Kuroshio path variation studied by a nested-grid OGCM

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Typical paths of the Kuroshio

- **Straight path** (nearashore non-large-meander path)
- **C-type path** (offshore non-large-meander path)
- **Meandering path** (typical large-meander path)

The straight and meandering paths alternatively appear in a time scale of several years to a decade.

Since Kuroshio path variation strongly affects fisheries, its prediction under future climate change is important.

Kawabe (1995)

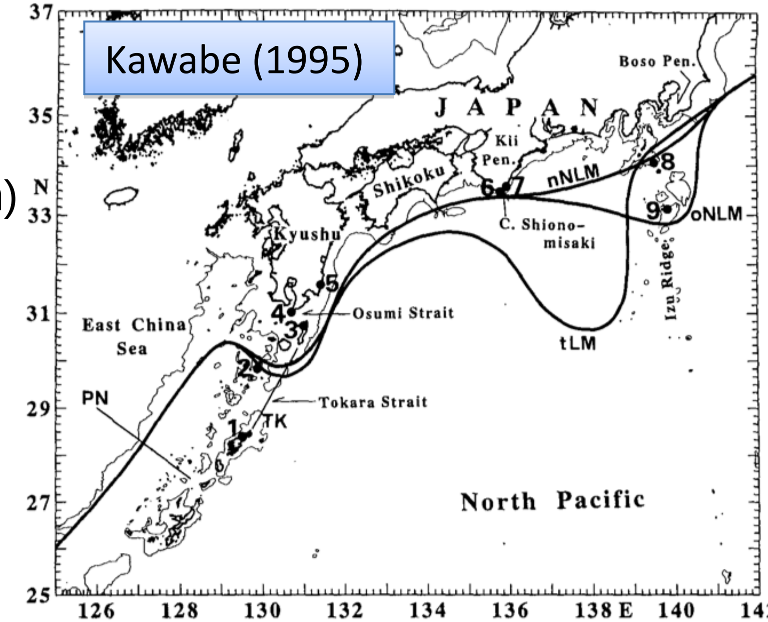
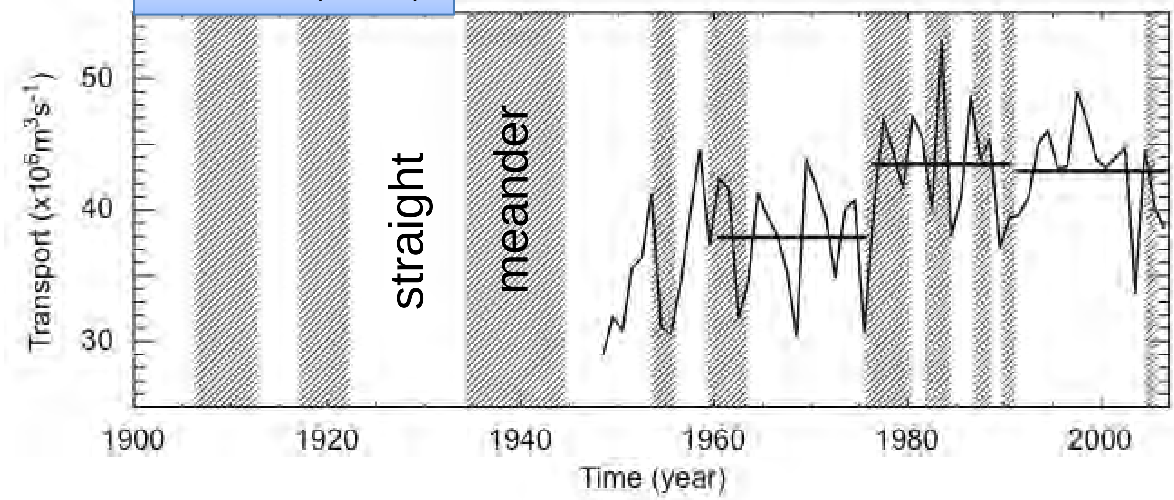


FIG. 1. Tide stations and the typical paths of the Kuroshio. Thin lines are 500-m isobaths. The lines of PN and TK are CTD lines of the JMA Nagasaki Marine Observatory's: 1) Naze, 2) Nakanoshima, 3) Nishinoomote, 4) Odomari, 5) Aburatsu, 6) Kushimoto, 7) Uragami, 8) Miyake-jima, 9) Hachijo-jima. nNLM is the nearshore non-large-meander (NLM) path; oNLM is the offshore NLM path; tLM is the typical large-meander (LM) path.

Akitomo (2008)



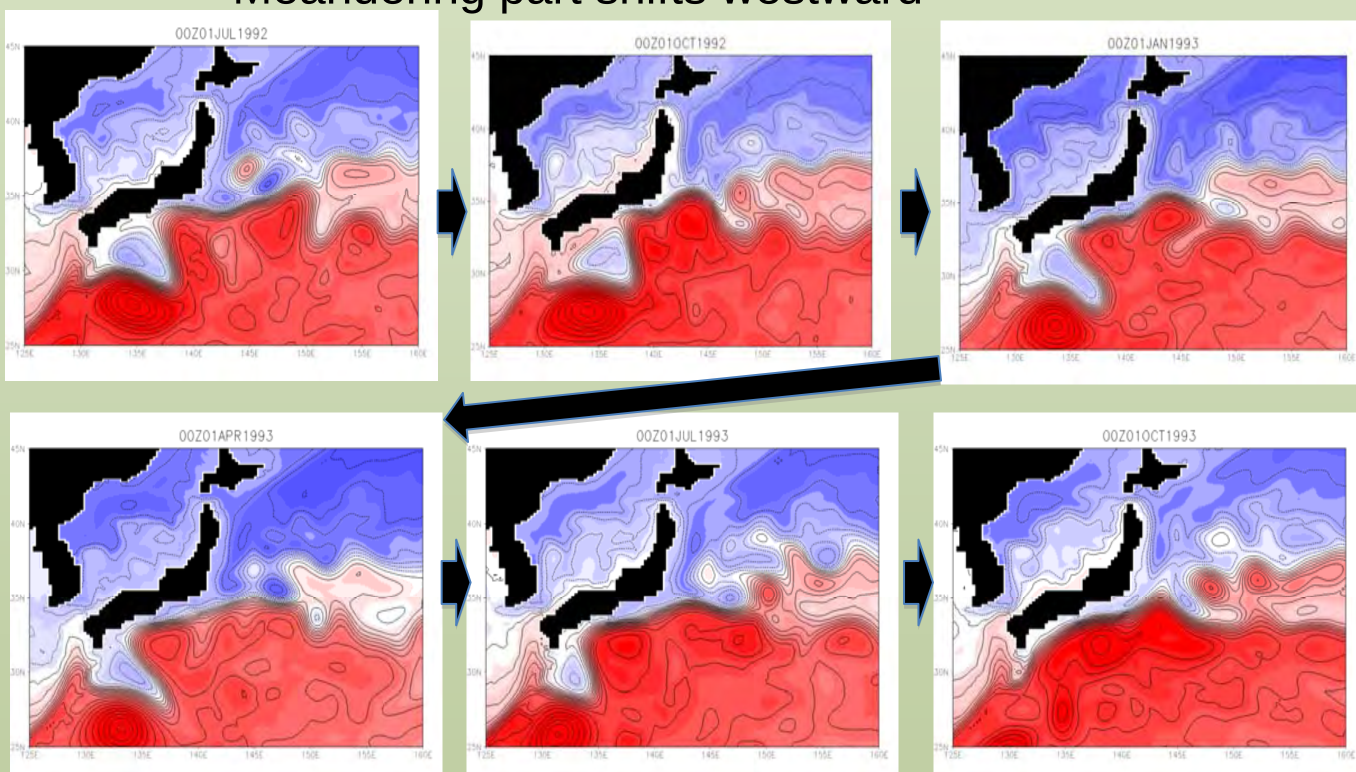
The straight (white) and meandering (shaded) type path periods

Horizontal resolution of current OGCM used for climate simulations is abuot 20km at the best (eddy-permitting).

