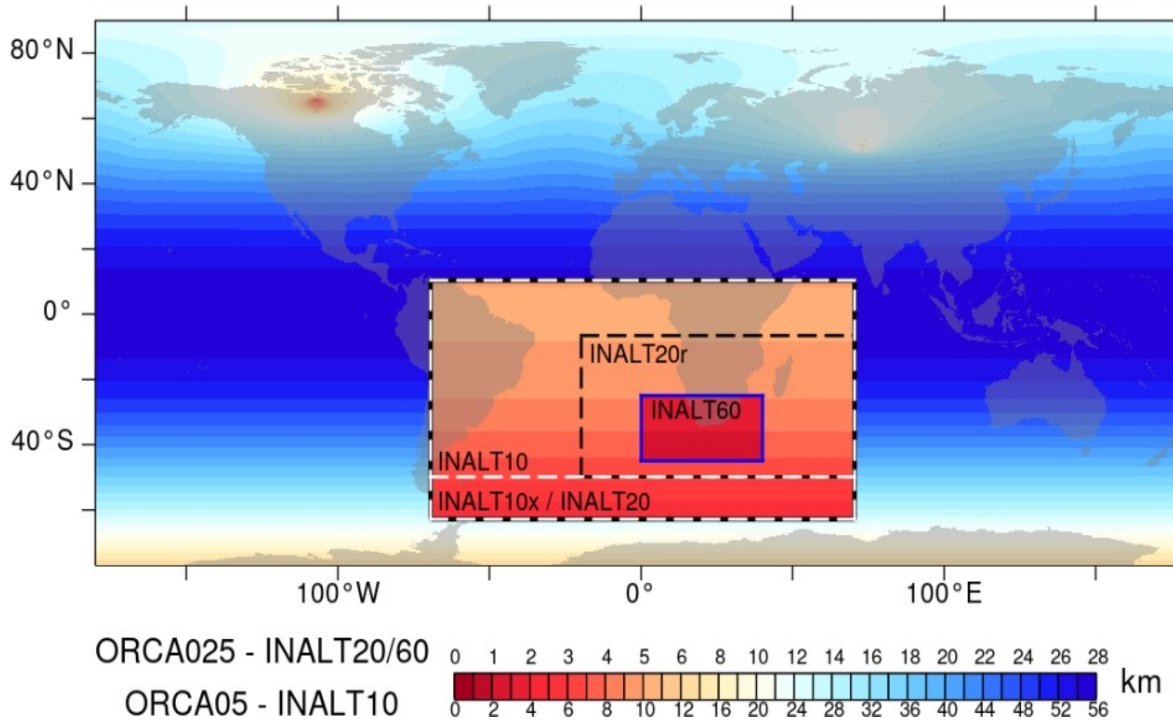
10~25km: eddy-rich / global operational

1~2km: submeso.-rich / state-of-the-art

<100m: LES, DNS

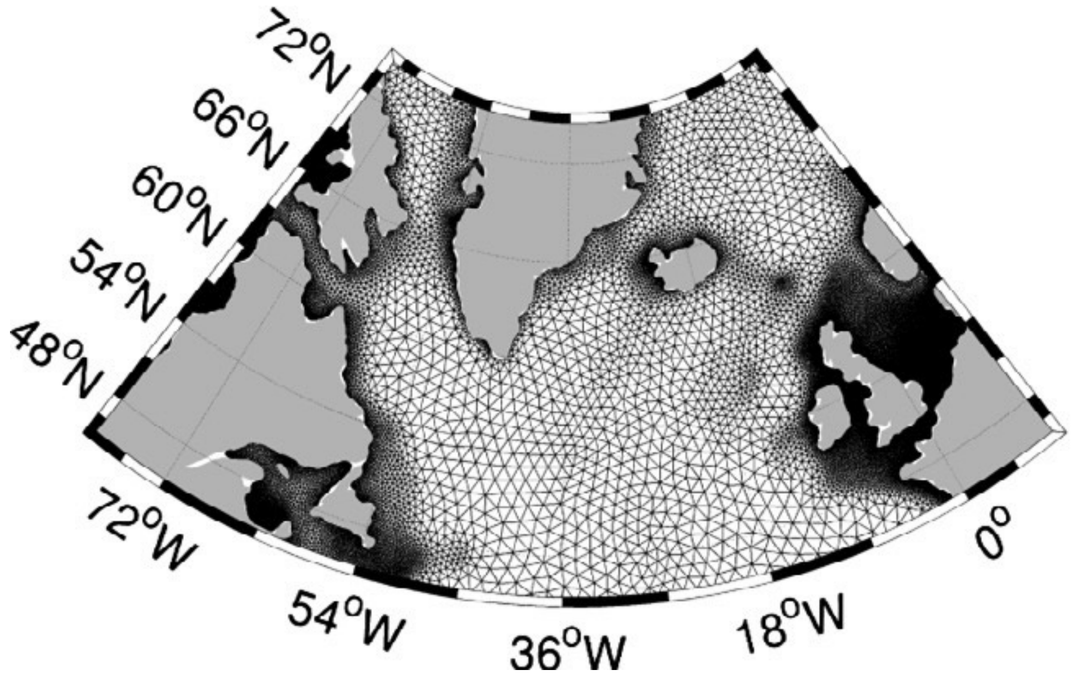
Two Typical Approaches to Multi-Res. Modeling

Nesting w/ Structured Grid
Traditional Finite-Difference, Finite-Volume



[Schwarzkopf et al., 2019]

