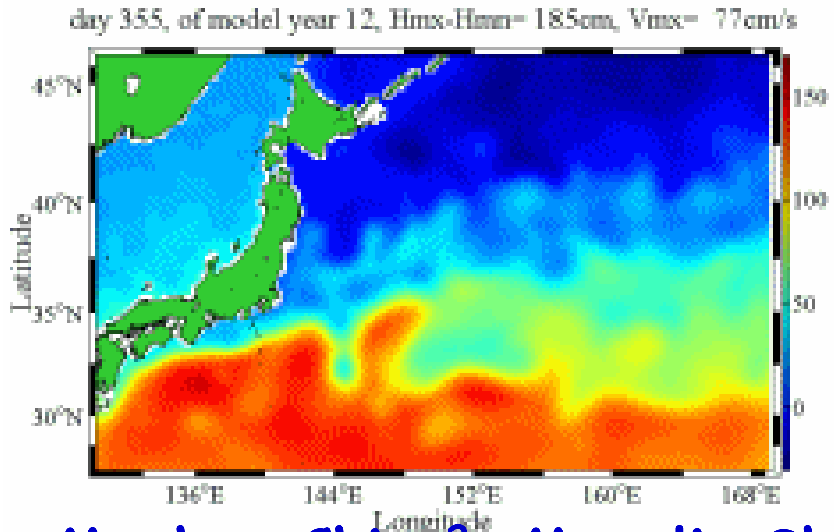
Parallel domain-decomposed Taiwan Multi-scale Community Ocean Model (PD-TIMCOM)



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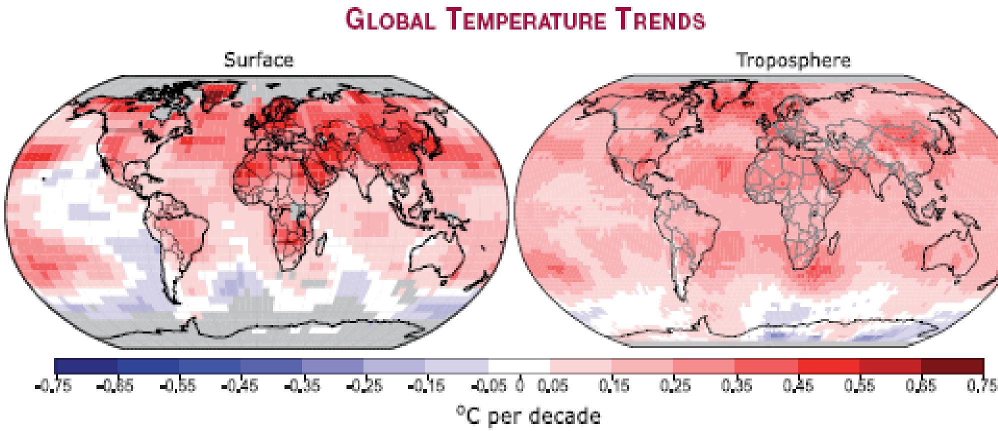
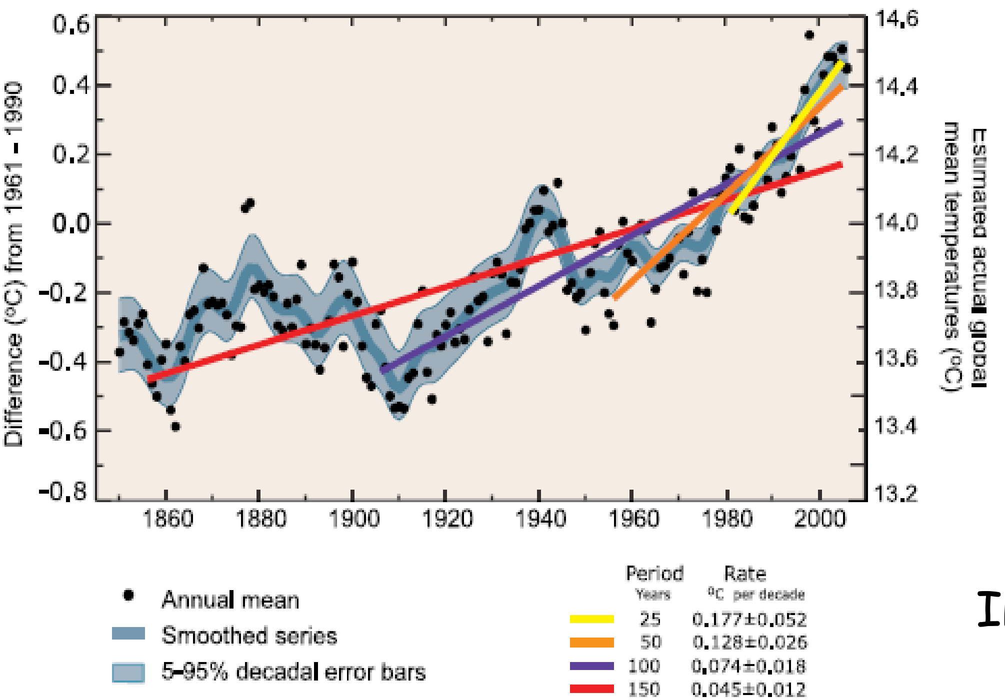
National Taiwan University

Acknowledgement: computing resources from NCHC, Taiwan and NERSC, USA

Climate change and ocean





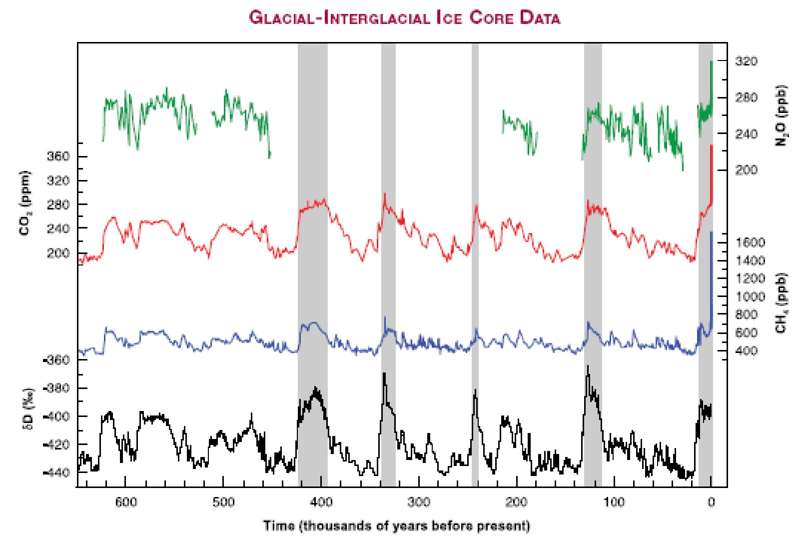
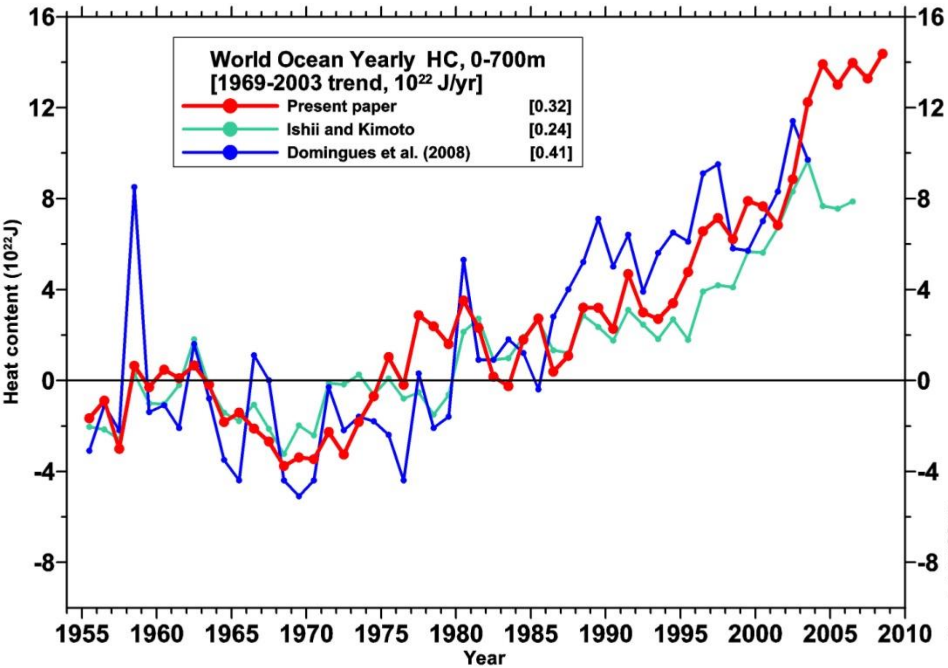
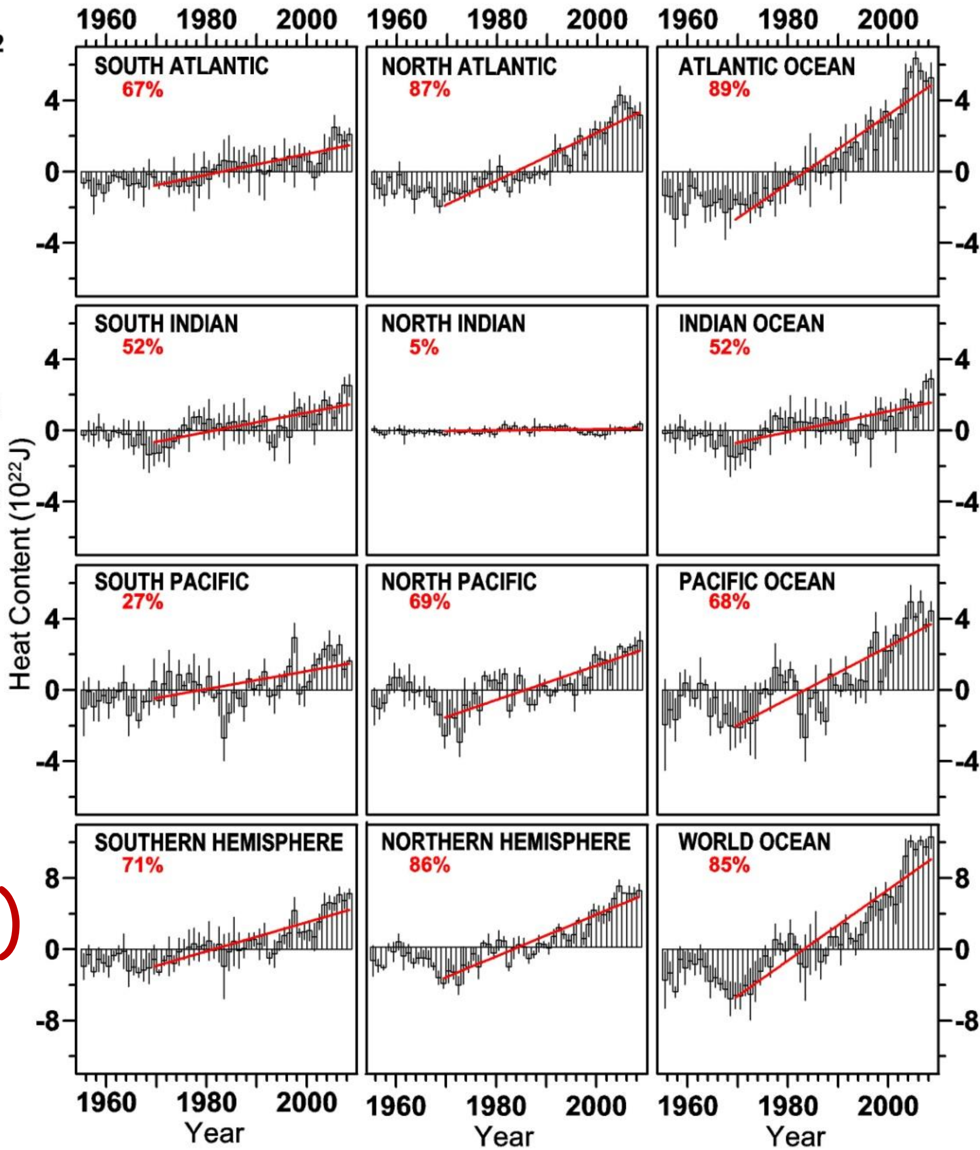