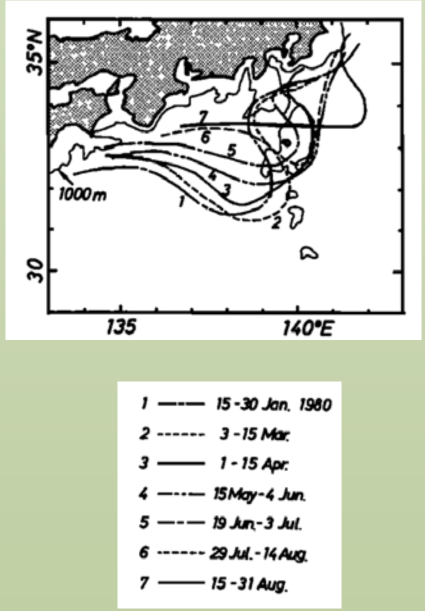
- Kuroshio separates from southern coast of Japan at a realistic latitude
- Kuroshio path variation can not be represented properly

Transition process from a meandering to straight path

SSH simulated by a high resolution coupled model
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 requires huge amount of computer resources. Instead, we are developing a two-way nested-grid OGCM which can be used for climate simulations.
- As a first step, an eddy-resolving model around Japan is nested into North Pacific model and Kuroshio path variation is examined.

Nested-grid model is based on COCO (CCSR Ocean Component Model) Ver. 4.2

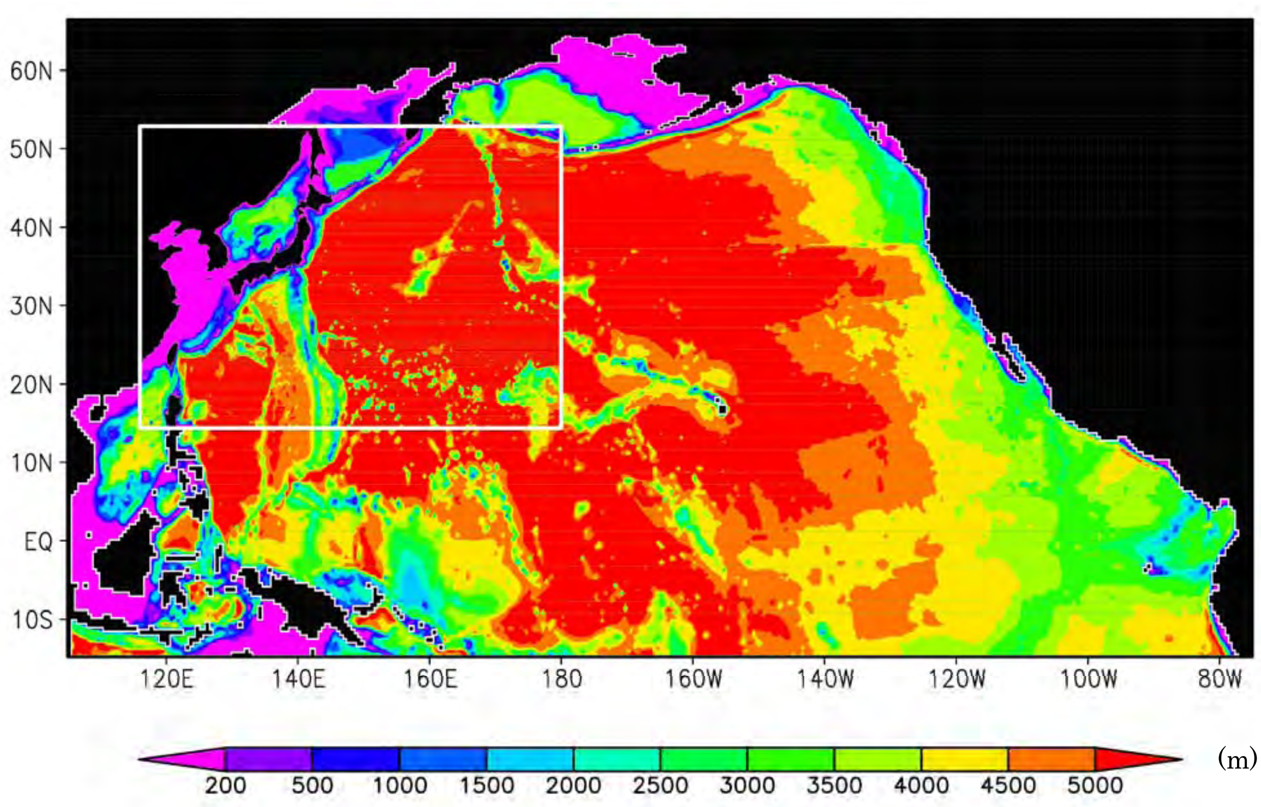
Model Basin

outer model

Δx=0.5°
Δy=0.5cosθ°
40 vertical levels

inner model (region bounded by white line)

Δx=0.1°
Δy=0.1cosθ°
40 vertical levels



Nesting is two-way

- Outer model variables are interpolated and used as inner model boundary condition
- Inner model variables are spatially averaged and replace the outer model ones

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

$$\boldsymbol{\tau} = \rho_a c_d |\boldsymbol{U}_a - \boldsymbol{U}_o| (\boldsymbol{U}_a - \boldsymbol{U}_o)$$

Three experiment are done changing ***Ua***.