Unstructured Grid
Finite-Element methods



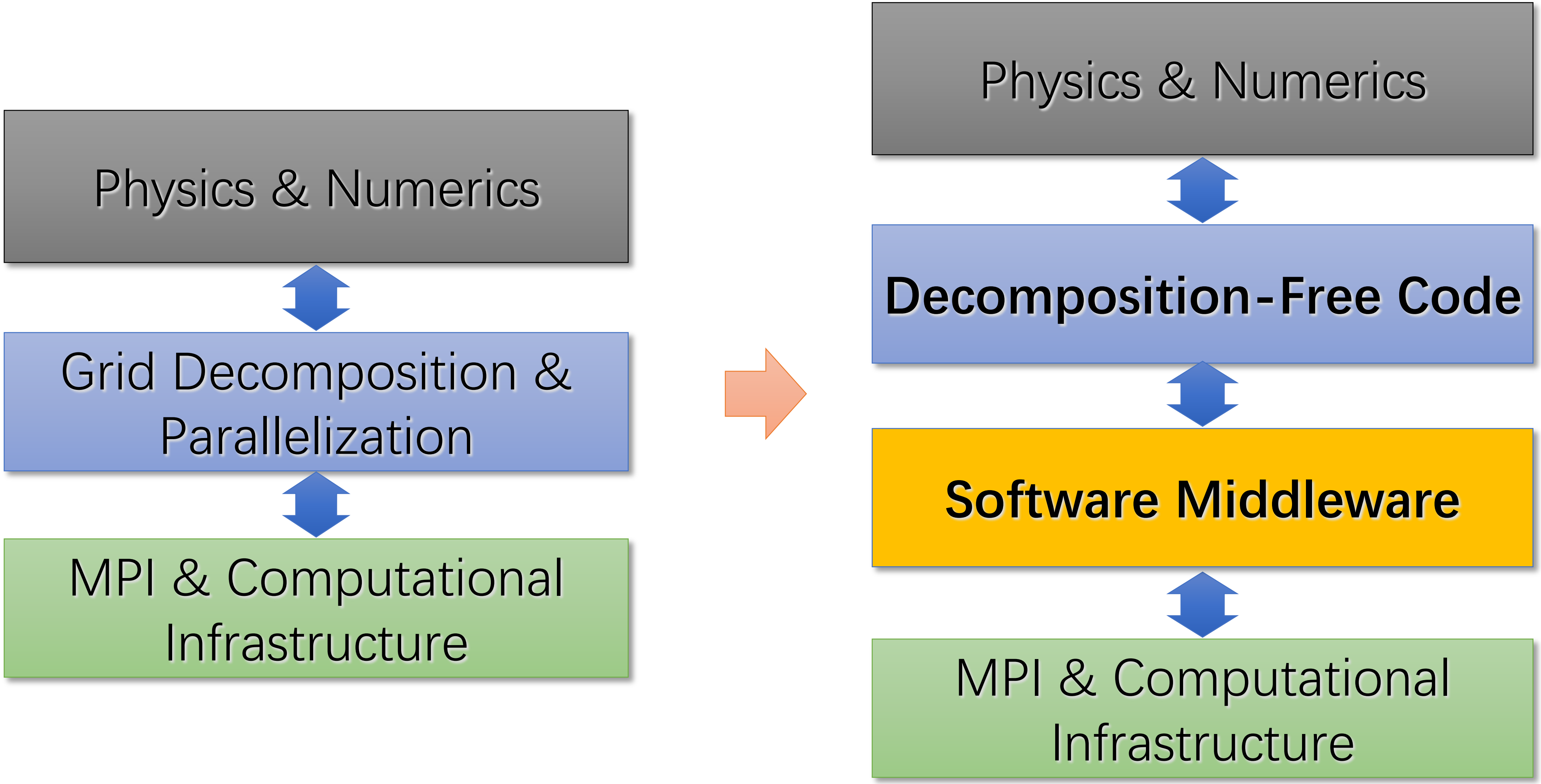
[Danilov, 2013]

Adaptive Mesh Refinement (AMR) as a Future-Proof Ocean Modeling Framework

Advantages:

1. Flexibility in resolving multi-scale processes: ***adding resolution only when & where it is `needed`***
   - Lateral boundaries, channels
   - Temporally changing features (i.e., ocean fronts, etc.)
2. Friendliness to existing parameterization (i.e., different parameterization on different refinement levels)
   - Also a platform for further improve parameterizations with upscaling
3. Good computability

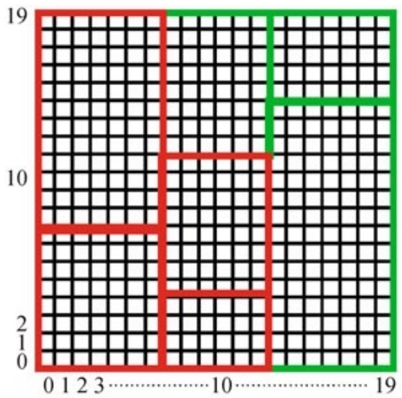
Model Grid As A Key Abstraction Layer



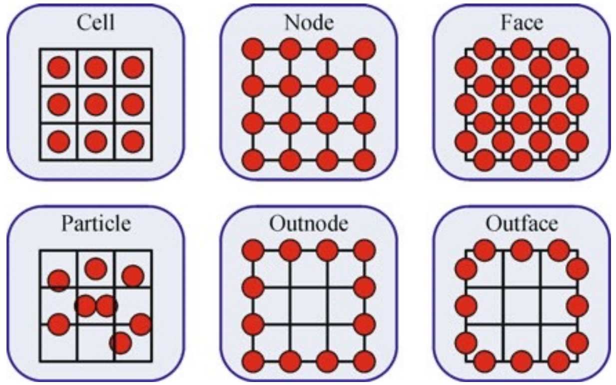
JASMIN – J parallel Adaptive Structured Mesh applications INfrastructure

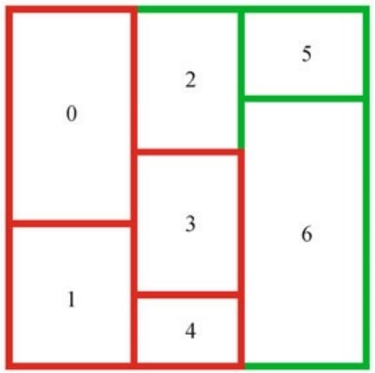
[Mo et al., 2010]

- JASMIN provides AMR supports:
  - Abstraction of structured grid (including staggered grids)
  - Management of domain decomposition & communications
  - Rule-based, automatic recursive grid refinement
  - Inter-level exchanges (boundary, interpolation, update, etc.)
  - Model restart
  - Parallel I/O
- JASMIN is based on C++

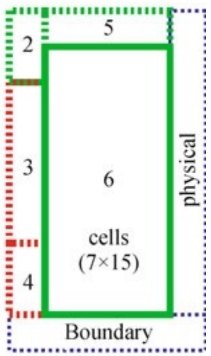


Mesh cells : 20×20
Cell indices : (i, j)
(a)

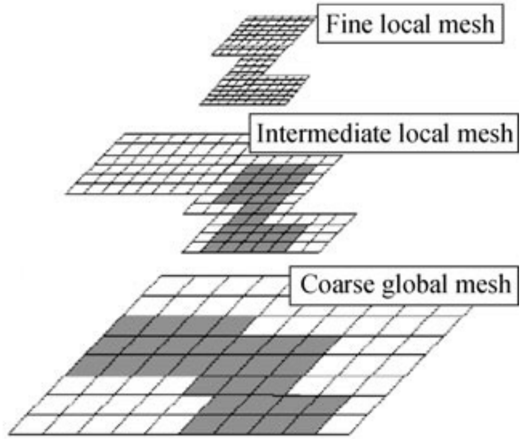




Mesh: 20×20 cells, 7 boxes
Load distribution: 2 proc.
(b)



Box, GhostBox
(width = 2)
(c)



OMARE – NEMO on JASMIN

- Porting NEMO (decomposition-independent code) onto JASMIN
  - Including full 3-D dynamic core, key parameterizations, sea ice, etc.
- Re-write the whole time-integration procedure in JASMIN
  - Patch & inter-level communication carried out by JASMIN
- HDF5-based history & restart files (parallel I/O)