Figure TS.1. *Variations of deuterium (δD) in antarctic ice, which is a proxy for local temperature, and the atmospheric concentrations the greenhouse gases carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) in air trapped within the ice cores and from rece atmospheric measurements. Data cover 650,000 years and the shaded bands indicate current and previous interglacial warm period {Adapted from Figure 6.3}*

IPCC AR4 WG1 Technical Summary





Global ocean variation (long term warming trend)

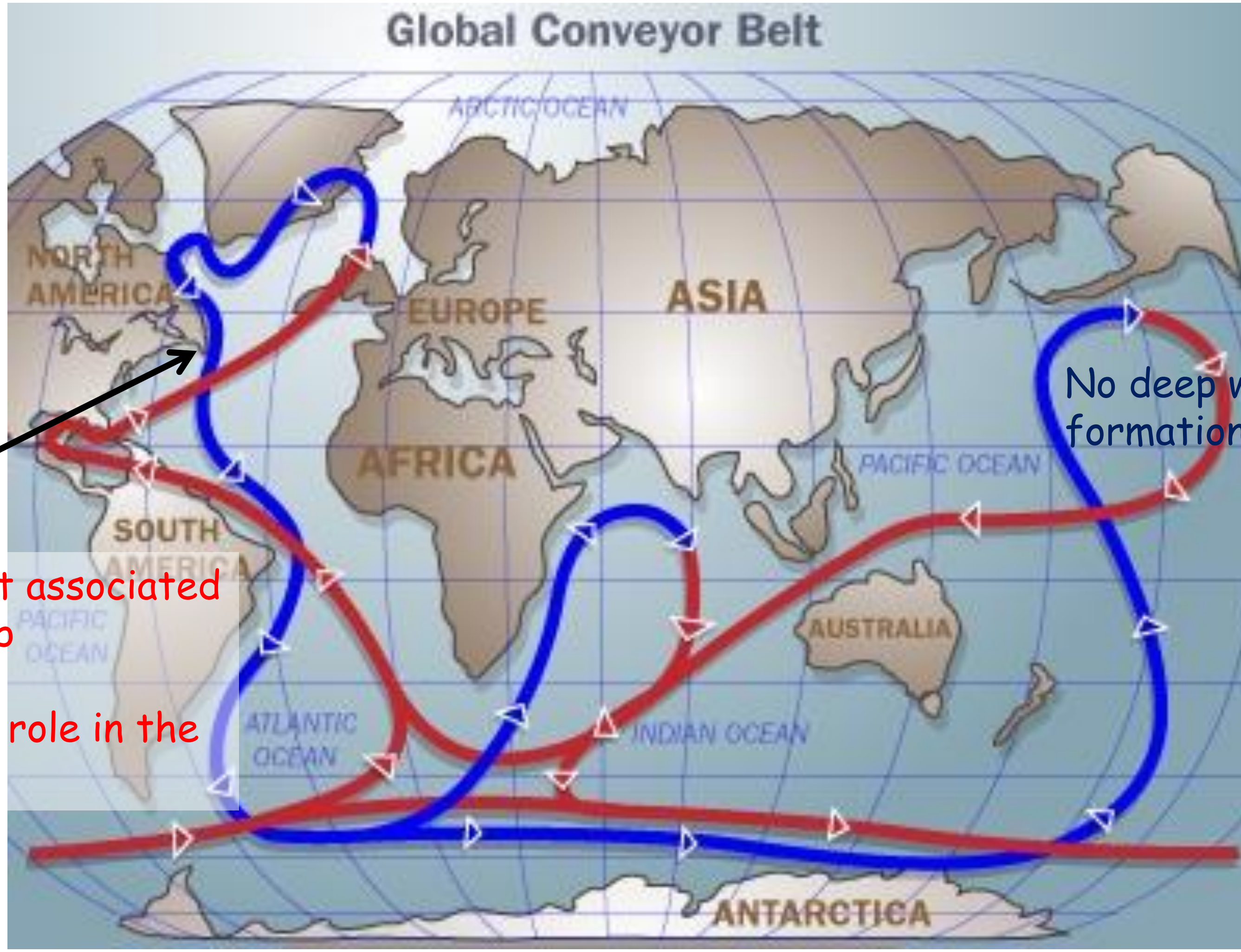
Levitus et al. (2009)

Global Thermohaline Circulation:

1, thermal forcing, when water is cooled and sinks, and

2, haline forcing, when excess precipitation makes water less dense, and thus resistant to sinking.

Driven by the sinking of cold, saline water



No deep water formation

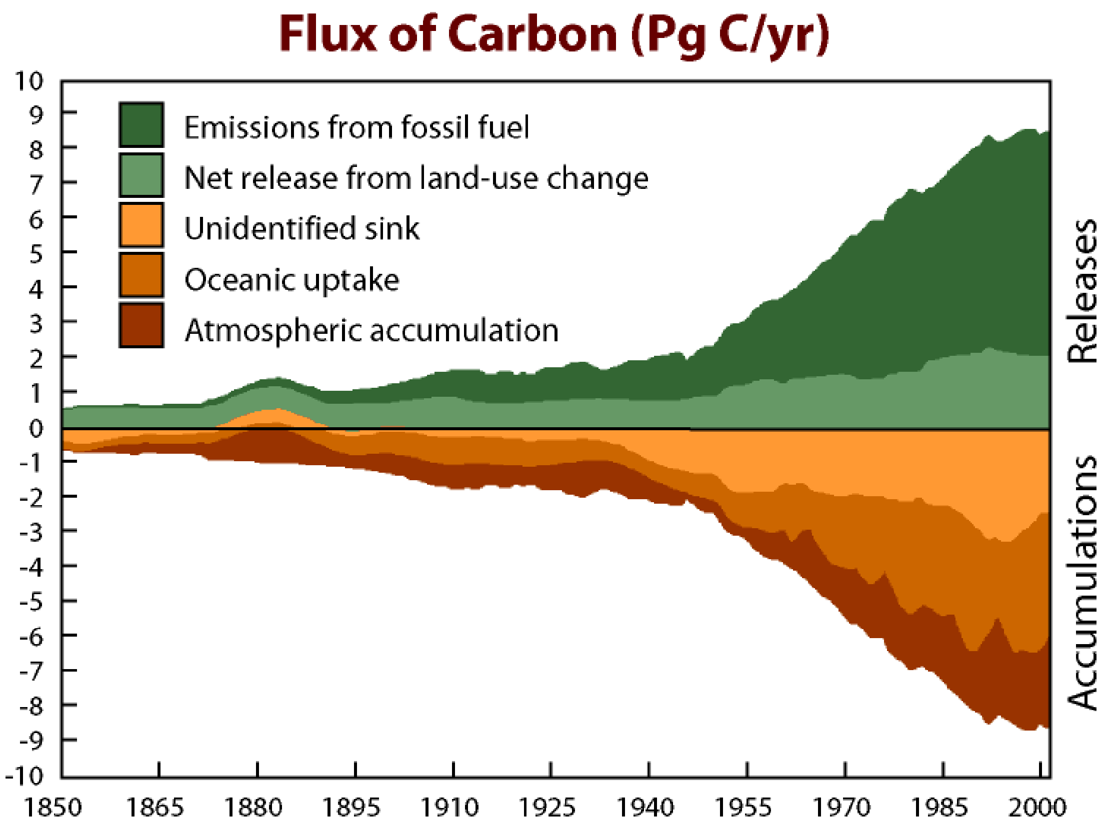
The heat transport associated with "Atlantic deep circulation"
plays an important role in the present climate.