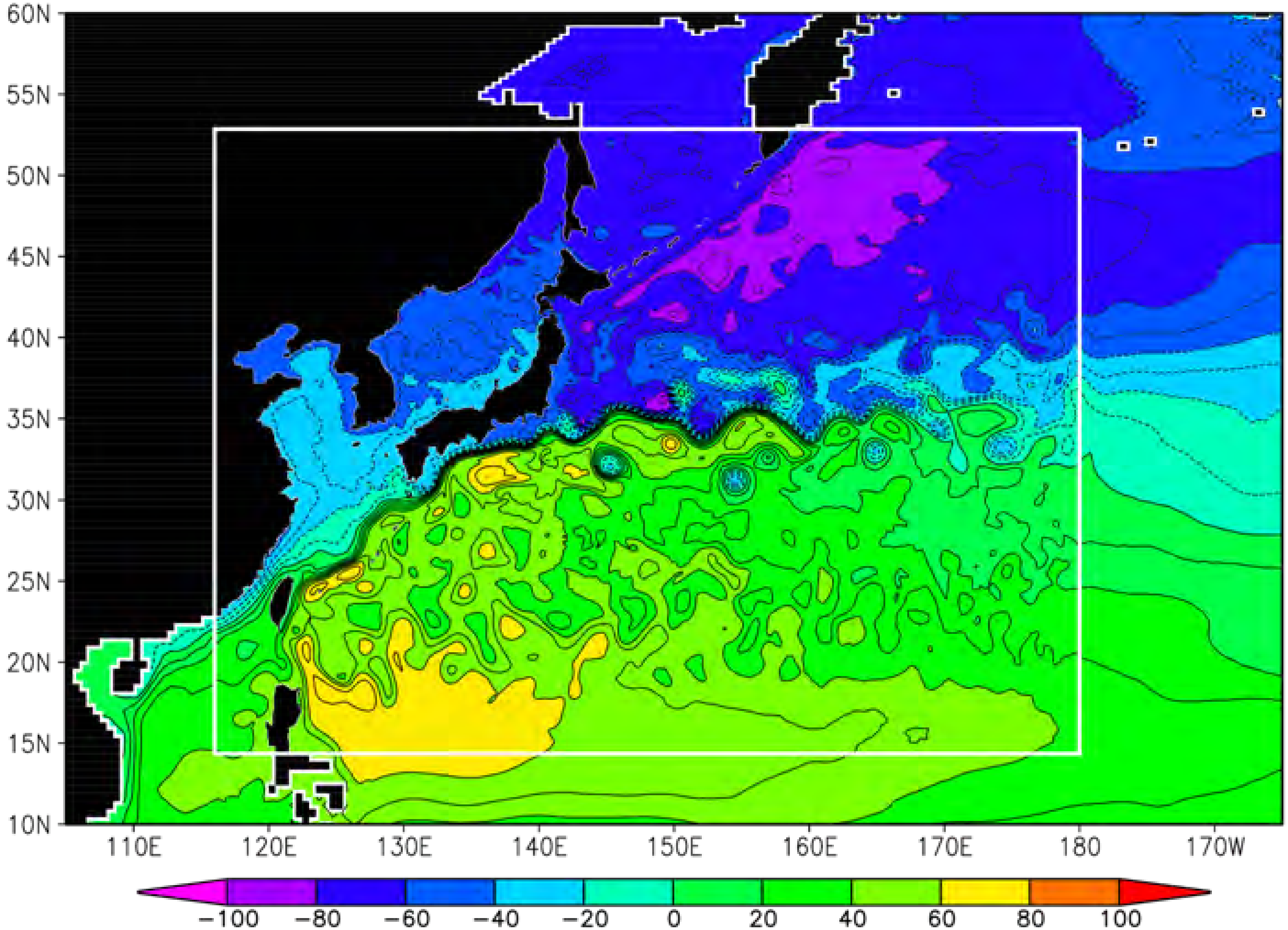
Ua×0.9, ***Ua***×1.0, ***Ua***×1.1

Ua: 10m wind velocity
Uo: ocean surface current
ρ_a: air density
c_d: bulk coefficient

Model was integrated 30 years on Earth Simulator 2

Snapshot of SSH for normal wind forcing

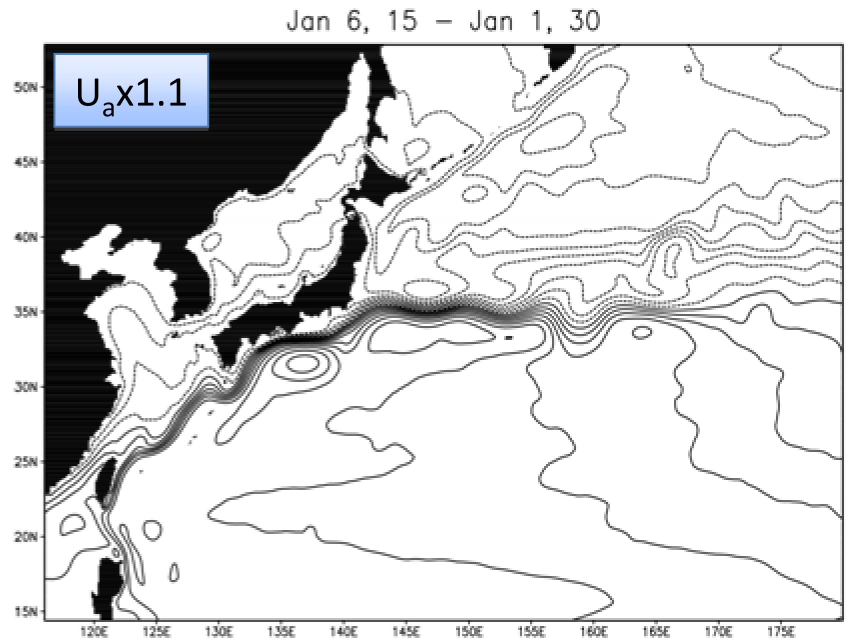
- Mesoscale eddies are well resolved in inner model region
- SSH connect smoothly at the boundary

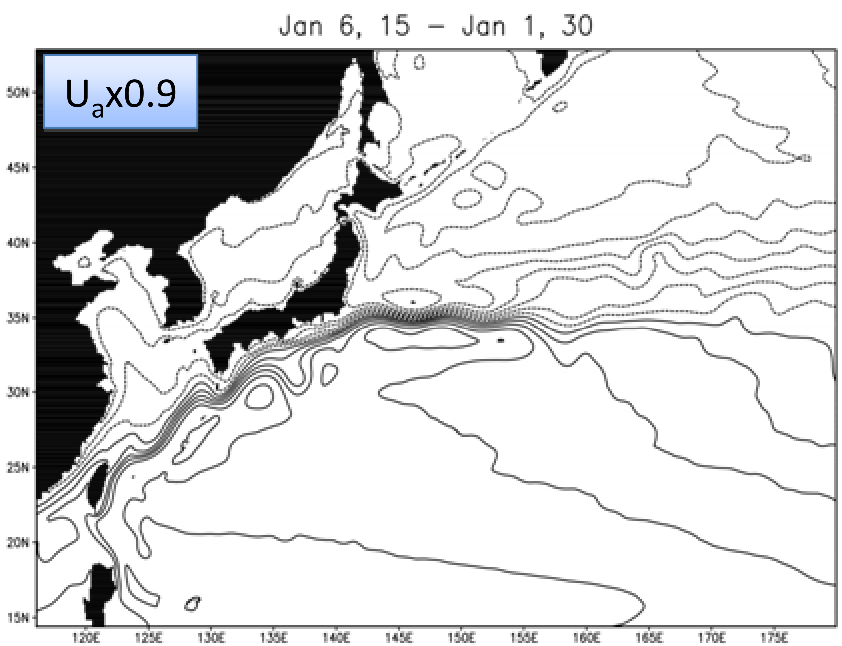


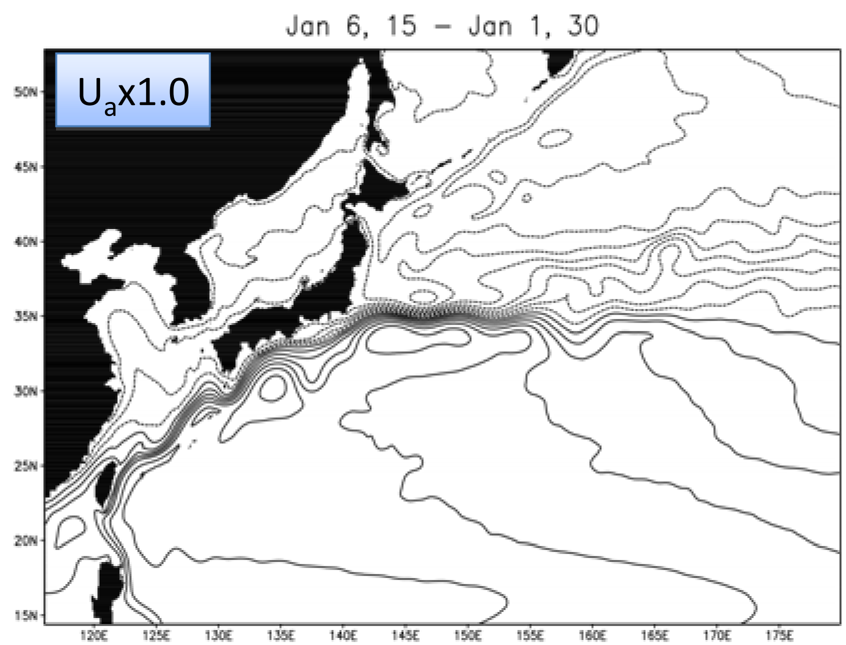
Time-averaged SSH (last 15 years)