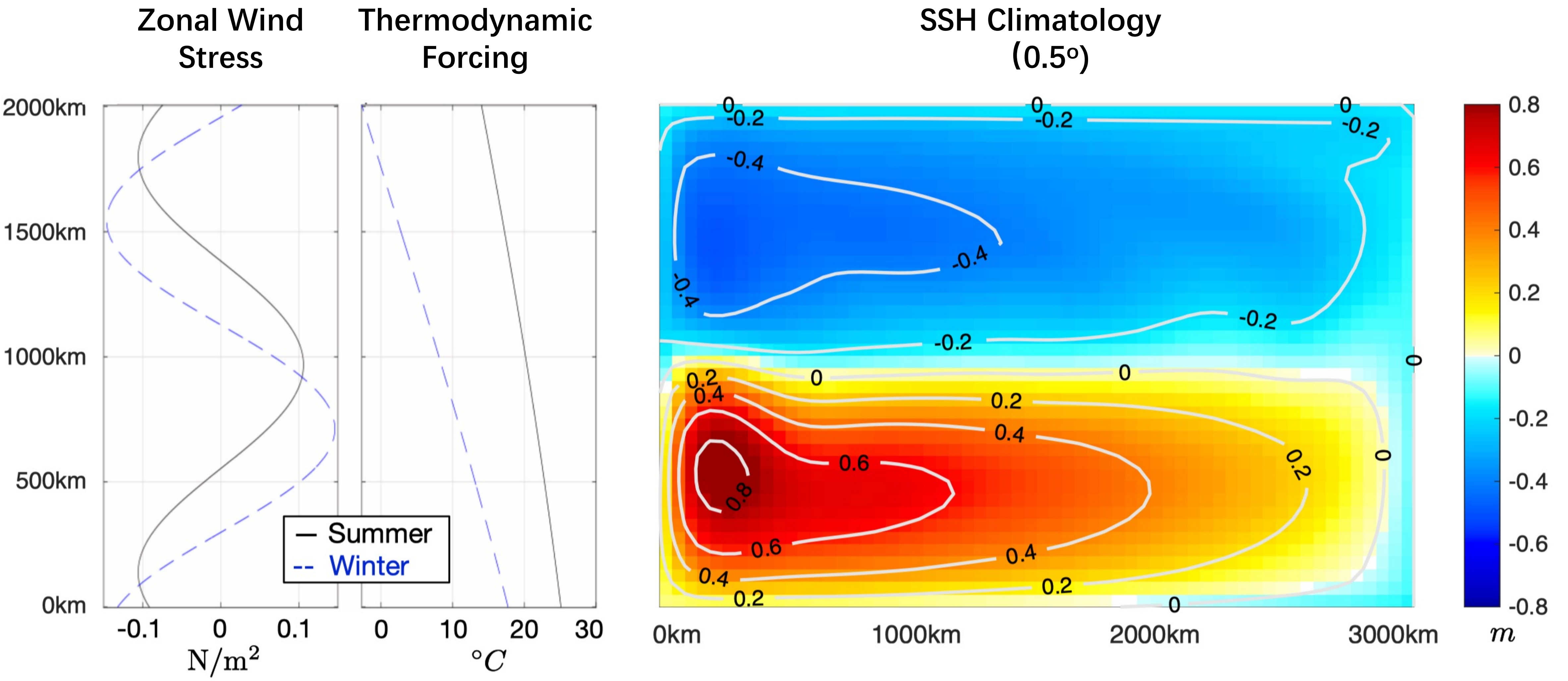
- **Result**: <u>O</u>cean <u>M</u>odeling with <u>A</u>daptive <u>RE</u>finement (**OMARE**)
- Codebase in FORTRAN & C++: ~127k lines (**27k new**) & **67k lines** respectively

Typical Resolutions of OMARE

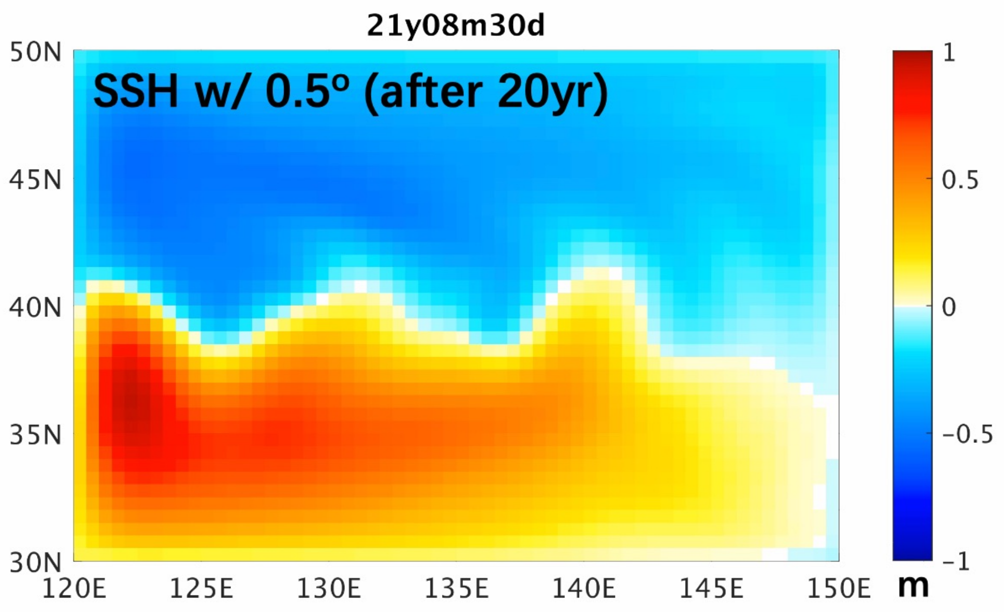
Level	Abbr.	Resolution	Time Step	Note
I	**L**aminar ocean (**L**ow res.)	0.5-deg	1 h	Climate modeling
II	**M**esoscale-resolving	0.1-deg	10 m (x6)	Eddying, or mesoscale-rich
III	**S**ubmesoscale-capable	0.02-deg	2 m (x5)	Mesoscale resolving, w/ certain submesoscale features
IV	e**X**perimental	0.004-deg	24 s (x5)	Resolving large portion of submesoscale Computational performance study

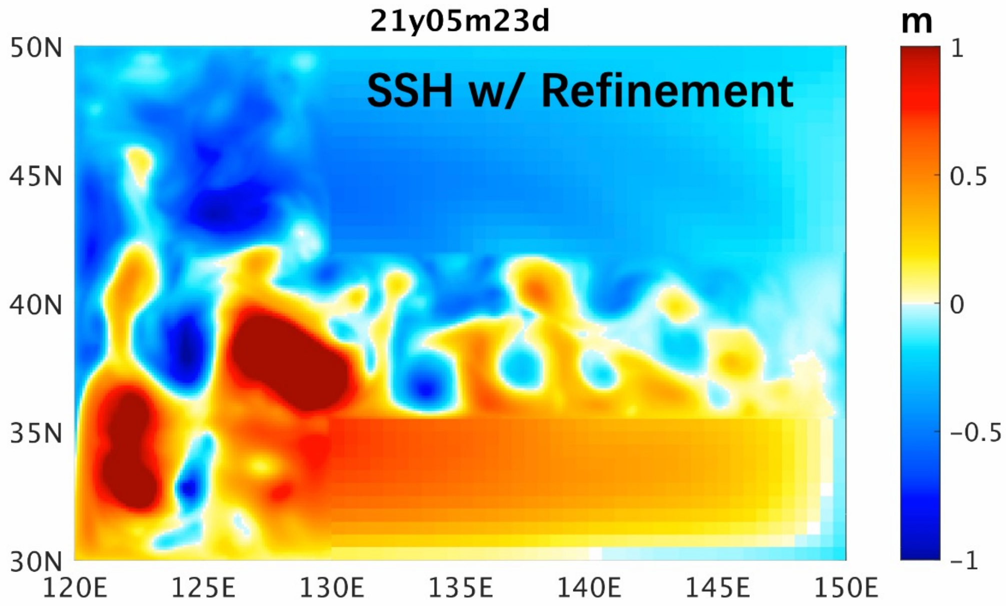
- Resolution range span: climate modeling & fine-scale process study
- 2-D refinement w/ shared z-coordinate
- Future extension to include NH & LES (i.e., multi-physics)