http://science.howstuffworks.com/ocean-current3.htm

Famous Japanese comic strip:
海賊王

Thermohaline circulation

Global Carbon Budget



Ocean uptake
~2.4 PgCyr^{-1}
Mainly biological

A small fraction of carbon-flow through the ocean system
So variability can have a big effect on balance

http://www.whrc.org/carbon/missingc.htm

Unidentified sink of 2.1+/-1.1 PgC/yr needed to balance budget

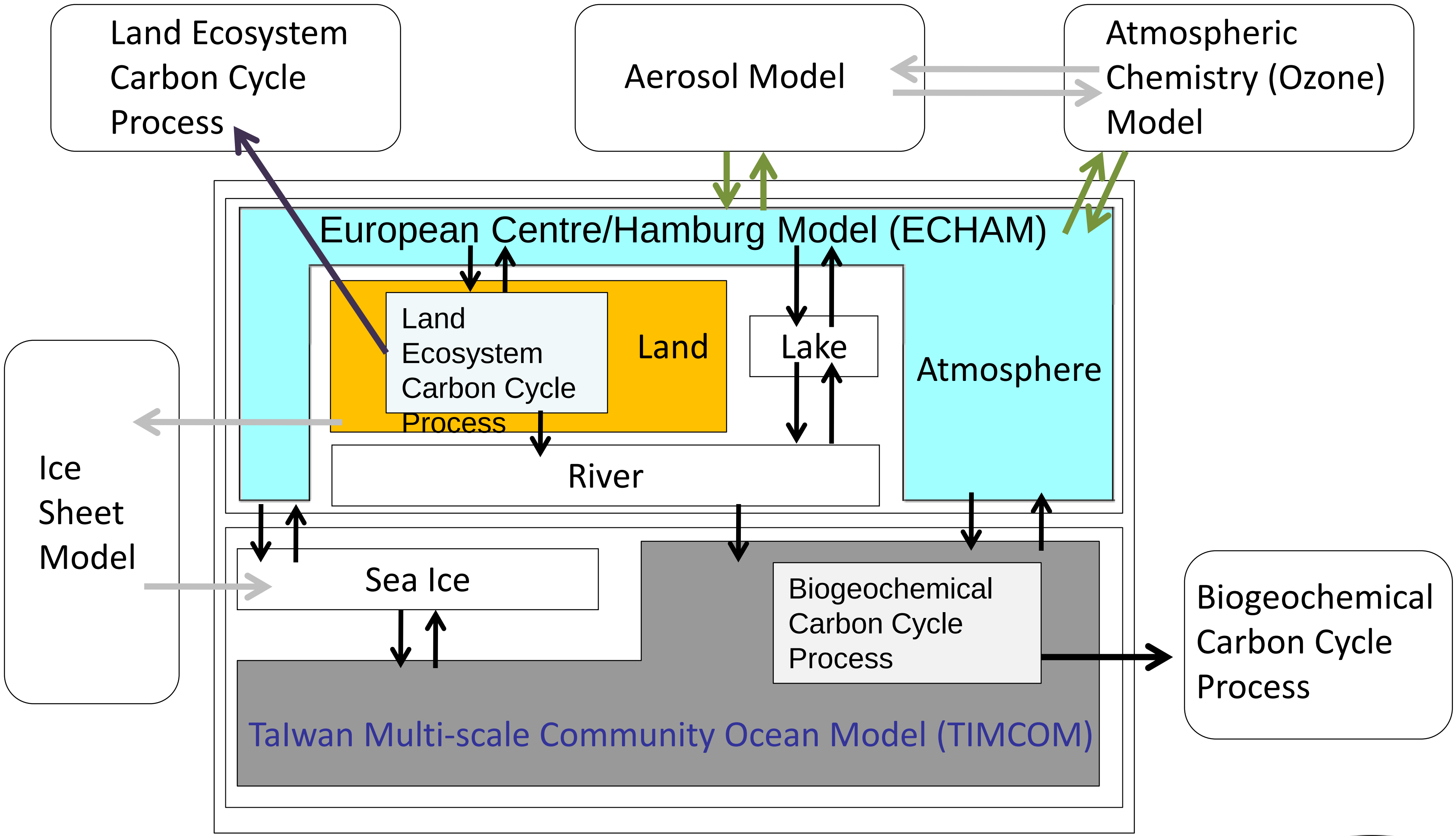
Outline

- Objectives and Backgrounds
- Development of TaIwan Multi-scale Community Ocean Model (TIMCOM)
  - http://140.112.66.144/research/timcom
  - North Atlantic Ocean Modeling System
  - North Pacific Ocean Modeling System
- Parallel Domain-decomposed TIMCOM (PD-TIMCOM)
  - Parallel EVP solver
  - Preliminary results
- Summary

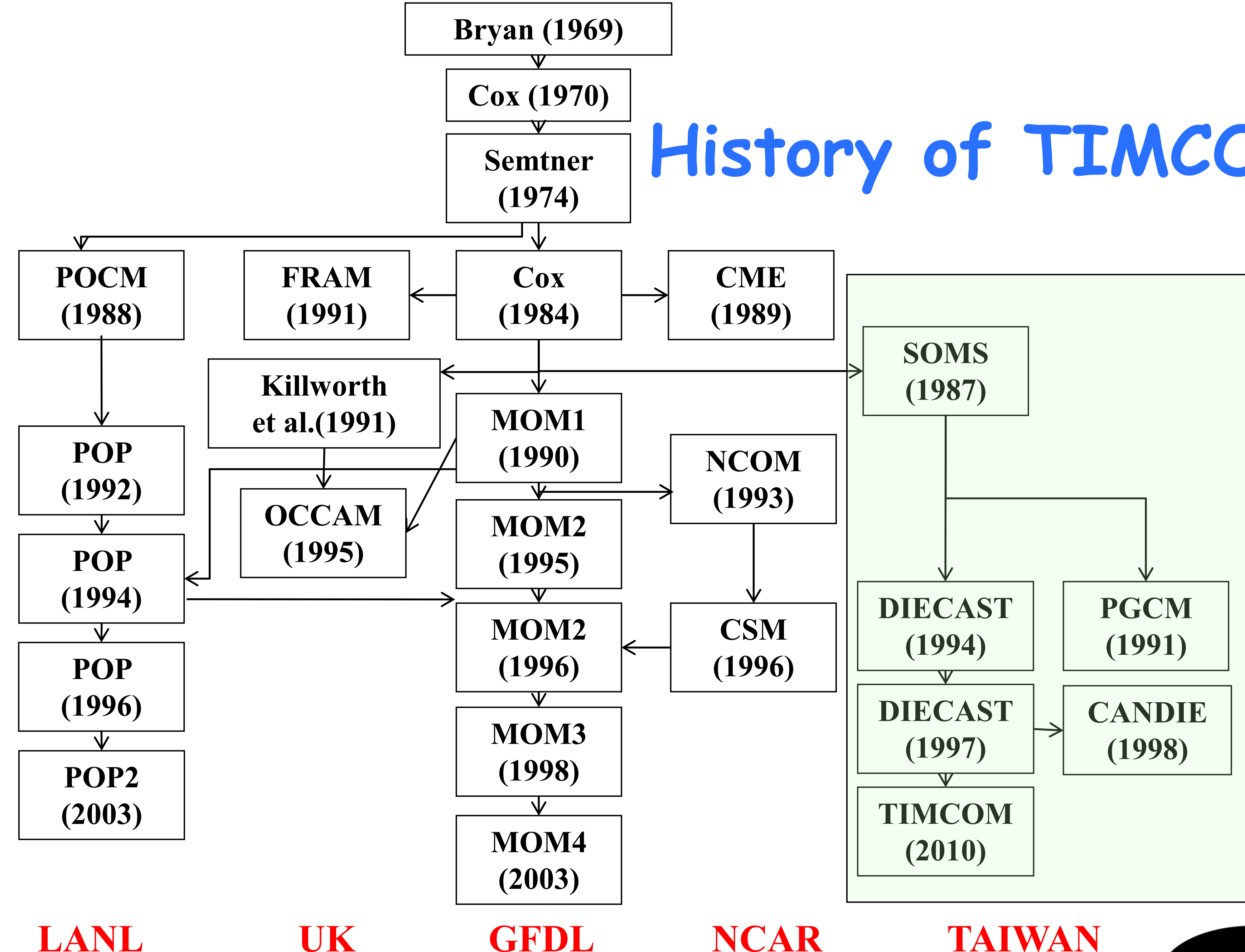
Objectives

- Building a high performance, multiple-grids global ocean circulation model for global ocean climate study in an Earth System Model Framework
- Resolving multi-scale dynamics with the most efficient two-ways coupling approach (serial code) or parallel solver (parallel code) in high accuracy
- Studying the Pacific ocean climate
- Investigating the regional circulation in the vicinity of Taiwan

Taiwan Earth System Model



History of TIMCOM



Governing Equations

λ: the longitudinal variable
ϕ: the latitudinal variable
z: the vertical variable

Continuity eqn. $$\frac{1}{R\cos\phi}\left(\frac{\partial u}{\partial \lambda}+\frac{\partial(v\cos\phi)}{\partial\phi}\right)+\frac{\partial\omega}{\partial z}=0$$

Momentum eqn.

$$\frac{\partial u}{\partial t}=-\mathcal{L}u+\left(f+\frac{u\tan\phi}{R}\right)v-\frac{1}{\rho_0 R\cos\phi}\frac{\partial p}{\partial\lambda}+D_m u+\frac{\partial}{\partial z}\left(A_u\frac{\partial u}{\partial z}\right)$$

$$\frac{\partial v}{\partial t}=-\mathcal{L}v-\left(f+\frac{u\tan\phi}{R}\right)u-\frac{1}{\rho_0 R}\frac{\partial p}{\partial\phi}+D_m v+\frac{\partial}{\partial z}\left(A_v\frac{\partial u}{\partial z}\right)$$

Conservation eqn. for temperature and salinity

$$\frac{\partial T}{\partial t}=-\mathcal{L}T+D_h T+\frac{\partial}{\partial z}\left(K_T\frac{\partial T}{\partial z}\right)$$

Eqn. of State

$$\rho=\rho(S,T,p)$$

Hydrostatic Eqn. $$\frac{\partial p}{\partial z}=-(\rho-\bar{\rho})g$$

$$D_{m(h)}=\frac{A_{m(h)}}{R^2}\left(\frac{1}{\cos^2\phi}\frac{\partial^2}{\partial\lambda^2}-\tan\phi\frac{\partial}{\partial\phi}+\frac{\partial^2}{\partial\phi^2}\right)\qquad \mathcal{L}=\frac{u}{R\cos\phi}\frac{\partial}{\partial\lambda}+\frac{v}{R}\frac{\partial}{\partial\phi}+\omega\frac{\partial}{\partial z}$$