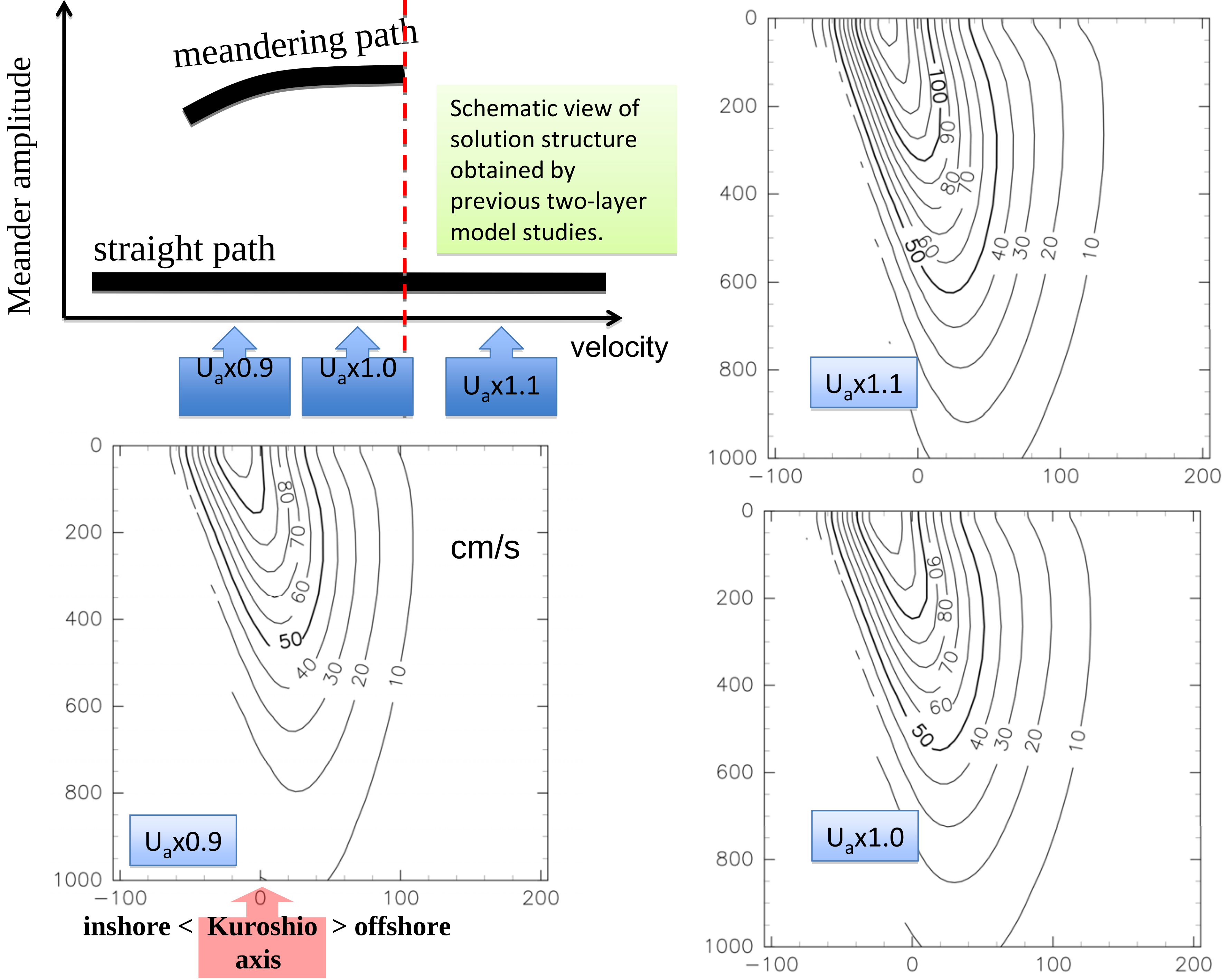
- Both straight and meandering path appear for normal and 10% weaker wind forcing