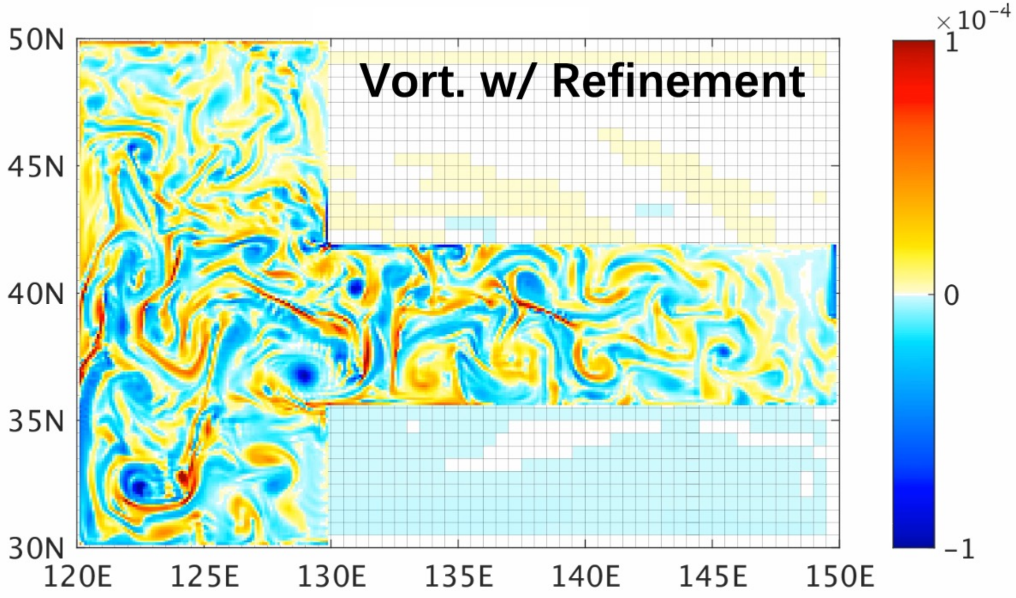
Double-Gyre: Idealized Test Case of WBC



1) Laminar Ocean → Turbulent Ocean (0.5º→0.1º)





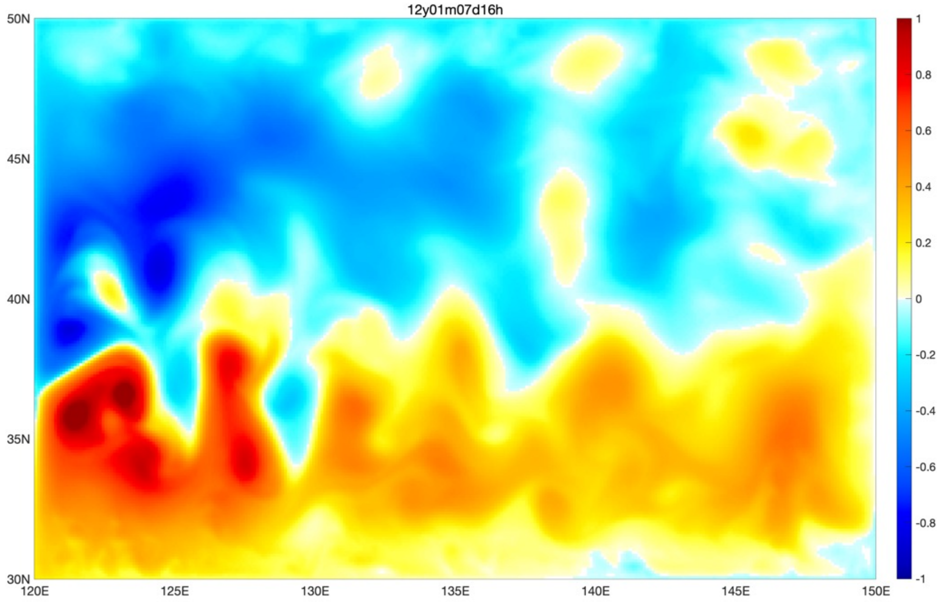


1. Spin-up w/ 0.5º (20-yr) →
2. T-shape refinement w/ 0.1º
   - Focus on western boundary & WBC
   - Shifting tail w/ seasonal cycle

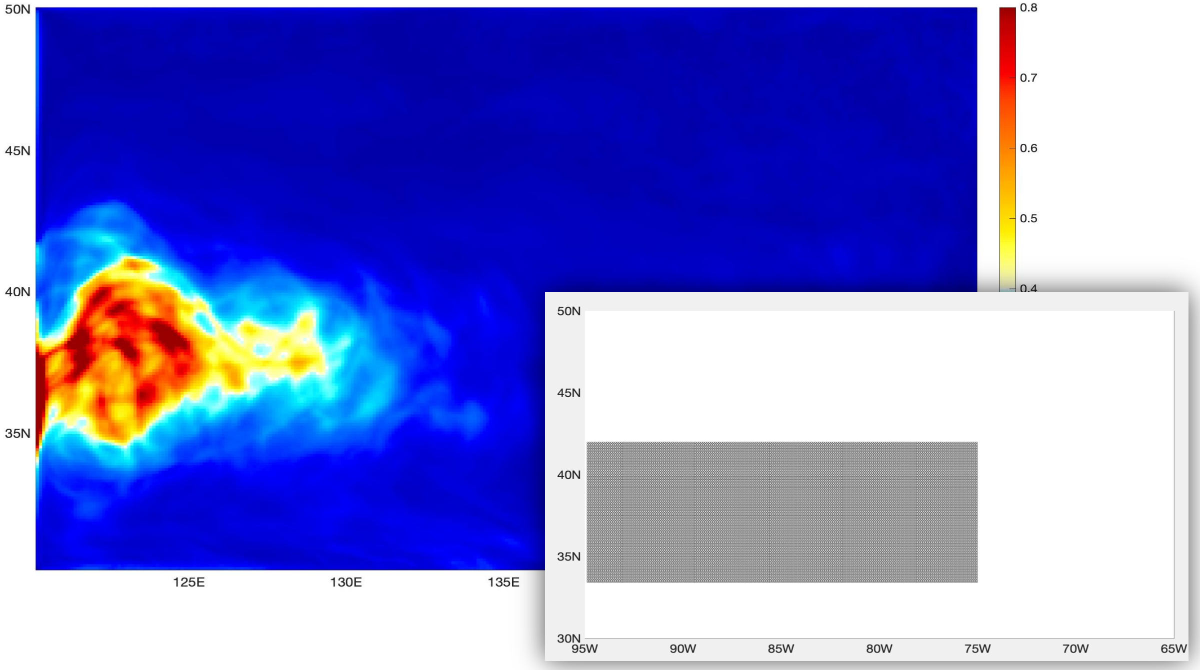
- **Result**: saturated & rich mesoscale features w/ refinement

2.1) Mesoscale → Submesoscale (0.1°→0.02°): Static Refinement

0.1° SSH (instantaneous)