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MEDiNA model: Bathymetry (km) and sub-domains

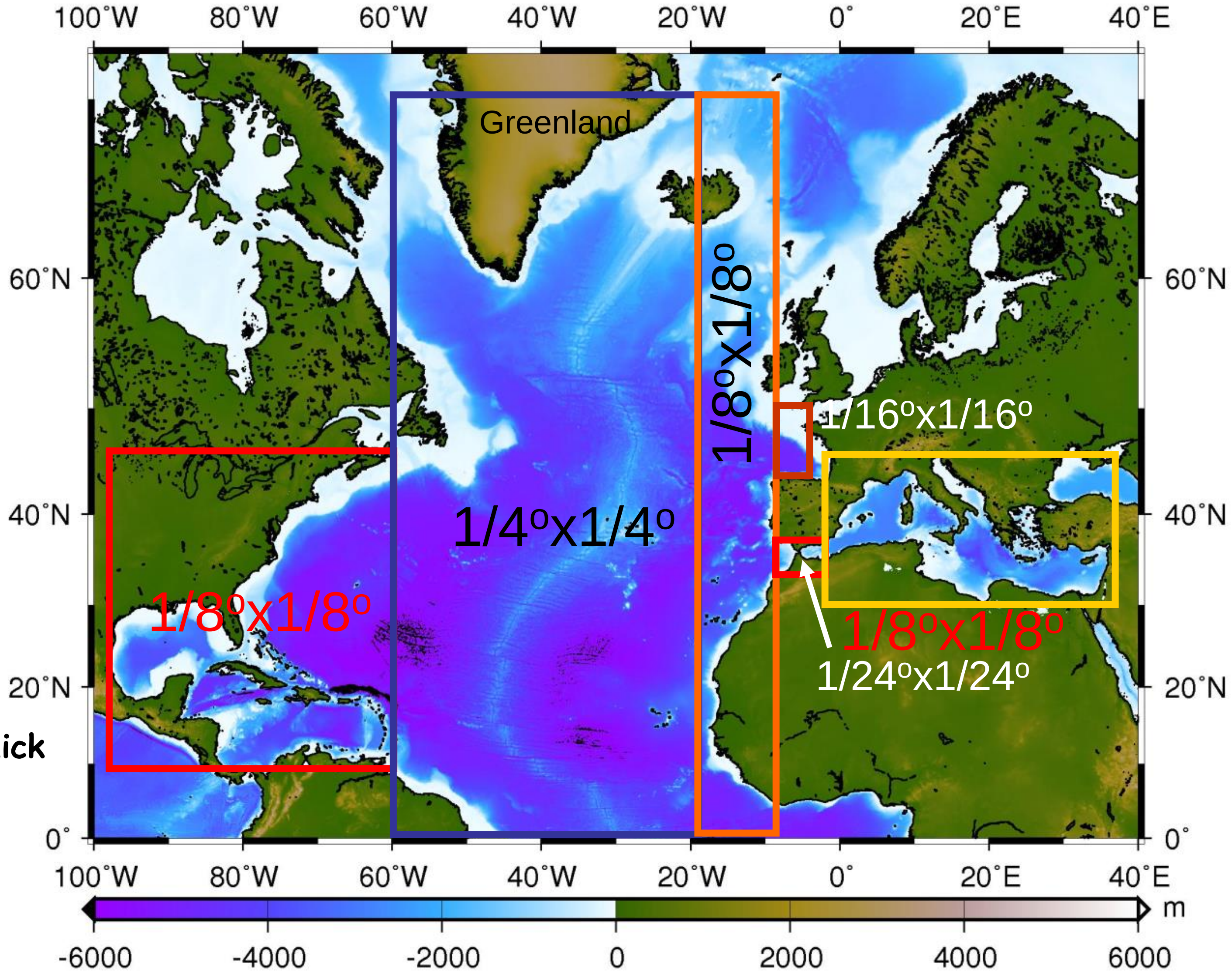
Six domain:

- GOM (1/8º) 304x336
- NAB (1/4º) 162x398
- IBE (1/8º) 100x794
- VIS (1/16º) 60x158
- GIB (1/24º) 125x107
- MED (1/8º) 316x157

30 vertical layers;

top layer 11 m thick;

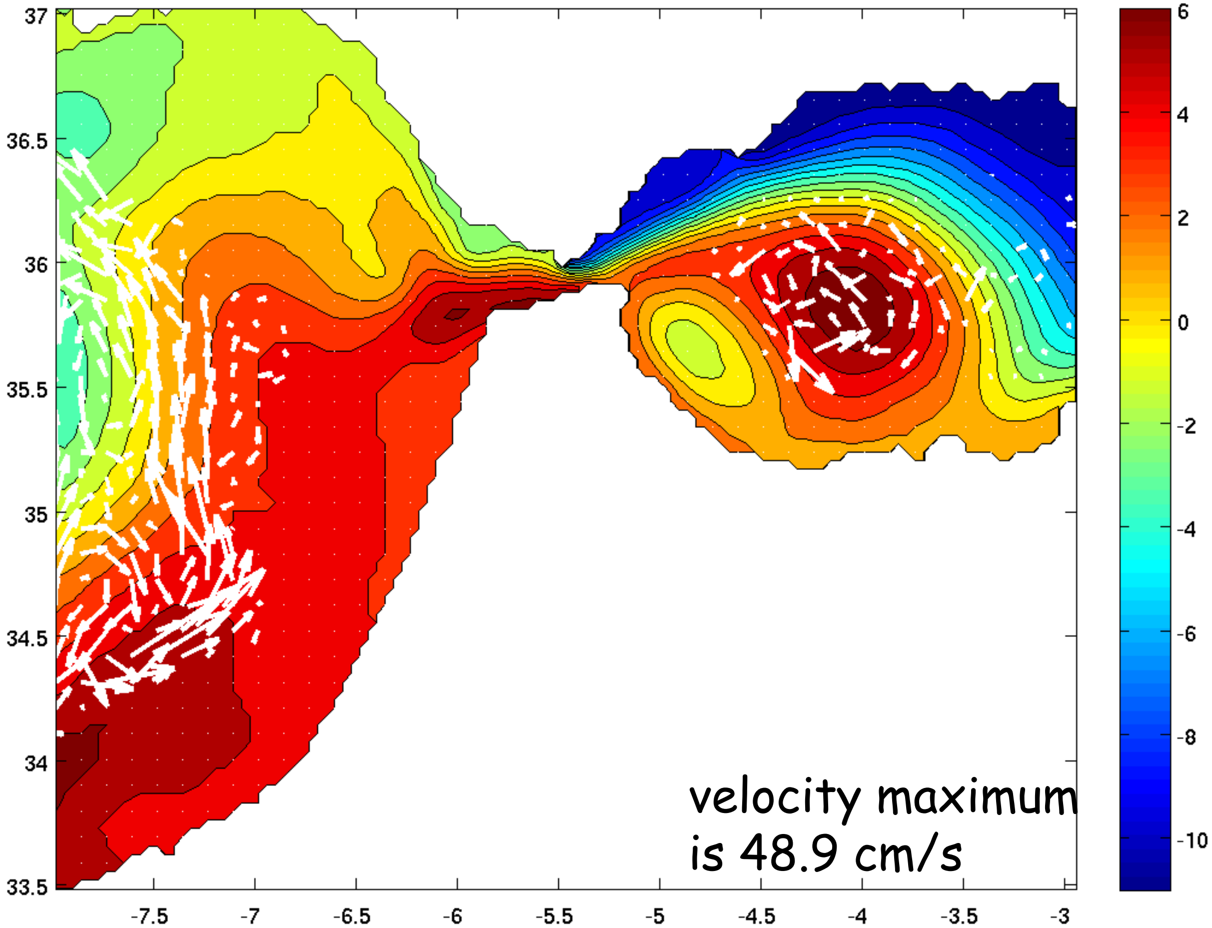
bottom layer 750 m thick



- 4^{th} order accurate, Z-level, rigid-lid approximation
- Mixed Arakawa "a" and "c" grid TaiCOM
- The control volume equations include fluxes of the conservation of **momentum**, **heat** and **salt** across control volume faces.
- Bathymetry:
  - Interpolated from unfiltered ETOPO2 depth data
  - Supplemented with NCOR's 1-minute high accuracy depth archive.
- The vertical resolution ~ linear-exponential stretched grid, 26 layers
  - Z=6, 20, 36, 54, 75, 98, 126, 159, 198, 244, 298, 364, 442, 537, 652, 790, 958, 1161, 1408, 1709, 2075, 2520, 3063, 3725, 4532 m.
- Varying latitude and uniform longitude grid (Mercator grid).
- Surface forcing:
  - Use interpolated monthly Hellerman and Rosentstein winds (Hellerman and Rosenstein, 1983).
  - Use Levitus'94 climatology (Levitus and Boyer, 1994) to initialize the model and determine its surface sources of heat and fresh water.
- The northern boundary is closed. The southern boundary condition (30°S) is slow nudging toward climatology in a sponge layer. The bottom is insulated, with non-slip conditions parameterized by a nonlinear bottom drag.
- Sub-grid scale vertical mixing is parameterized by eddy diffusivity (for temperature and salinity) and viscosity (for momentum) using a modified Richardson number based approach based on Pacanowski and Philander (1982)

Theory, observation and modelling

Strait of Gibraltar domain



Annual averaged sea surface height and velocity vectors (1000m)

Dietrich et al. (2008)

Theory, observation and modelling

Strait of Gibraltar domain

Western Alboran Gyre (WAG)