- Only straight path appears for 10% stronger wind forcing

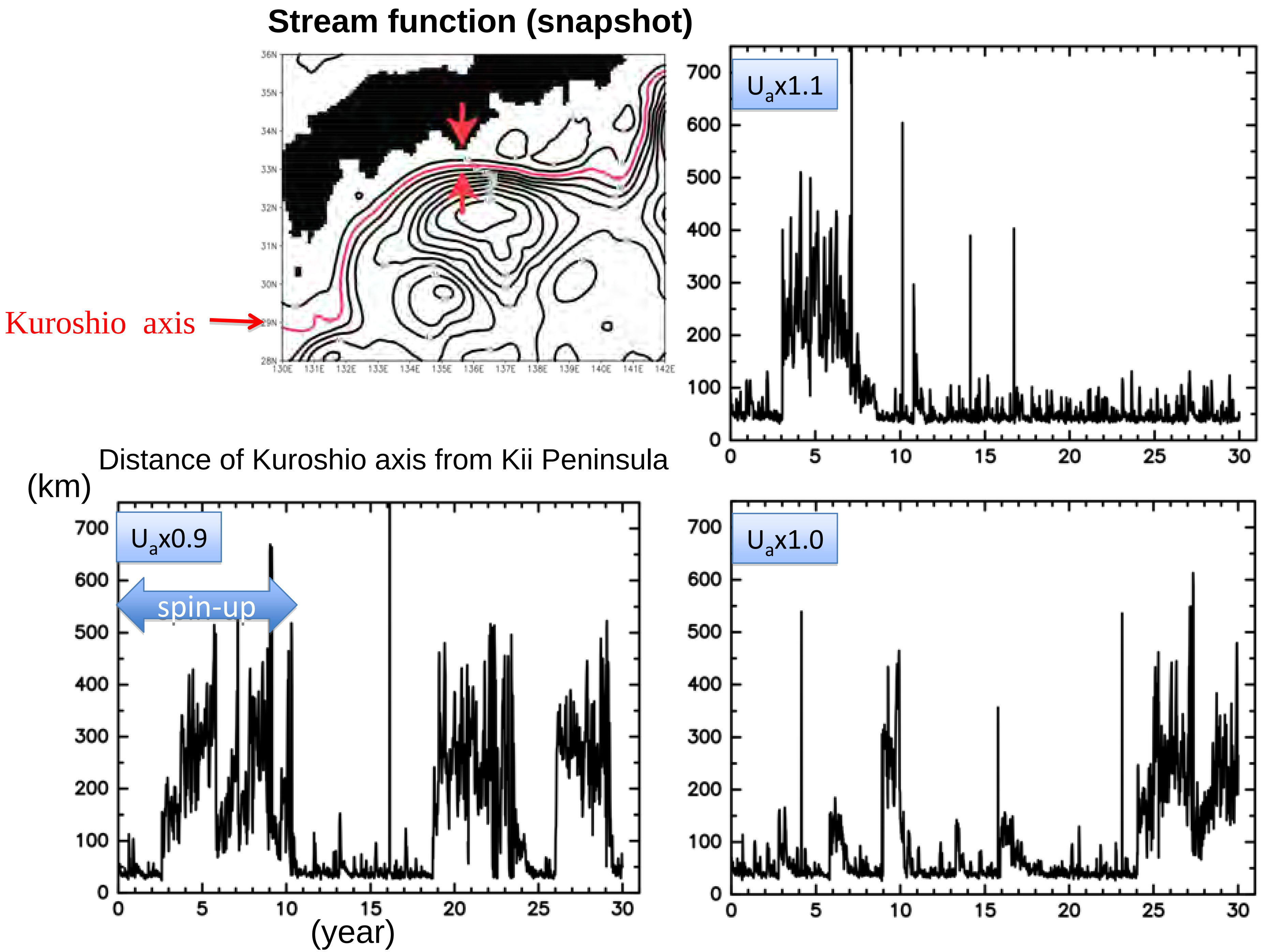








meandering path
straight path
Meander amplitude
velocity
Schematic view of solution structure obtained by previous two-layer model studies.
U_ax0.9
U_ax1.0
U_ax1.1
cm/s
inshore < Kuroshio axis > offshore


Stream function (snapshot)
Kuroshio axis
36N
35N
34N
33N
32N
31N
30N
29N
28N
130E 131E 132E 133E 134E 135E 136E 137E 138E 139E 140E 141E 142E
Distance of Kuroshio axis from Kii Peninsula
(km)
U_ax1.1
U_ax0.9
U_ax1.0
spin-up
0
100
200
300
400
500
600
700
0 5 10 15 20 25 30
(year)

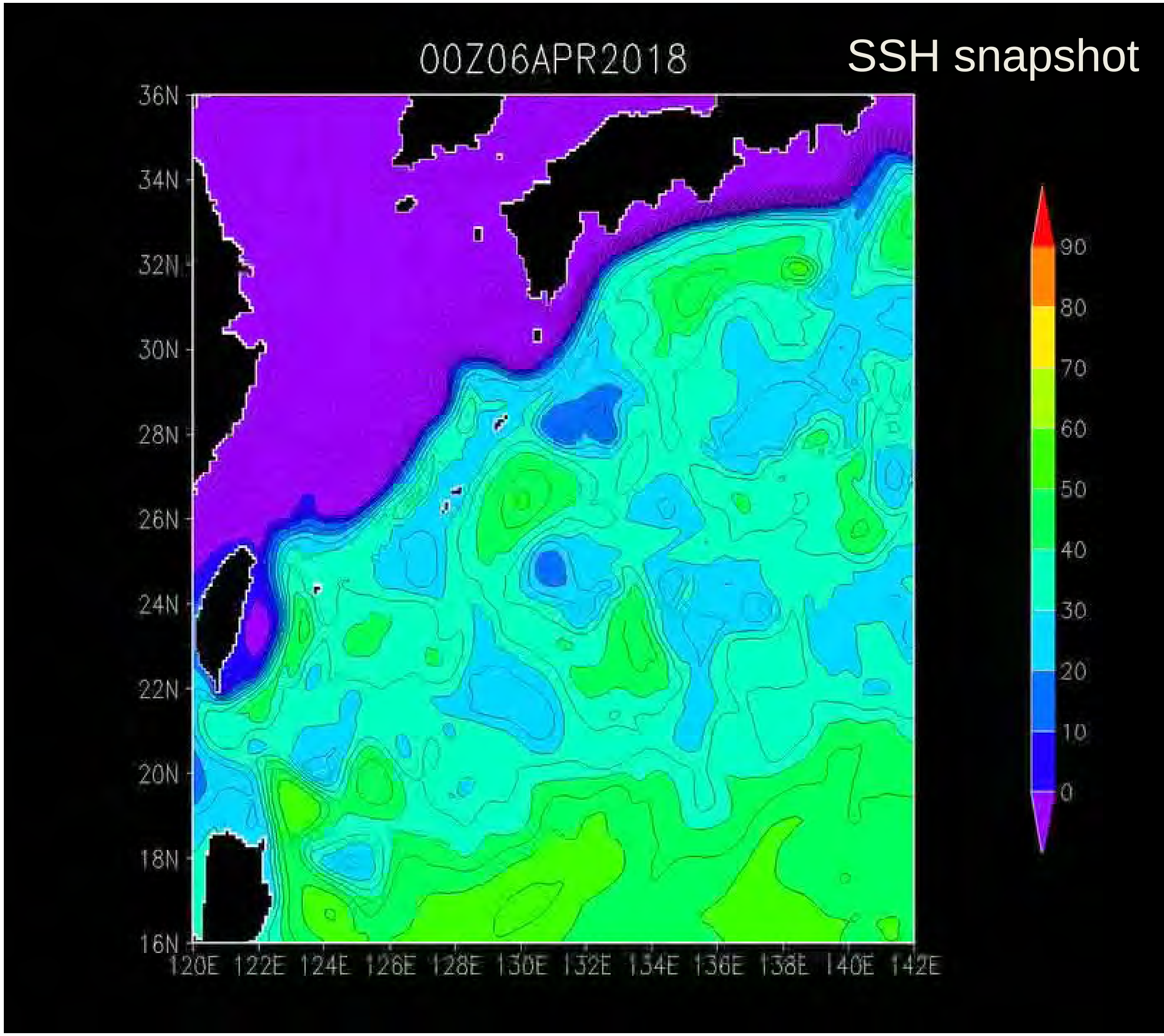
Transition process from the straight to meandering path

Anticyclonic eddy east of Taiwan is advected to south of Kyushu

↓

Generated small meander develops to a meandering path (consistent to observation)