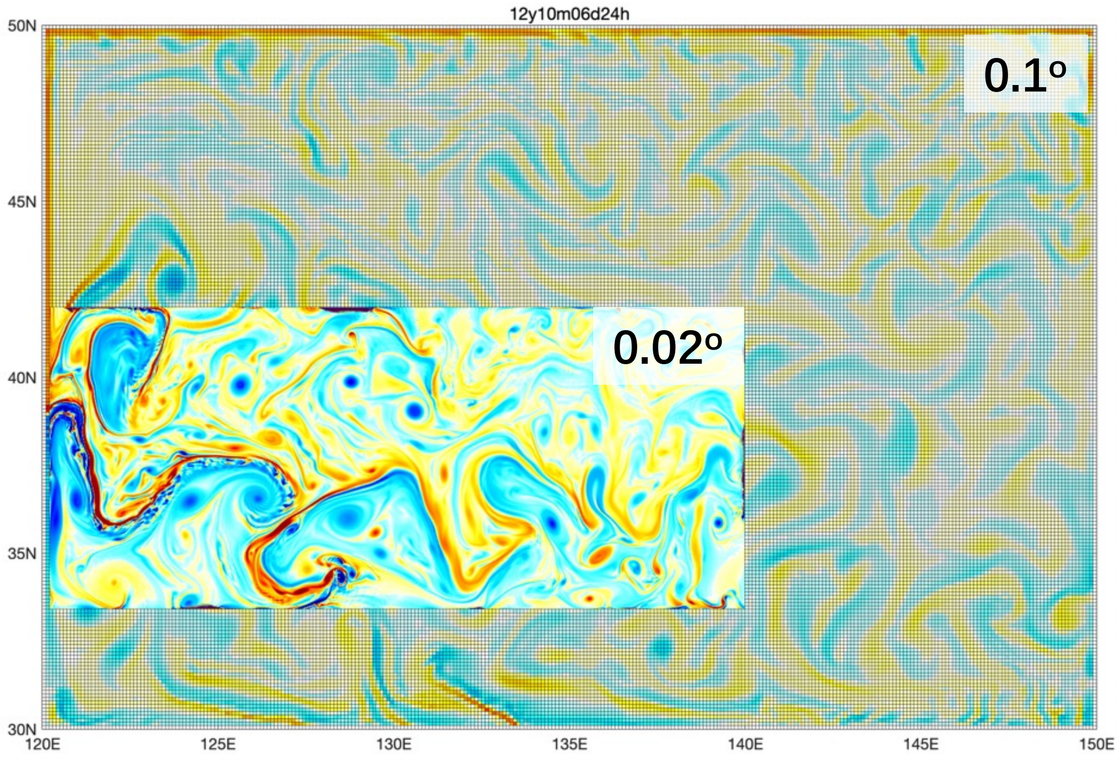
Surface KE (annual mean)



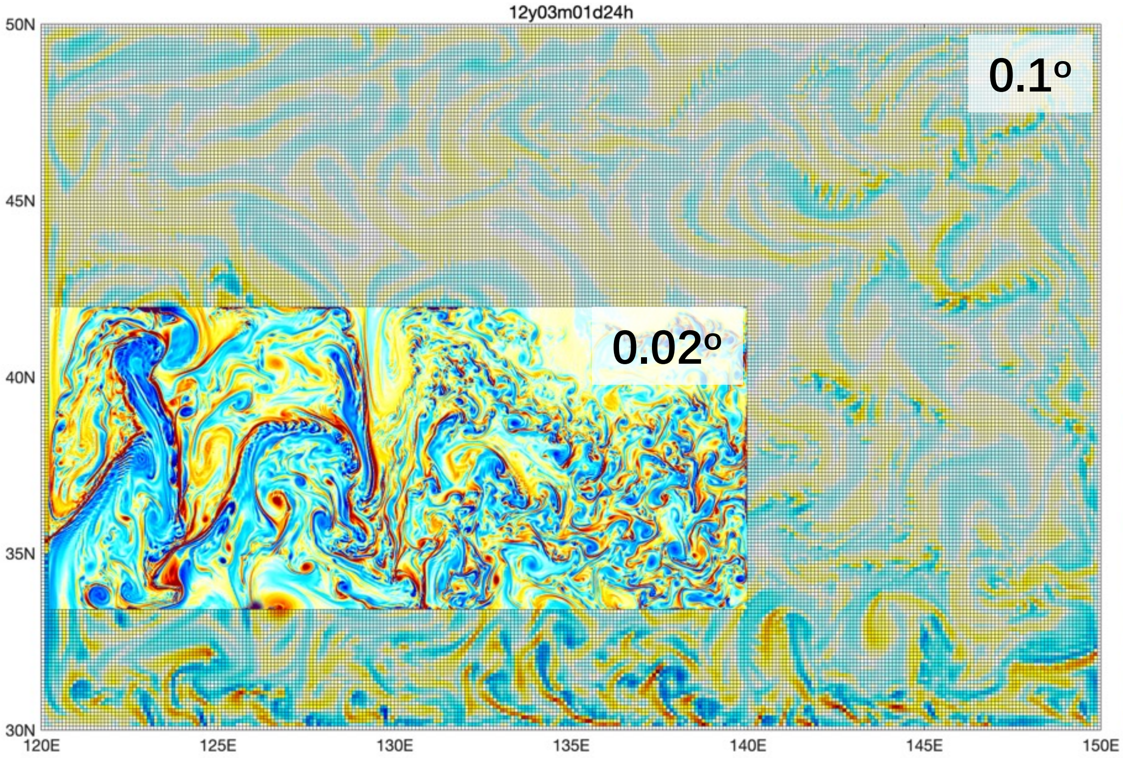
- **Refinement setting**: a regular (i.e., rectangular) refined region encapsulating the kinematically active region