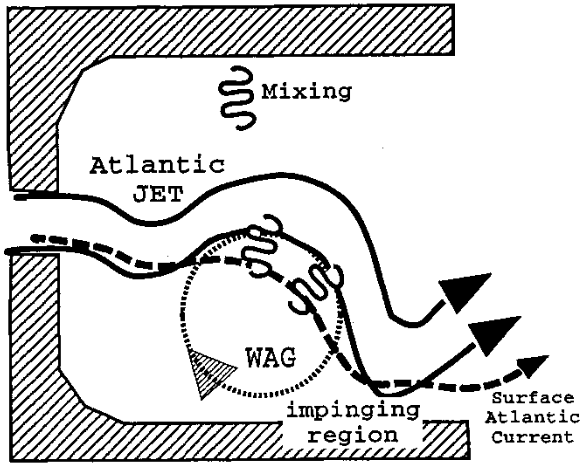
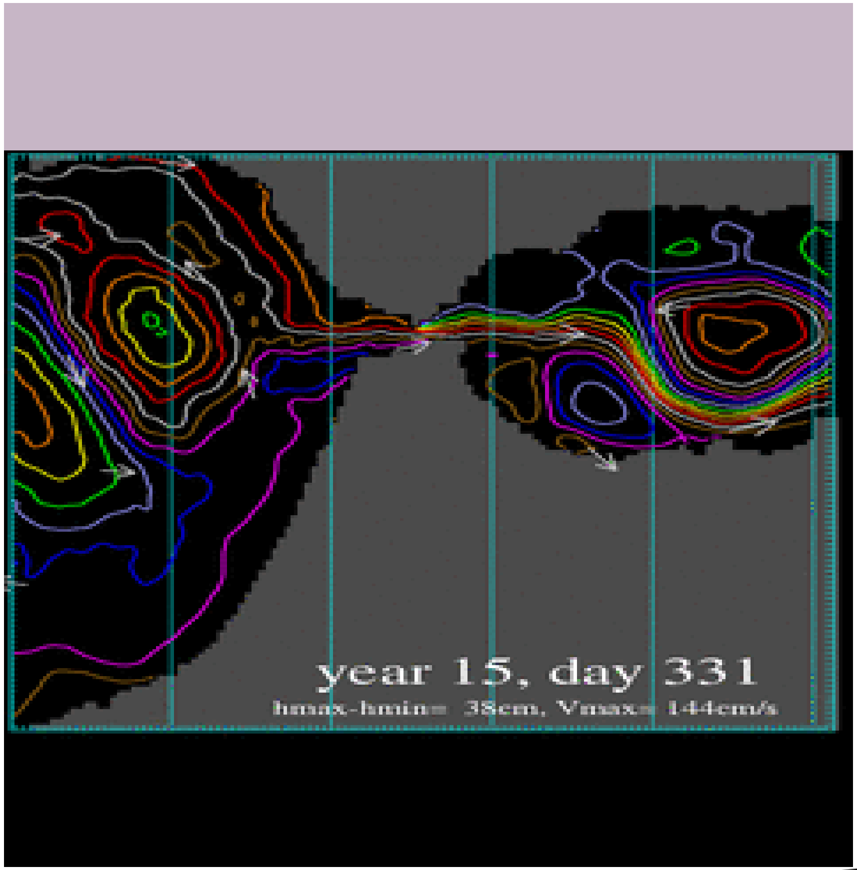
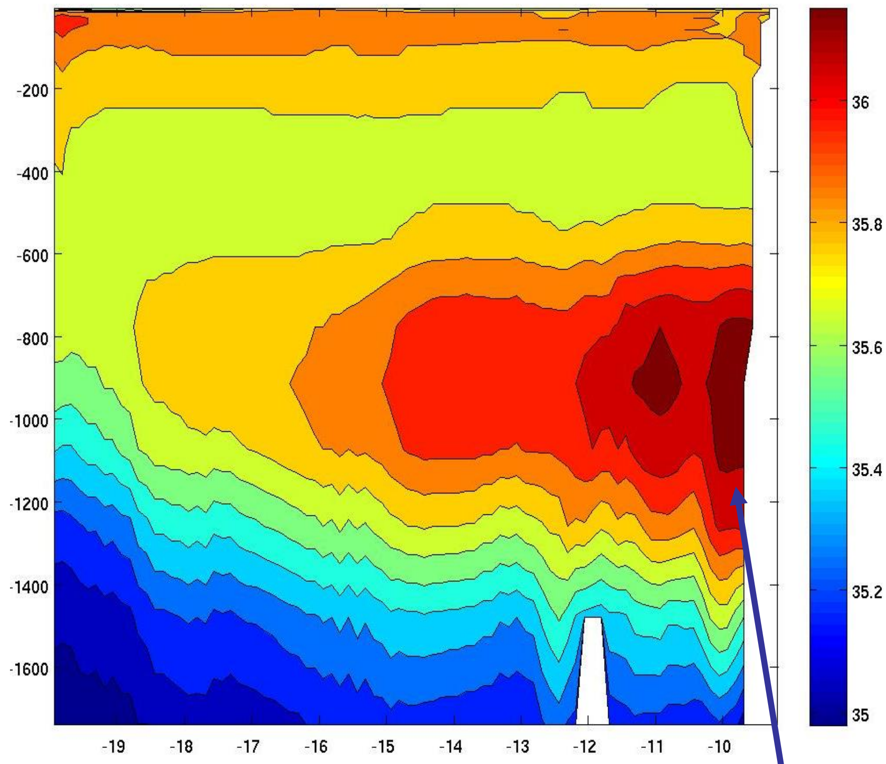


Figure 3. Sketch of the upper circulation (0-200 m) in the western Alboran basin. The surface Atlantic current, characterized by a salinity minimum, may enter into the western Alboran gyre (WAG) crossing the isolines of dynamic height anomaly produced by the deeper density gradients of the gyre. After mixing briefly with water in the core of the WAG, this surface Atlantic current leaves the WAG through the impinging region on the African coast.

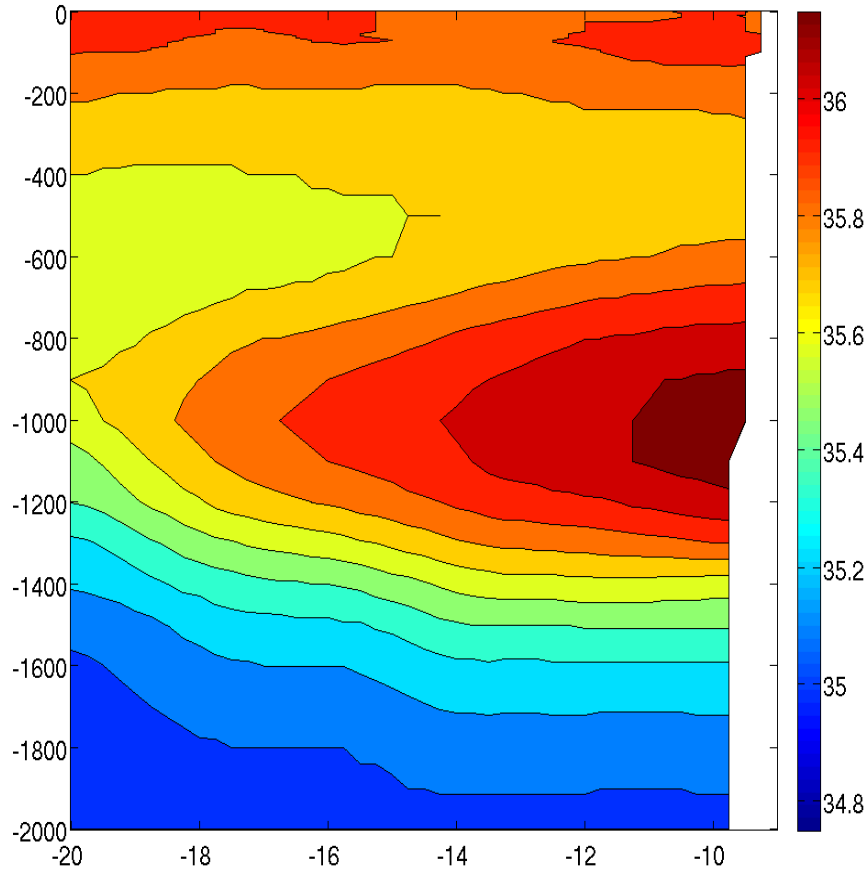
Viúdez, Pinot and Haney (1998)



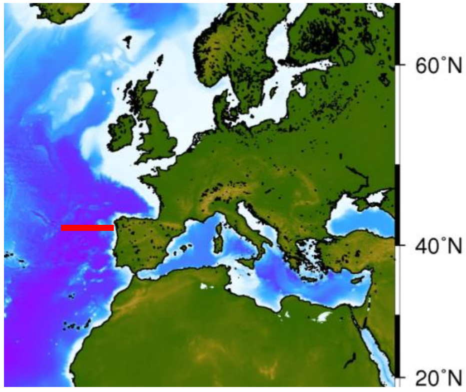
Vertical/longitudinal salinity section at 43°N