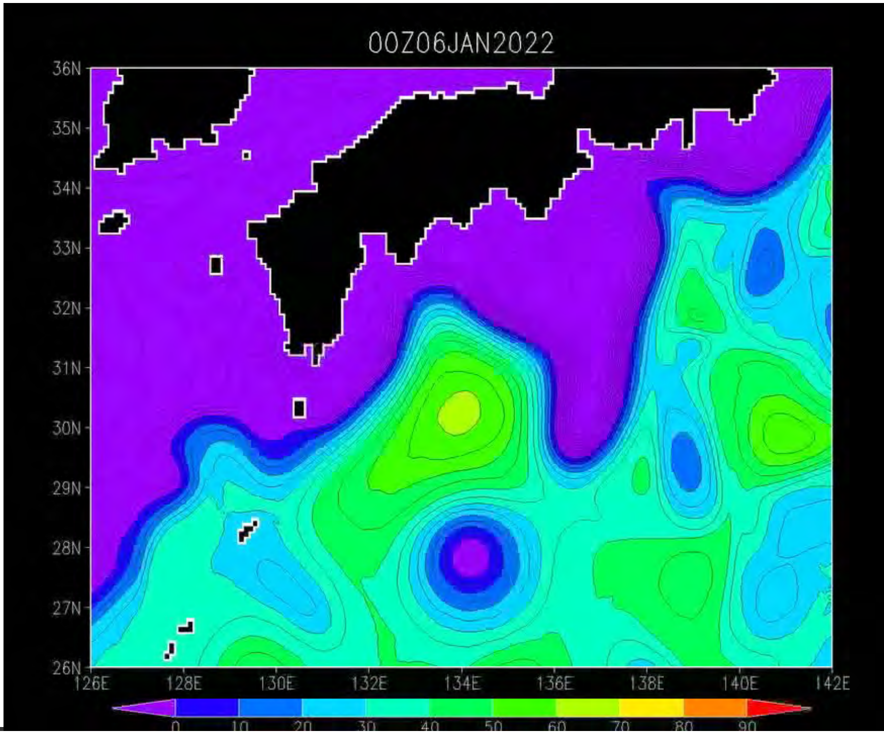
Similar process is pointed out by previous studies (eg., Akitomo and Kurogi 2001; Miyazawa et al., 2008)



Transition process from the meandering to straight path

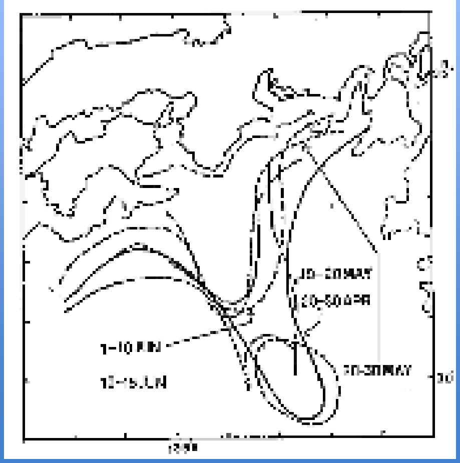
After several separation and coalescence of cold core eddy, the meandering part shifts eastward and shrinks into a straight path.

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

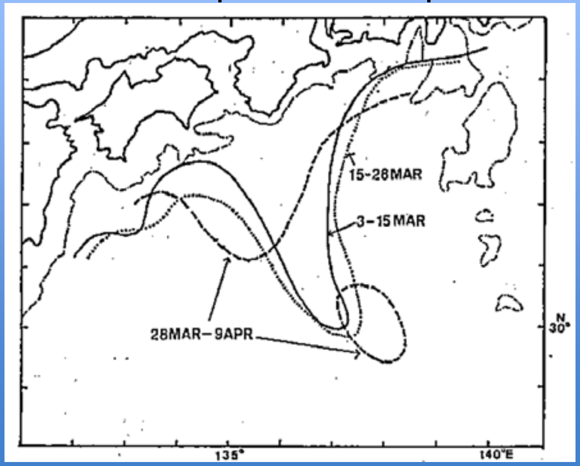


Separation of cold core eddy in the meandering period of 1975-1980 (Nishida 1982)

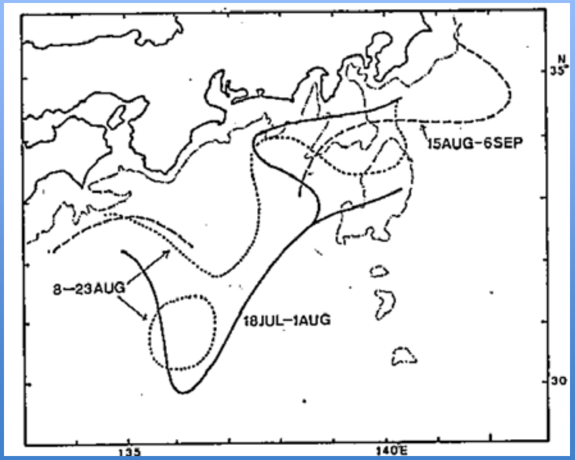
First separation in May 1977



Second separation in April1979



Third separation in August 1979



Summary

- Two-way nested-grid OGCM is developed and 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 is supposed to occur in multiple equilibrium regime and transition processes are consistent to observations.

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

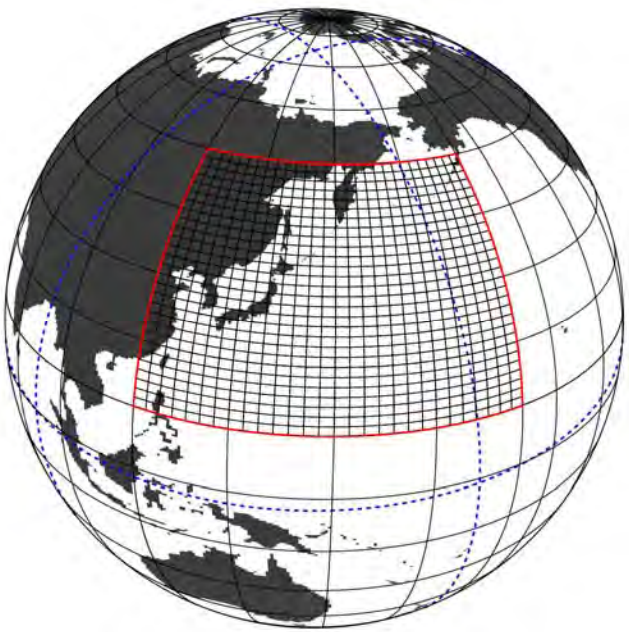
- The upper bound of velocity for the meandering path seems to be near the realistic range of velocity.

Thank you for your attention.

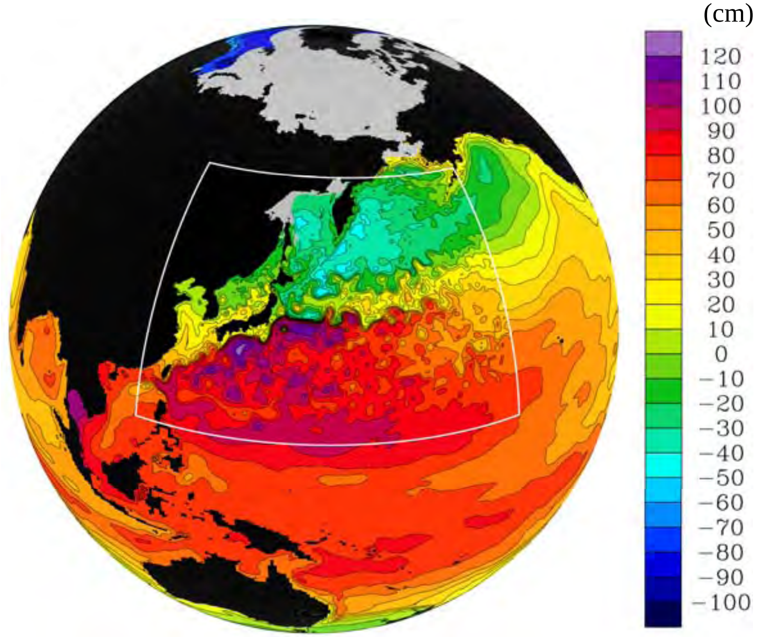
We are now developing global nested-grid OGCM

Example:

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



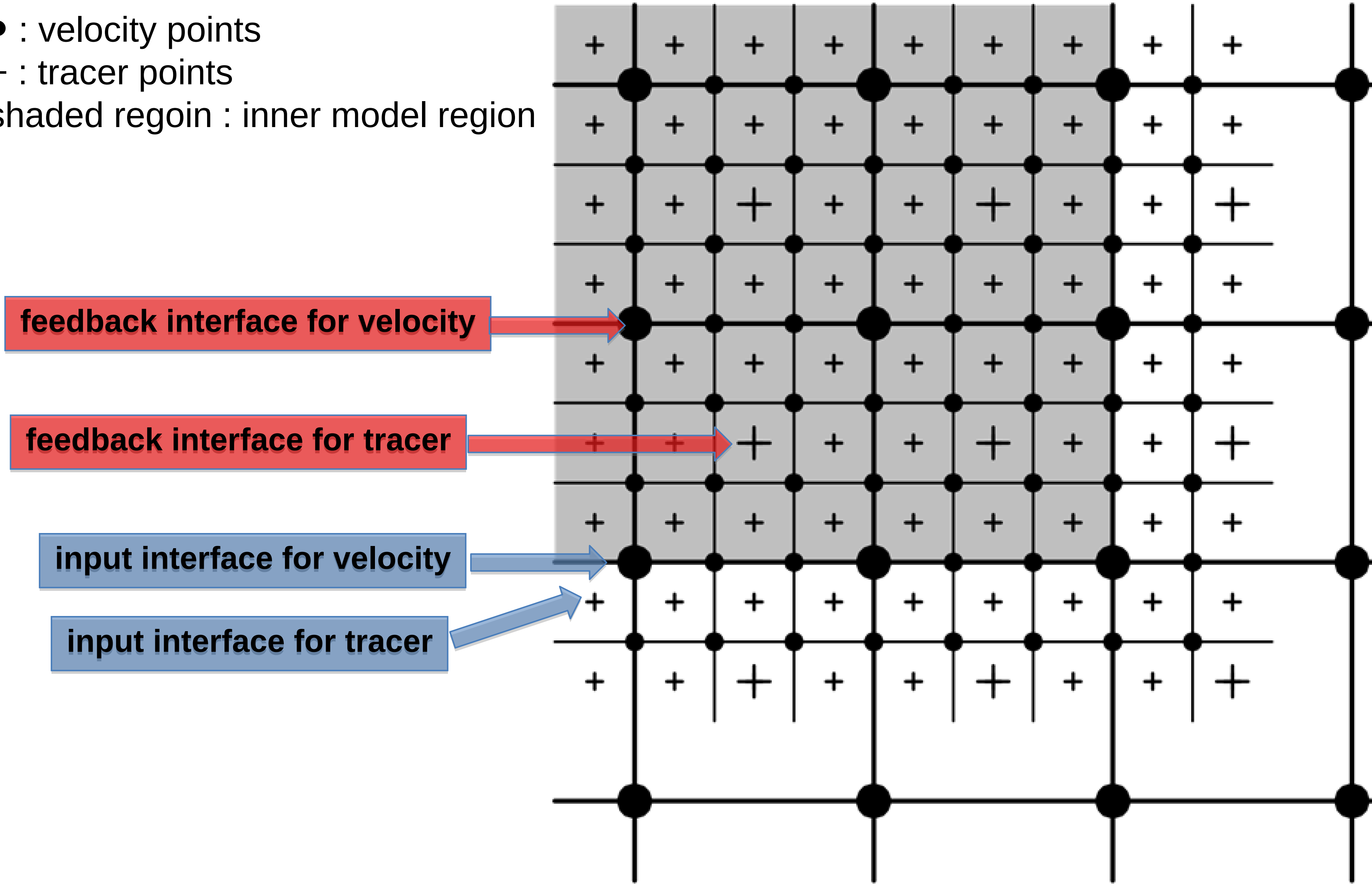
Grid arrangement of a nested-grid model (each box contains 32×32 grids). An region bounded by red line is nested into global model. Dotted lines indicate the equator and meridian (0, 90, 180, 270°E).



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.

An example of grid arrangement

● : velocity points
\+ : tracer points
shaded regoin : inner model region

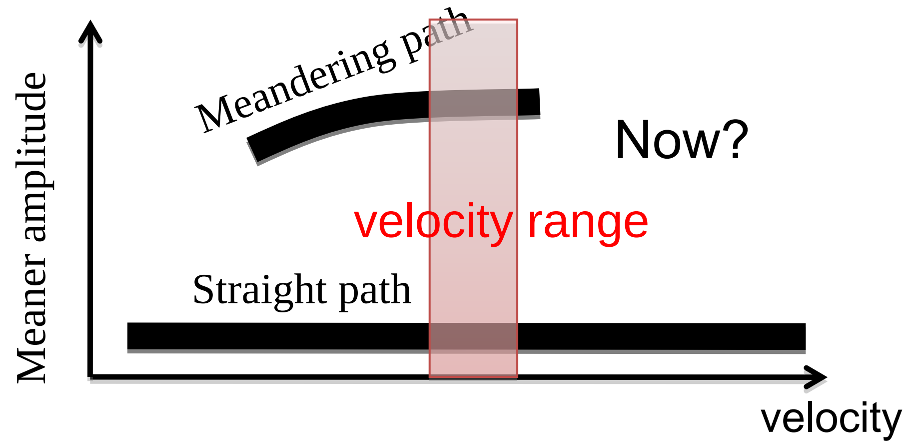


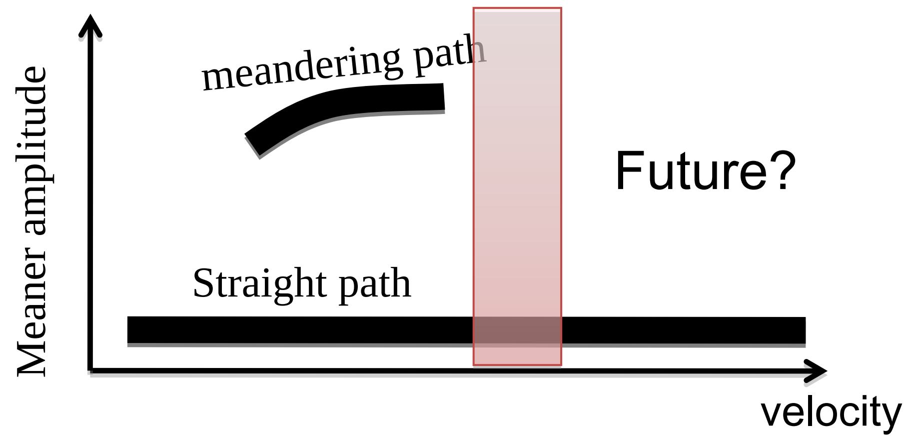
If global warming progress in the future,