2.1) Mesoscale → Submesoscale (0.1°→0.02°): Static Refinement

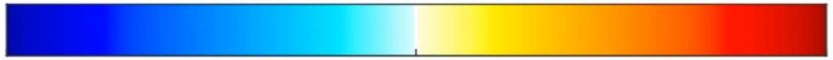
- **Summer**



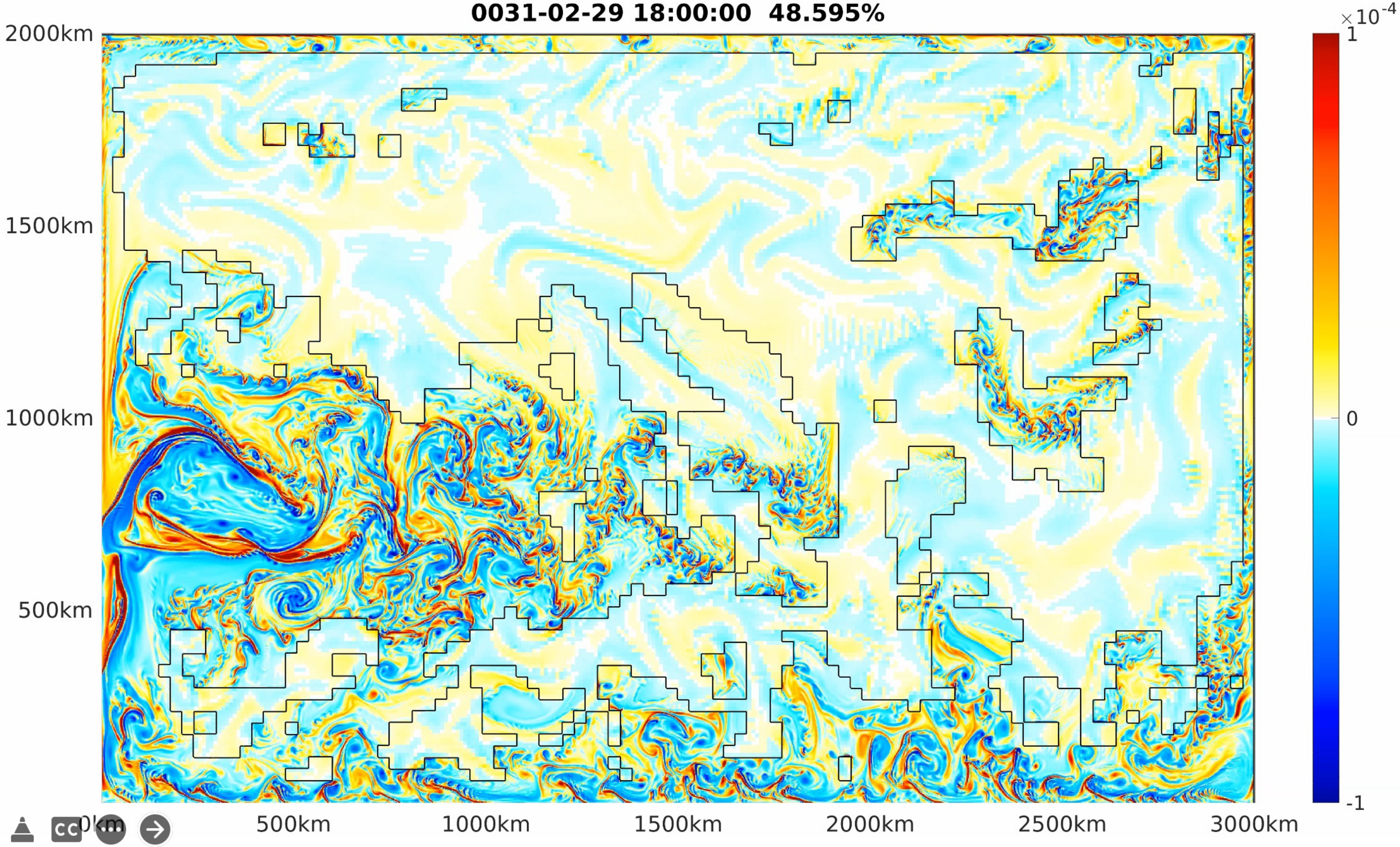
- **Winter**



Surface vorticity:



2.2) Mesoscale → Submesoscale (0.1° → 0.02°): Adaptive Refinement (since Feb.-1st)



