Development of a parallel nested-grid ocean circulation model for petaflop supercomputers

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Horizontal resolution of current OGCM used for climate simulations is about 20km at the best (eddy-permitting). At this resolution, Kuroshio separates from southern coast of Japan at a realistic latitude.
Kuroshio path variation can not be represented properly

Transition process from a meandering to straight path

Simulated SSH (MIROC-hi (AR4))
Meandering part shifts westward

Observed
Kuroshio axis
Meandering part shifts eastward
To represent realistic Kuroshio path variation, eddy-resolving OGCM is necessary (e.g., Tsujino et al., 2006).

Climate simulations with eddy-resolving OGCM may be realizable in petaflop supercomputers. But,

- computational cost may be still high
- smaller scale phenomena, such as submesoscale eddy, can not be represented

For efficient calculation and representation of smaller scale phenomena, we are developing a two-way nested-grid OGCM which can be used for climate simulations.
Nested-grid model is based on COCO (CCSR Ocean Component Model) Ver. 4.2

Ocean
- primitive equation under hydrostatic and Boussinesq approximation
- explicit free surface
- generalized curvilinear horizontal coordinate and z-σ hybrid vertical coordinate

Sea Ice
- two-category thickness representation, zero-layer thermodynamics
- dynamics with elastic-viscous-plastic rheology

COCO is parallelized by MPI

Nested-grid model consists of two model. (MPMD program)
Communication between outer and inner model occurs only between ranks whose horizontal domains overlap.

0-7: outer model rank
0-63: inner model rank
An example of grid arrangement

- : velocity points
+ : tracer points
shaded region : inner model region
Timing of communication between outer and inner model

Outer model

Tracer
Ice variables
Baroclinic velocity

Inner model

Tracer Velocity
Barotropic velocity
Sea surface height

ICE → BC → BT → TR
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Performance check with North Pacific model

Model Basin

outer model
\[ \Delta x = 0.5^\circ \]
\[ \Delta y = 0.5\cos \theta^\circ \]
40 vertical levels

inner model
(region bounded by white line)
\[ \Delta x = 0.1^\circ \]
\[ \Delta y = 0.1\cos \theta^\circ \]
40 vertical levels
**Initial and boundary condition**

- **Initial condition**
  - T, S: based on WOA 2001
  - Velocity: state of rest

- **Horizontal boundary condition**
  - No slip, noflux at the coast
  - Near the outer model southern boundary, T and S are restored to the climatological values

- **Sea surface**
  - CORE ver.2 normal year forcing
  - No water and snow flux
  - Sea surface salt is restored to the climatological monthly mean in 6 days

Wind stress is defines as

\[ \tau = \rho_a c_d |U_a - U_o|(U_a - U_o) \]

Three experiment are done changing \( U_a \).

\( U_a \times 0.9, U_a \times 1.0, U_a \times 1.1 \)
Performance on T2K open supercomputer (Tokyo)

1 node: 16core (quad core x 4) Hitachi fortran compilar is used.

Model is integrated changing core number and parallelization method.

- 240, 480, 960 core calculation is done with core number ratio between outer and inner fixed (inner/outer=4).

- Parallelization method
  - Pure MPI
  - Hybrid Open MP (4 threads) & MPI
  - Auto parallelization(4 threads) & MPI
Pure MPI parallelization is slow compared with Hybrid one.

For hybrid parallelization, auto parallelization is slightly faster than OpenMP (only do loops are parallelized).

Speed-up for hybrid parallelization is not bad. (About 0.7 of the ideal value)
Model was integrated 30 years on ES2 (It takes about 24h using 5 nodes)

Snapshot of SSH for normal wind forcing
- Kuroshio separates at realistic latitude
- Mesoscale eddies are well resolved in inner model region
- SSH connect smoothly at the boundary
Time-averaged SSH (last 15 years)

- Both straight and meandering path appear for normal and 10% weaker wind forcing

- Only straight path appears for 10% stronger wind forcing
Stream function (snapshot)

Distance of Kuroshio axis from Kii Peninsula (km)

Kuroshio axis

Spin-up
Transition process from the straight to meandering path

Anticyclonic eddy east of Taiwan is advected to south of Kyushu
↓
Generated small meander develops to a meandering path (consistent to observation)

Similar process is pointed out by Akitomo and Kurogi (2001), and Miyazawa et al. (2008)
After several separation and coalescence of cold core eddy, the meandering part shifts eastward and shrinks into a straight path.

Similar process is observed in disappearing stage of the meandering path (Nishida, 1982)

Separation of cold core eddy in the meandering period of 1975-1980 (Nishida 1982)
Summary

- Two-way nested-grid OGCM is developed.
- Parallelization performance is checked on T2K open supercomputer. Speed-up for hybrid parallelization is favorable.
- Responses of Kuroshio path variation is studied changing an amplitude of wind forcing.

  - Both straight and meandering paths alternatively appear for normal and 10% weaker wind forcing. Path transition processes are consistent to observation.

  - Only the straight path appears for 10% stronger wind forcing. Stronger velocity is considered to be responsible for absence of the meandering path.

  - The upper bound of velocity for the meandering path seems to be near the realistic range of velocity.
If global warming progress in the future,

1) Stratification will be stronger and this causes decrease of the upper bound velocity for the meandering path (Kurogi and Akitomo, 2006).

1) Kuroshio velocity may be strengthen (Sakamoto et al., 2005).

The meandering path may be hard to appear in the future. Possibly, this tendency may be already appear.
We are now developing global nested-grid OGCM

Example:

- Model North Pole is located in Greenland
- Outer model: global (resolution is about 60km around Japan)
- Inner model: region bounded by red line (resolution is about 8km)

Grid arrangement of a nested-grid model (each box contains $32 \times 32$ grids). An region bounded by red line is nested into global model. Dotted lines indicate the equator and meridian ($0, 90, 180, 270^\circ$ E).

Snapshot of sea surface height (January 1 of the 15th year). A region bounded by white line is nested into global model. Gray regions are covered by sea ice.