Annual averaged model results



U. S. Navy's GDEM climatology



High salinity water affecting the global THC

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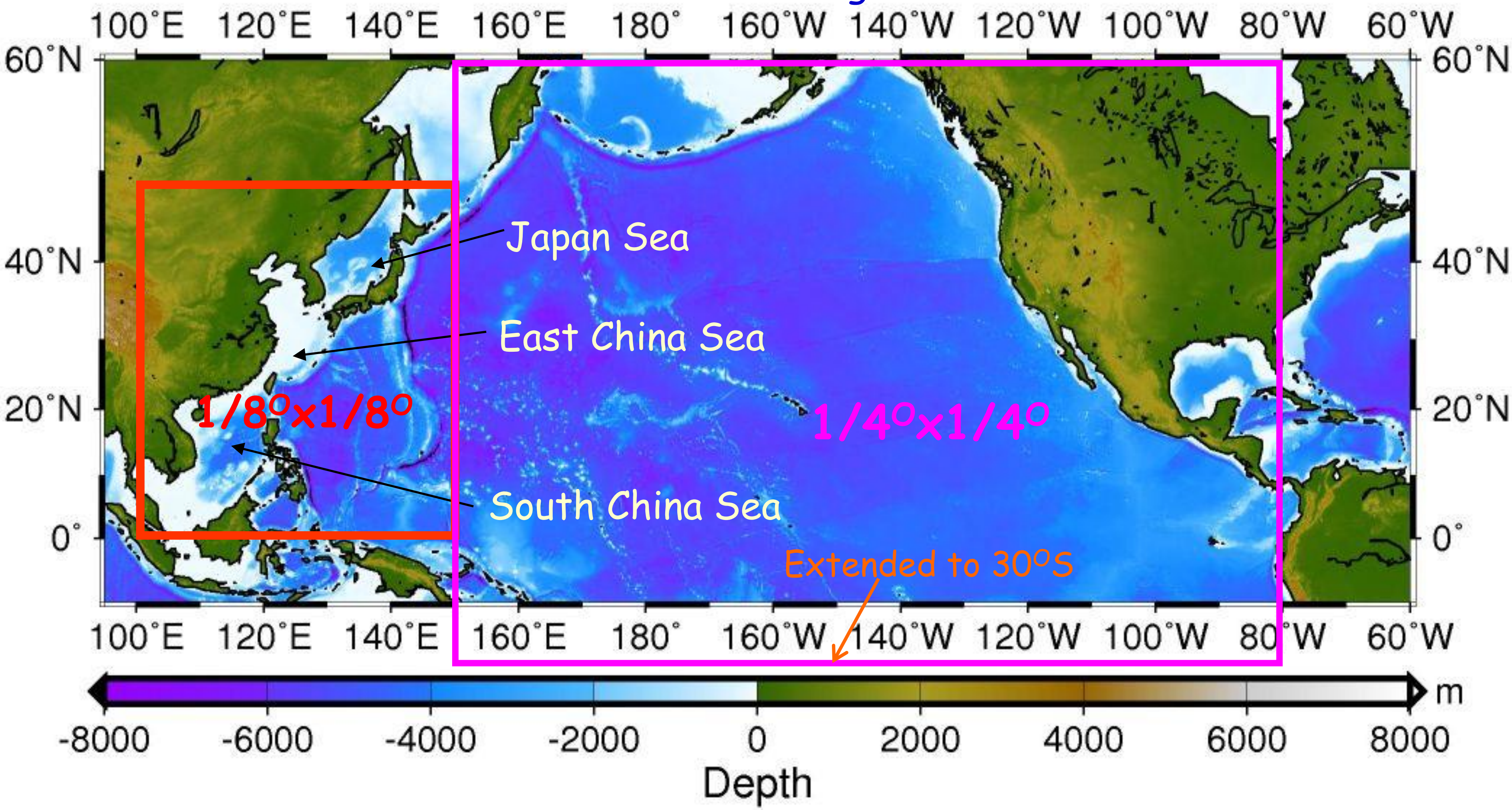
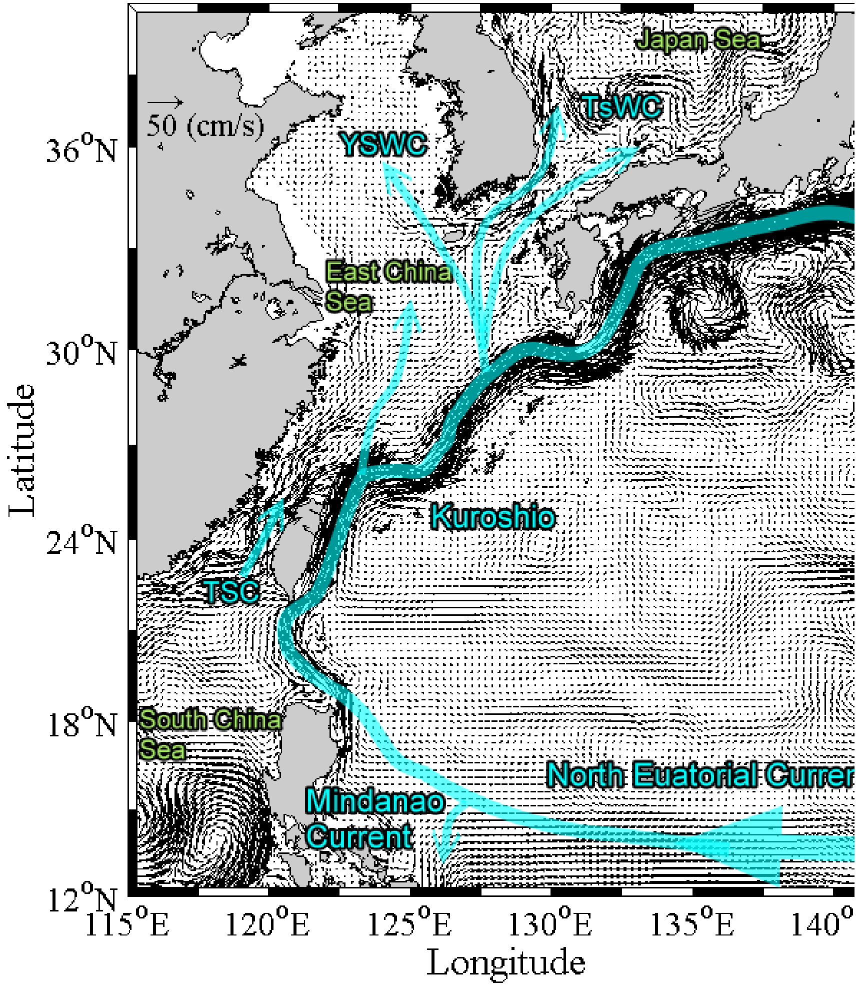
Dual-grid Pacific Ocean Model (DUPOM)

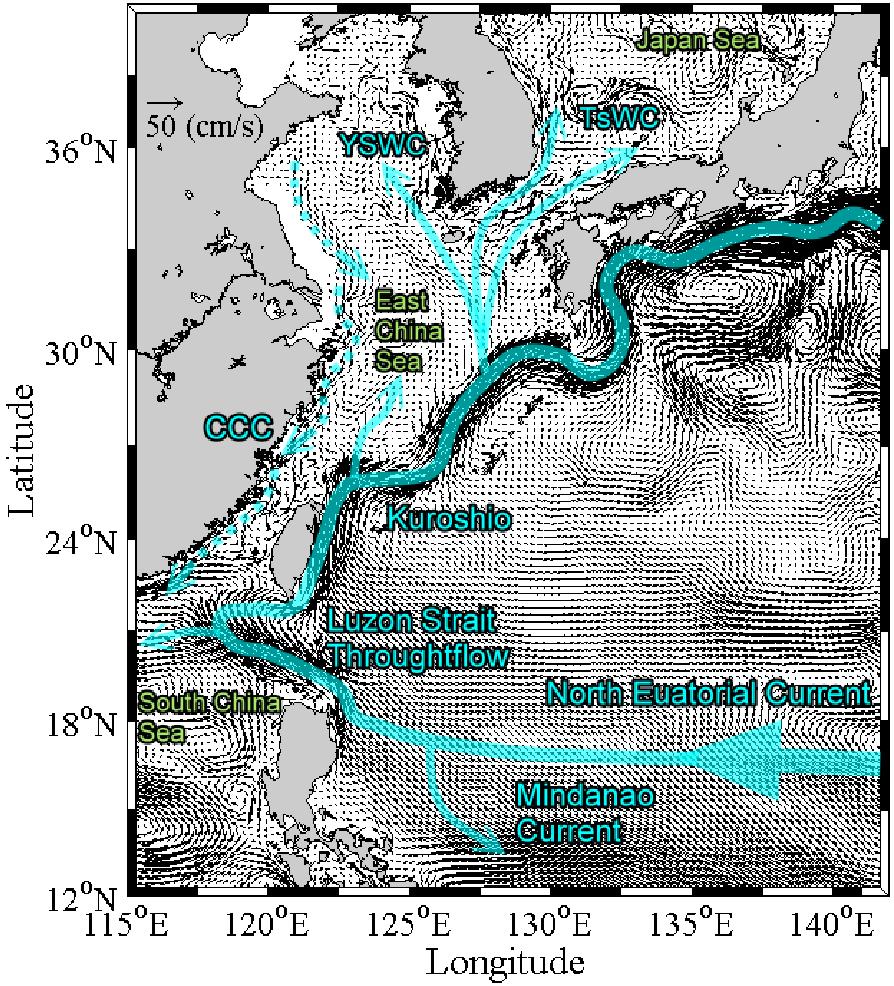
NPB (North Pacific Basin) Domain:
30°S to 60°N and 150°E to 80°W
grid resolution 1/4°
TAI Domain:
0° to 50°N and 100°E to 150°E
grid resolution 1/8°



General seasonal circulation pattern-DUPOM



Summer



Winter

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- To solve the pressure correction equation in OGCMs with hydrostatic approach, an efficient Poisson equation solver is needed.

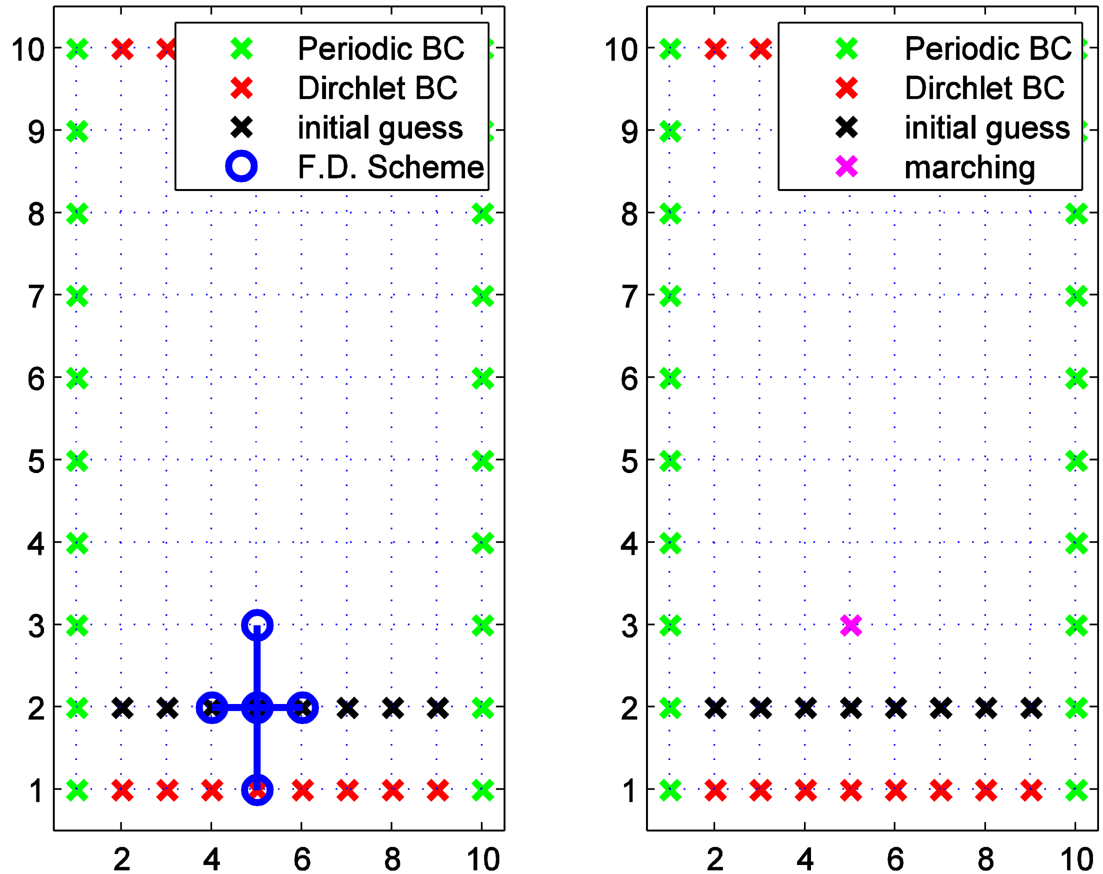
$$\begin{cases} \dfrac{\partial^2 u}{\partial x^2} + \dfrac{\partial^2 u}{\partial y^2} = \Phi \\ Boundary\ Condtion \end{cases}$$