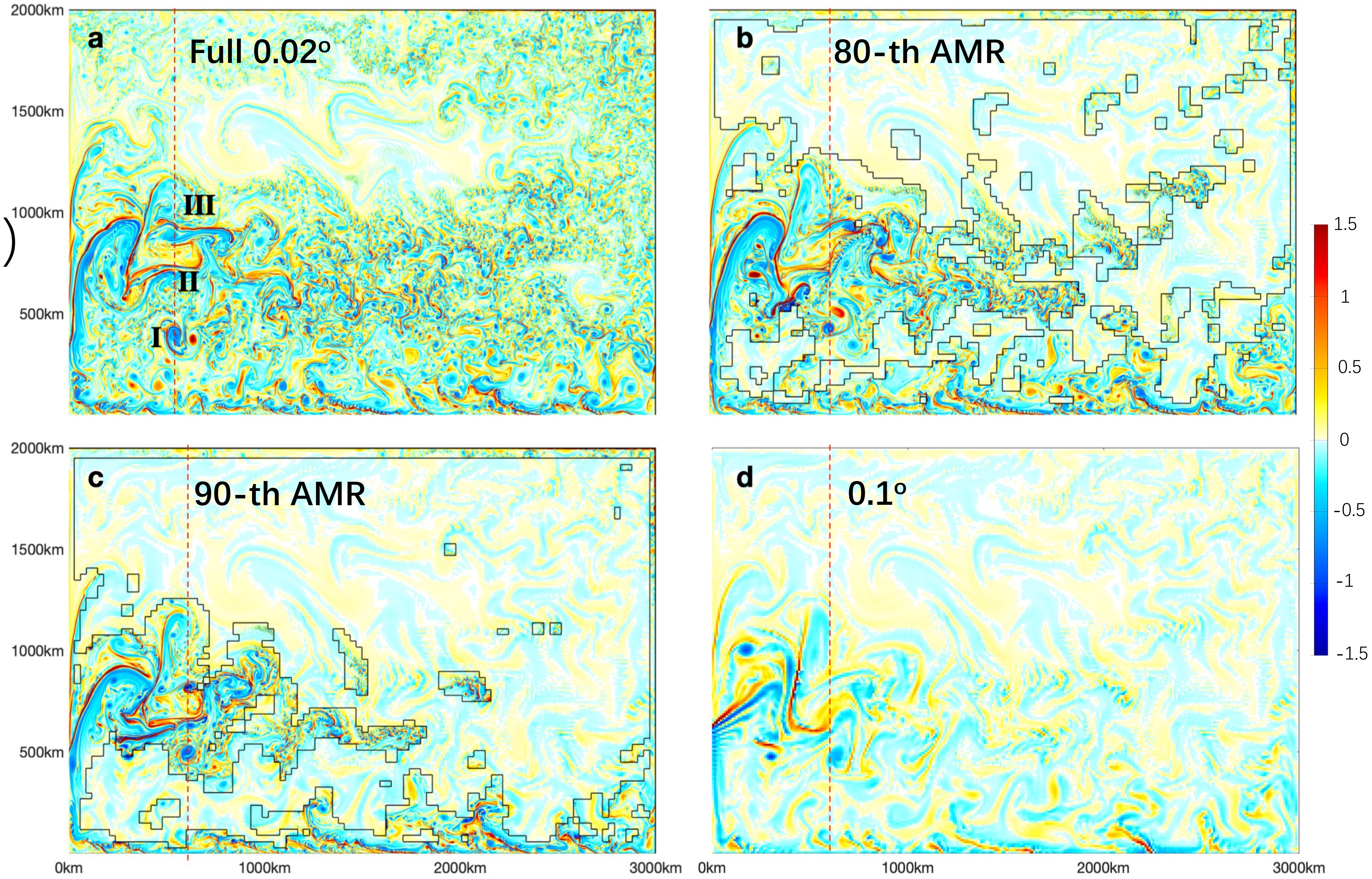
Surface Vorticity

|U| & |Vor|:
80-th percentile
Coarsening: 5 times
Tile Size: 3

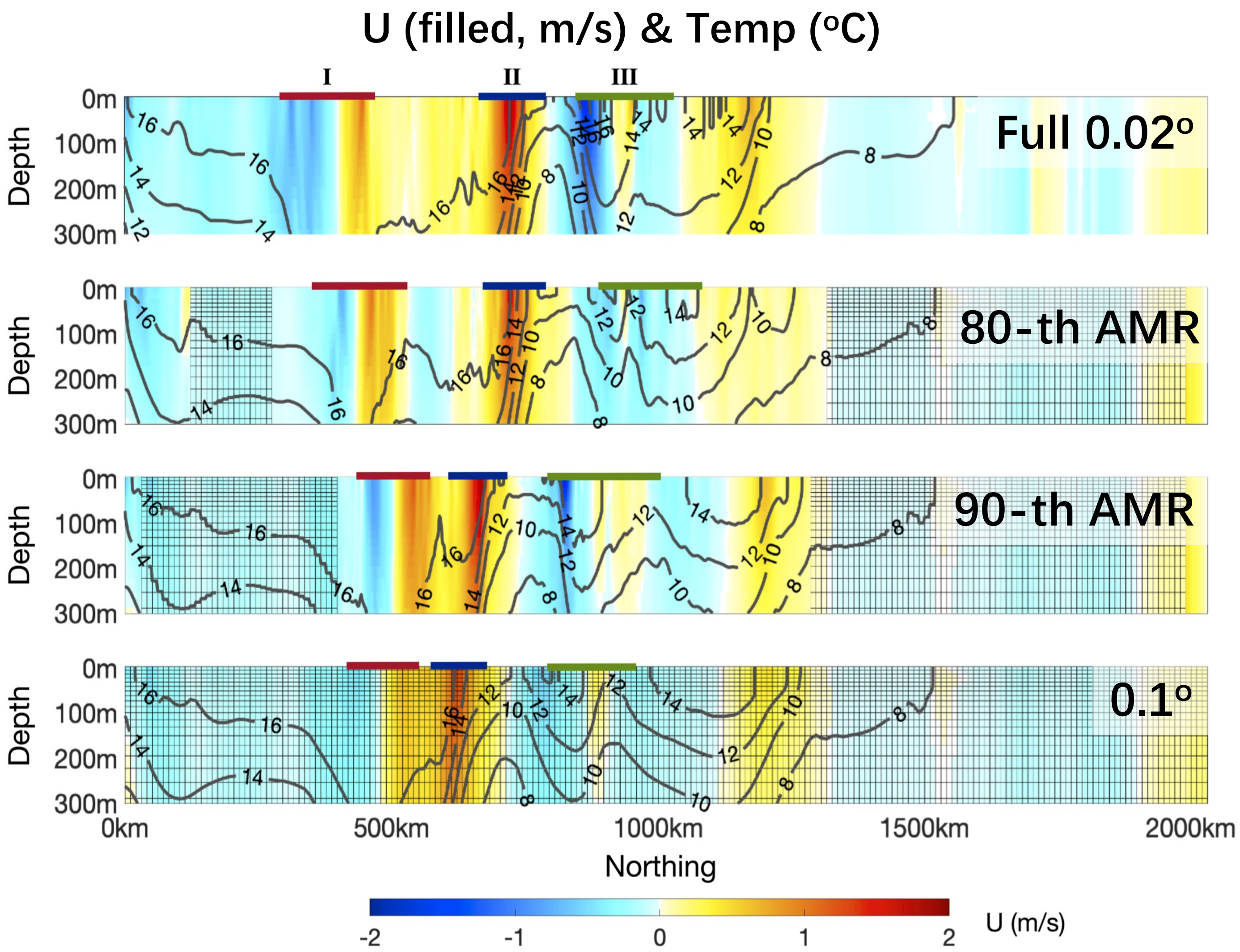
AMR Freq.: 5 days
w/ Instant. Fields

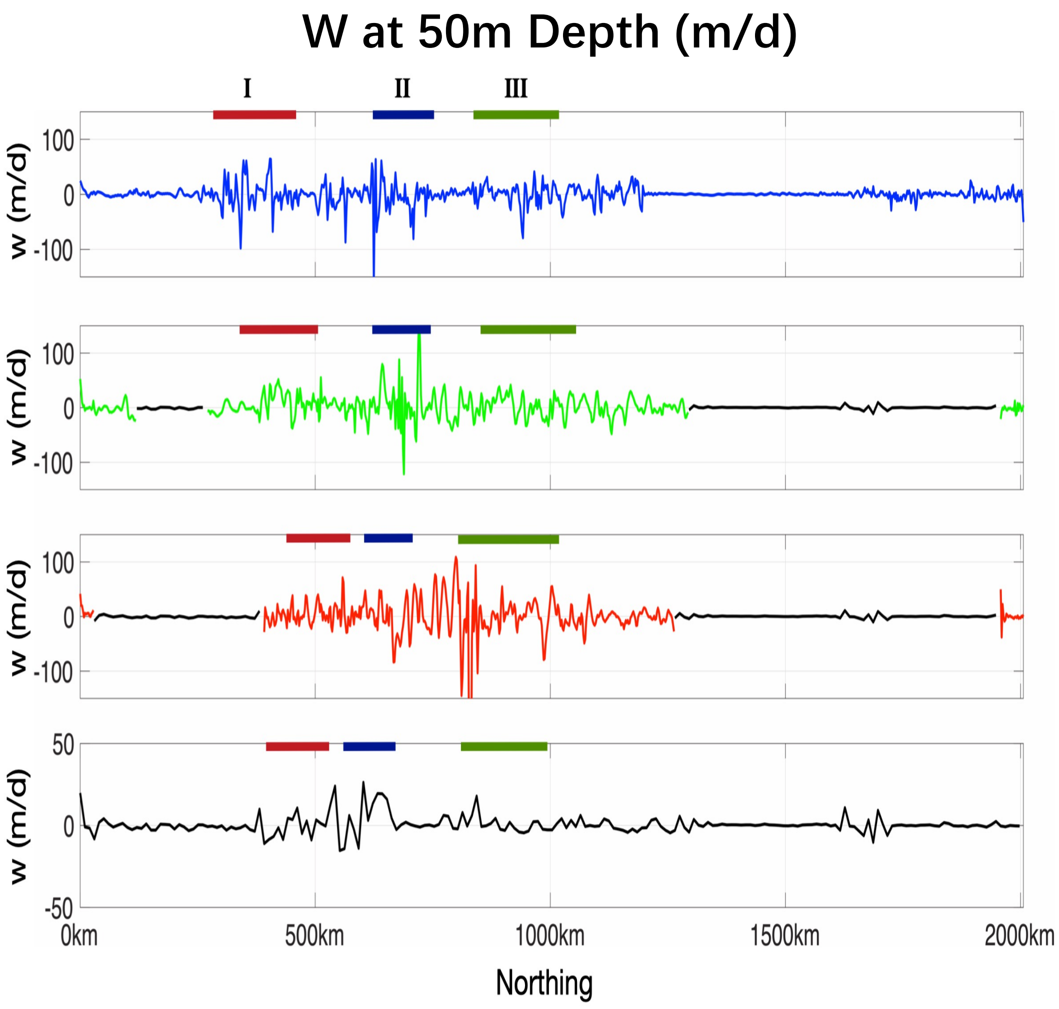
50 Days after AMR in Winter (since Feb.)