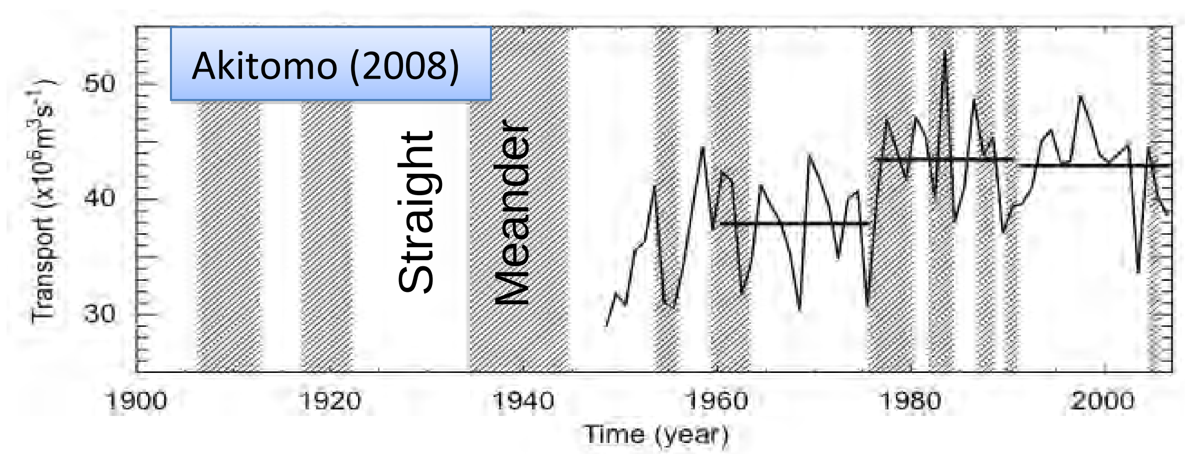
1)Stratification will be stronger and this causes decrease of the upper bound velocity for the meandering path (Kurogi and Akitomo, 2006)

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

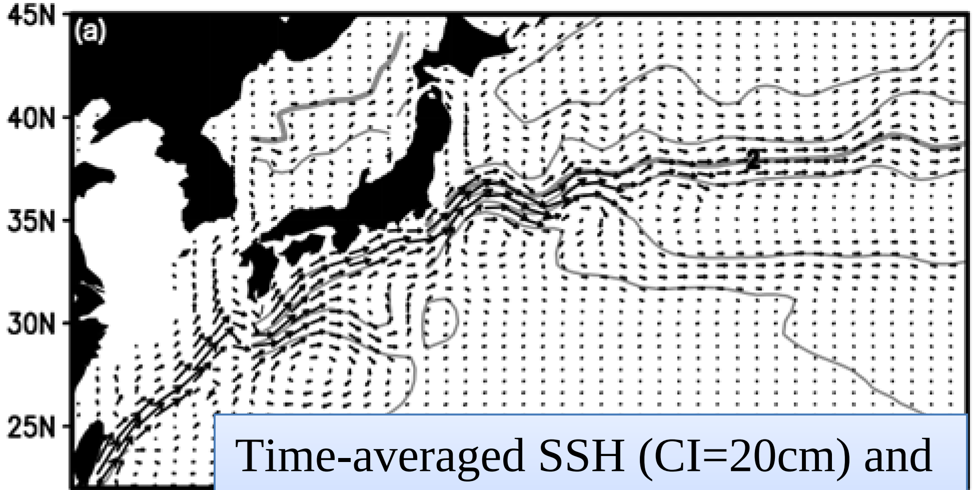
The meandering path may be hard to appear in the future. Possibly, this tendency may be already appear.





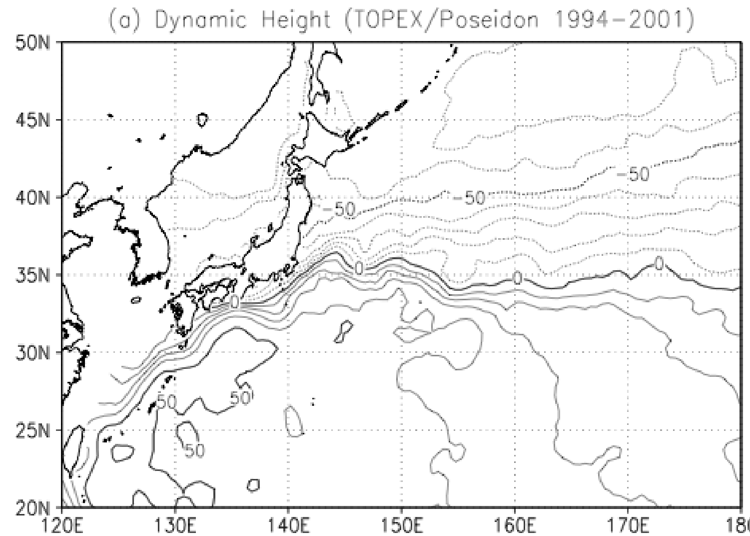


Horizontal resolution of current OGCM used for climate simulations is abuot 20km at the best (eddy-permitting). At this resolution, Kuroshio separates from southern coast of Japan at a realistic latitude.



Time-averaged SSH (CI=20cm) and 100m depth velocity (arrow) for high resolution coupled model. (Sakamoto et al., 2005)

Observed SSH (1984-2001, Tsujino et al., 2006)



Nested-grid model is based on COCO (CCSR Ocean Component Model) Ver. 4.2

Ocean

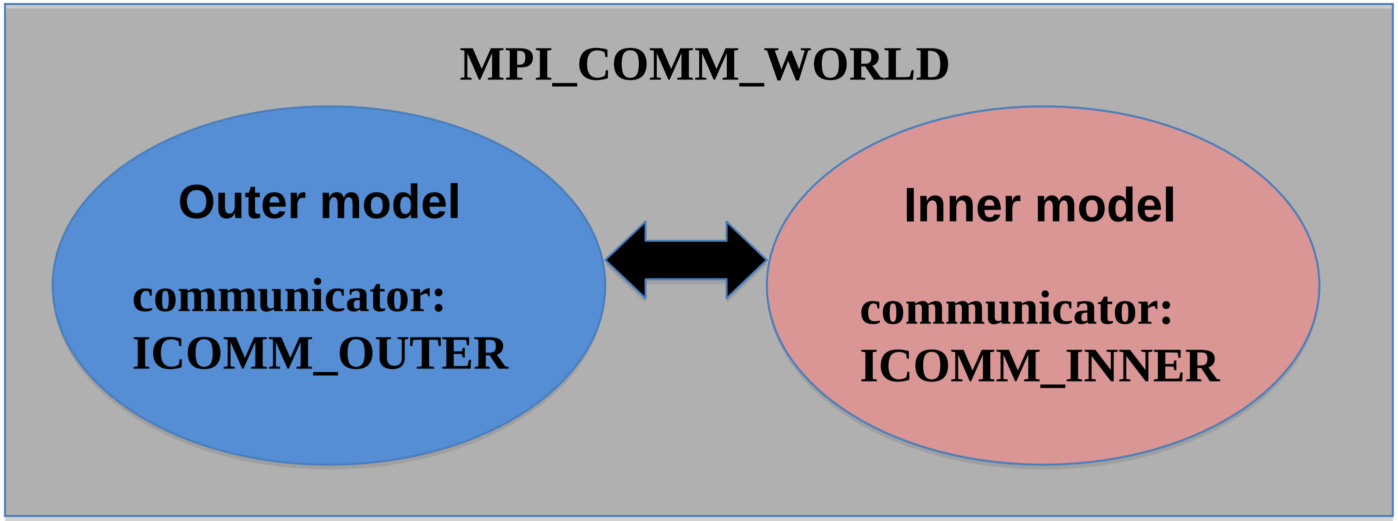
- primitive equation under hydrostatic and Boussinesq approximation
- explicit free surface
- generalized curvilinear horizontal coordinate and z-σ hybrid vertical coordinate

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)



Timing of communication between outer and inner model