- In a finite difference discretization form

$$\frac{u_{i+1,j} - 2u_{i,j} + u_{i-1,j}}{\delta x^2} + \frac{u_{i,j+1} - 2u_{i.j} + u_{i,j-1}}{\delta y^2} = \phi_{i,j}$$

- Choose an initial guess $u'_{i,2}$ from the boundary, where $u_{i,2}= u'_{i,2}+e$
- March the solution over the whole domain.

$$u'_{i,j+1} = \delta y^2 \phi_{i,j} + 2u'_{i,j}\left(1+\frac{\delta y^2}{\delta x^2}\right) - \frac{\delta y^2}{\delta x^2}\left(u'_{i-1,j} + u'_{i+1.j}\right) - u'_{i.j-1}$$

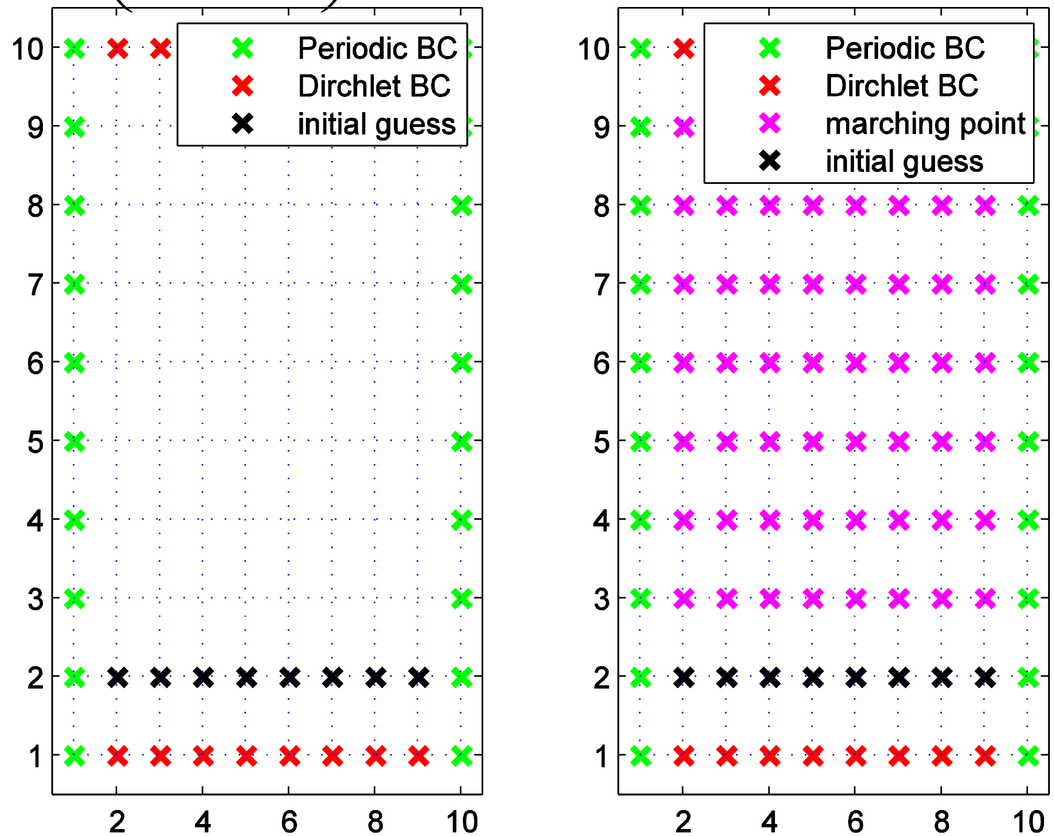


- To establish the linear relation between vector along $e_{i,2}$ in terms of $e_{i,J0.}$ We obtain the recursion relation for the error propagation.

$$e_{i,j+1} = 2e_{i,j}\left(1+\frac{\delta y^2}{\delta x^2}\right) - \frac{\delta y^2}{\delta x^2}\left(e_{i-1,j} + e_{i+1.j}\right) - e_{i.j-1}$$

- With this formula, we can establish the linear system of $e_{i,2}$ and $e_{i,J0.}$

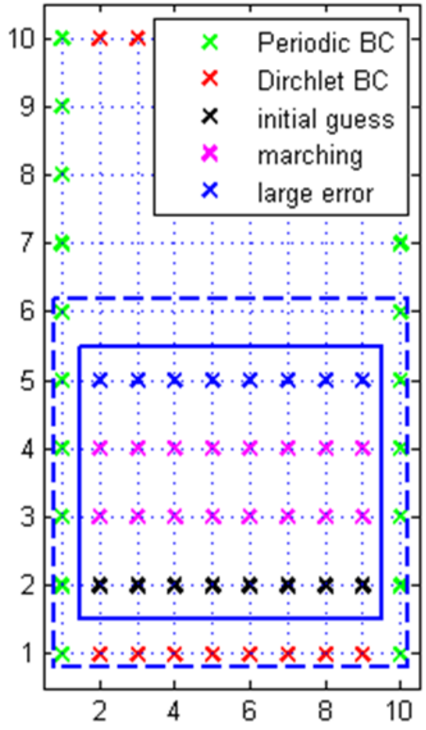
$$F_l = C_{lm} E_m$$

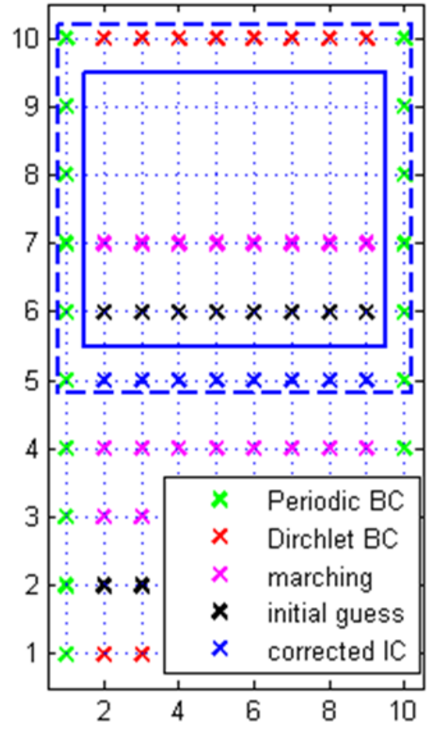


Stabilized Error Vector Propagation Method

- However, EVP will failed because influence matrix can't afford the round-off error.

$$R = \frac{u'_{i+1,j} - 2u'_{i,j} + u'_{i-1,j}}{\delta x_i^{\ 2}} + \frac{u'_{i,j+1} - 2u'_{i.j} + u'_{i,j-1}}{\delta y^2} - \phi_{i,j}$$