Ro (ζ/f)

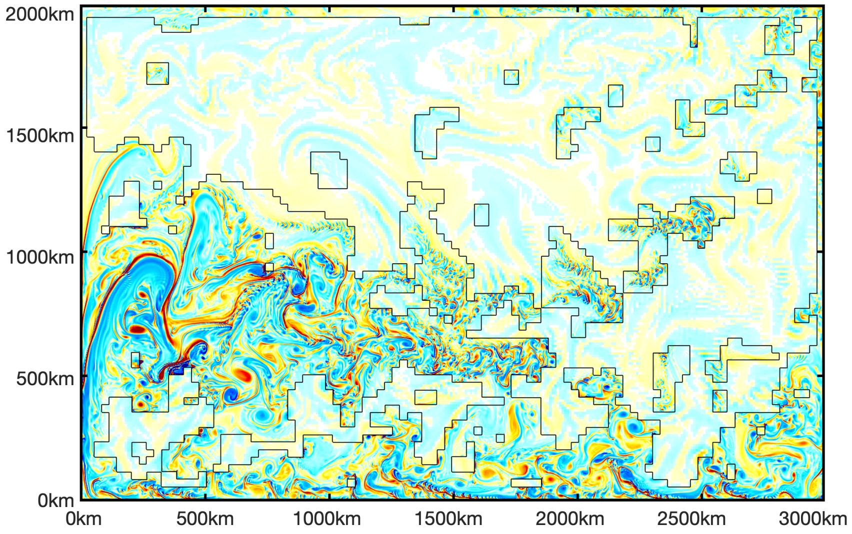


2.2) Mesoscale → Submesoscale (0.1°→0.02°): Vertical Transect in WBC



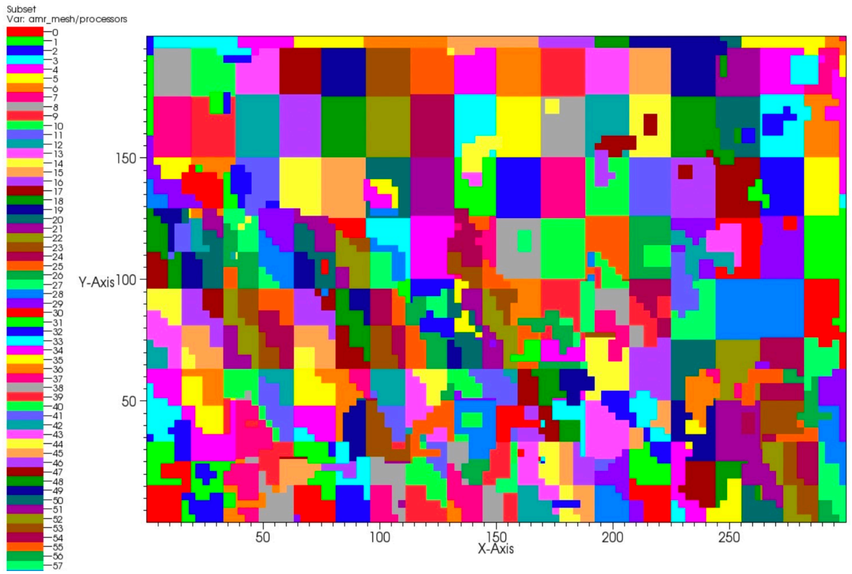


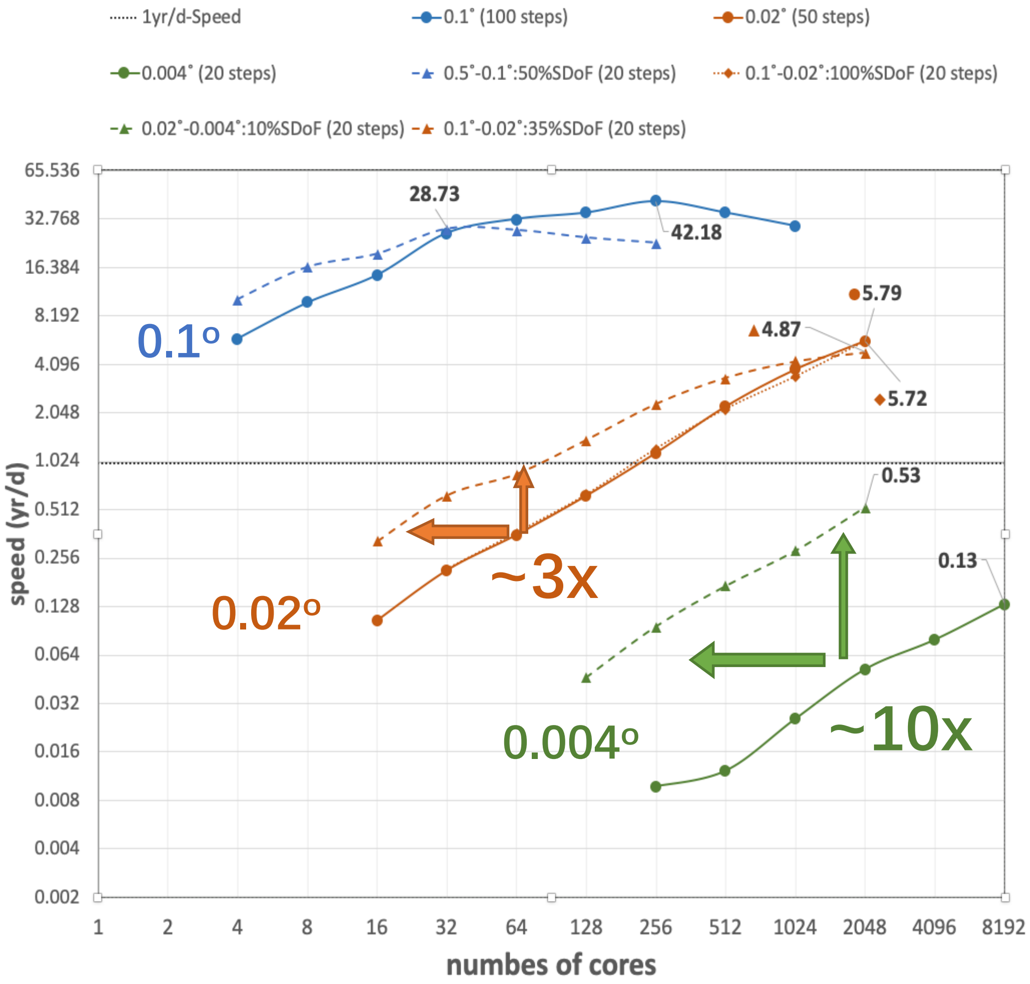
Computational Aspects



AMR Example:
0.01º~0.02º

Processor Mapping (128 proc.)





- Platform: Intel multi-core (28c/node) w/ IB interconnect
- Refinement ratio: **0.1º-0.02º@35%**, **0.02º-0.004º@10%**
- Ongoing analysis & optimization

Summary & Outlook

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1. **OMARE**: a framework for flexible, multi-scale ocean modeling
2. ***Physics***: mesoscale & submesoscale w/ AMR in Double-Gyre
3. ***Computation***: reasonable speed
4. A basis model to study WBC & related issues

- *Paper to be submitted to GMD journal*

- Outlook:
  1. Realistic cases: bathymetry, atm. forcings, tide, sea ice, etc.
  2. Computational aspects: optimization for AMR & arch.-specific optimizations
  3. Focus region/process: polar & sub-polar regions, ocean & sea ice
  4. Upscaling of small-scale ocean processes