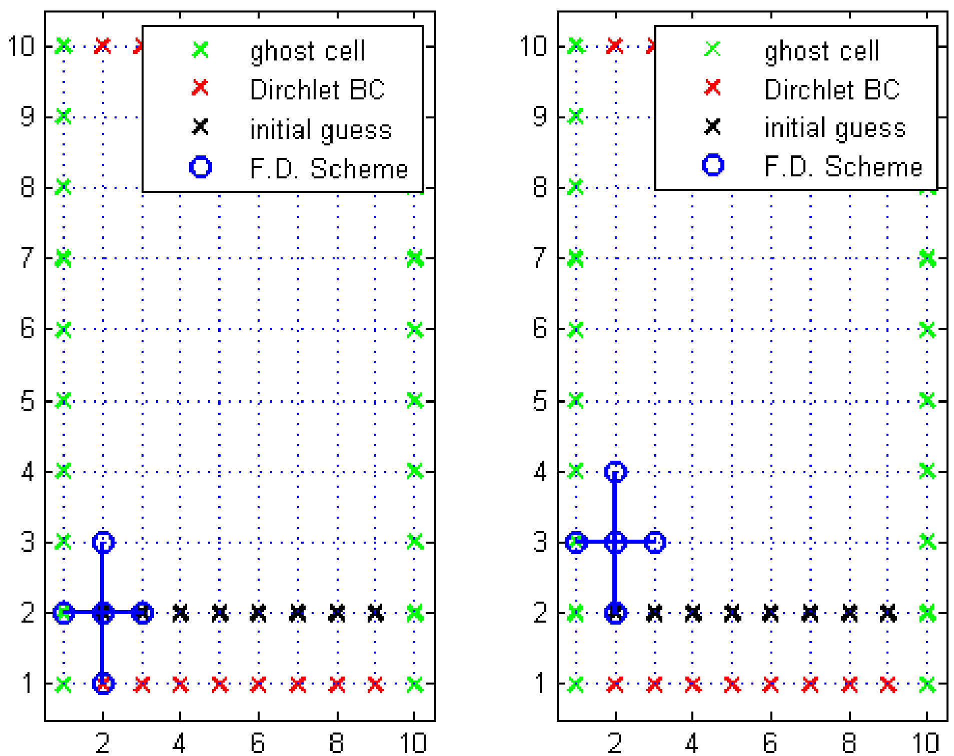


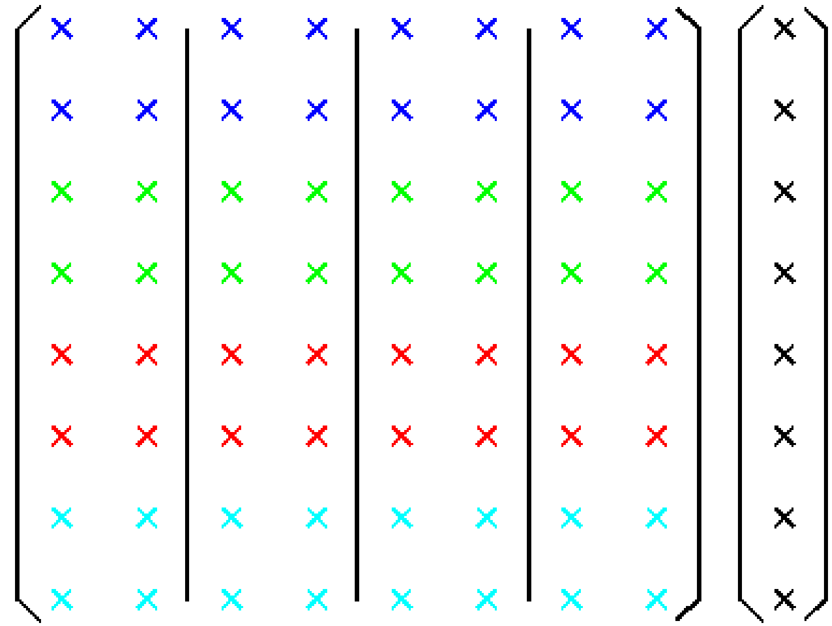
We may apply the residual at blue point, take the influence matrix product and march again to get corrected interior initial condition (IC).

The error of EVP will not blow up enough block along y direction is applied.

Parallel Implement to SEVP

- Requirement of differential operator.
- Use of ghost-cell to compete the scheme.

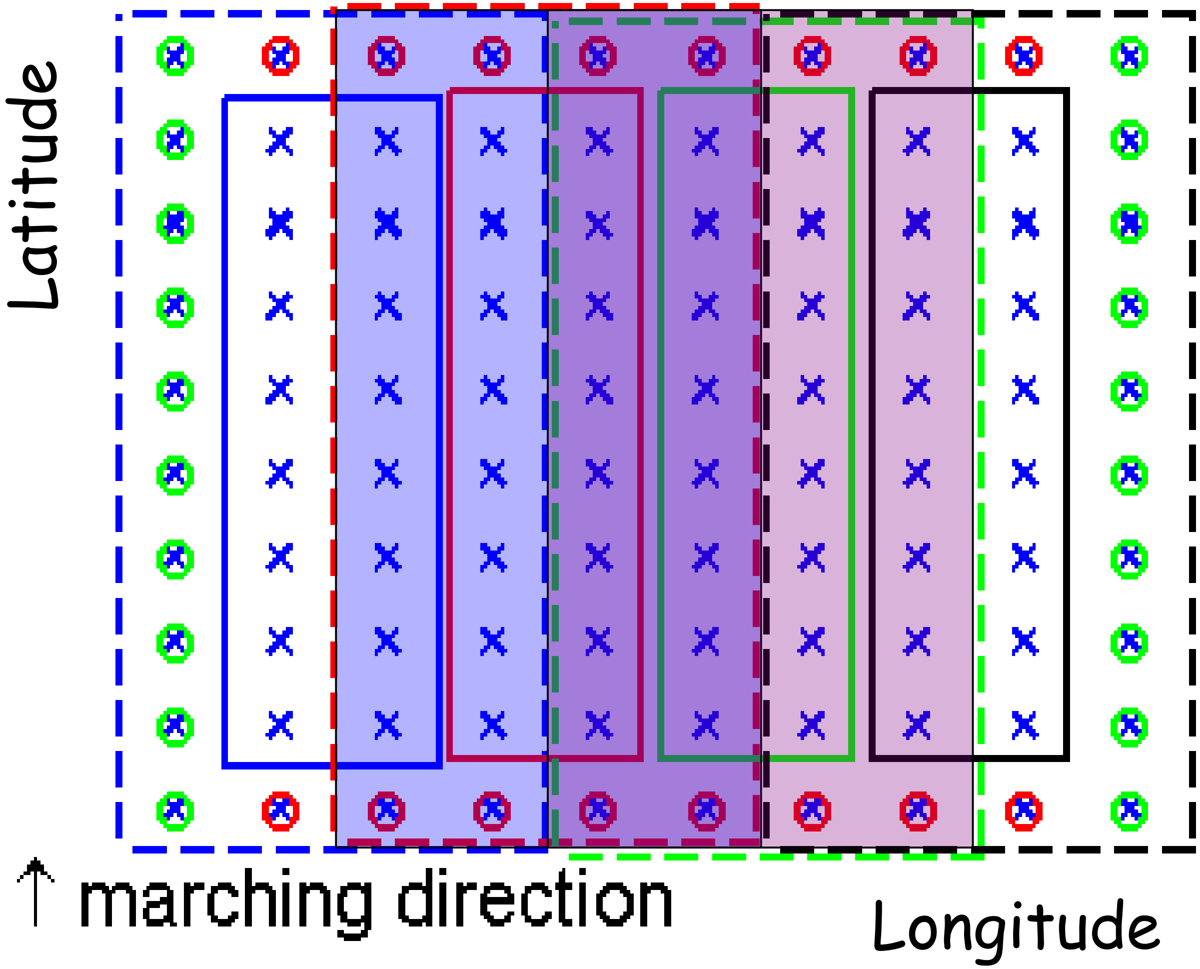




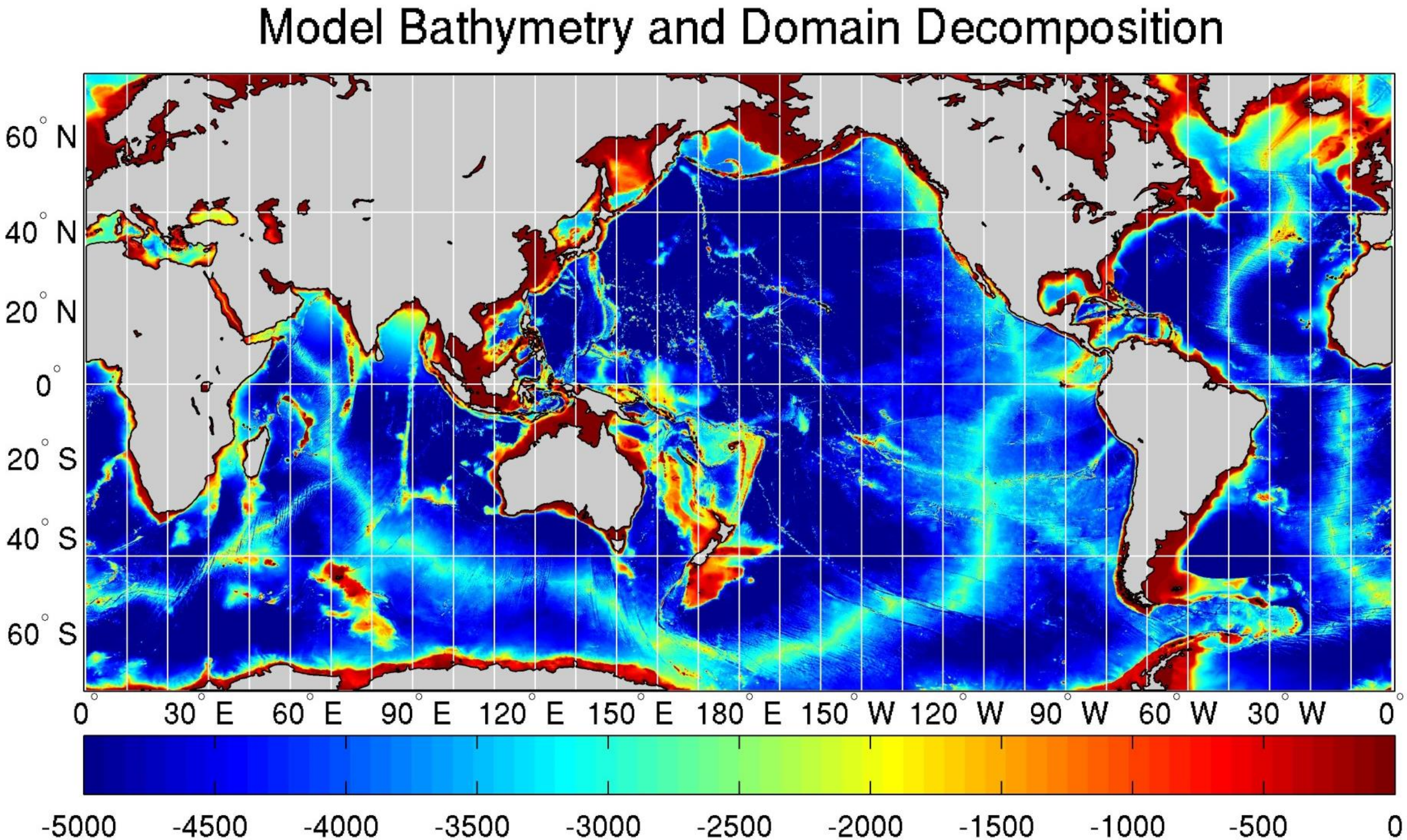
Decomposed matrix product, colorful point denotes the vertical processor and solid line denote the horizontal processor.

Parallel overlapping and marching

-Parallel Error Vector Propagation Method (Parallel EVP)



Example: 192(16x12) decomposed domains

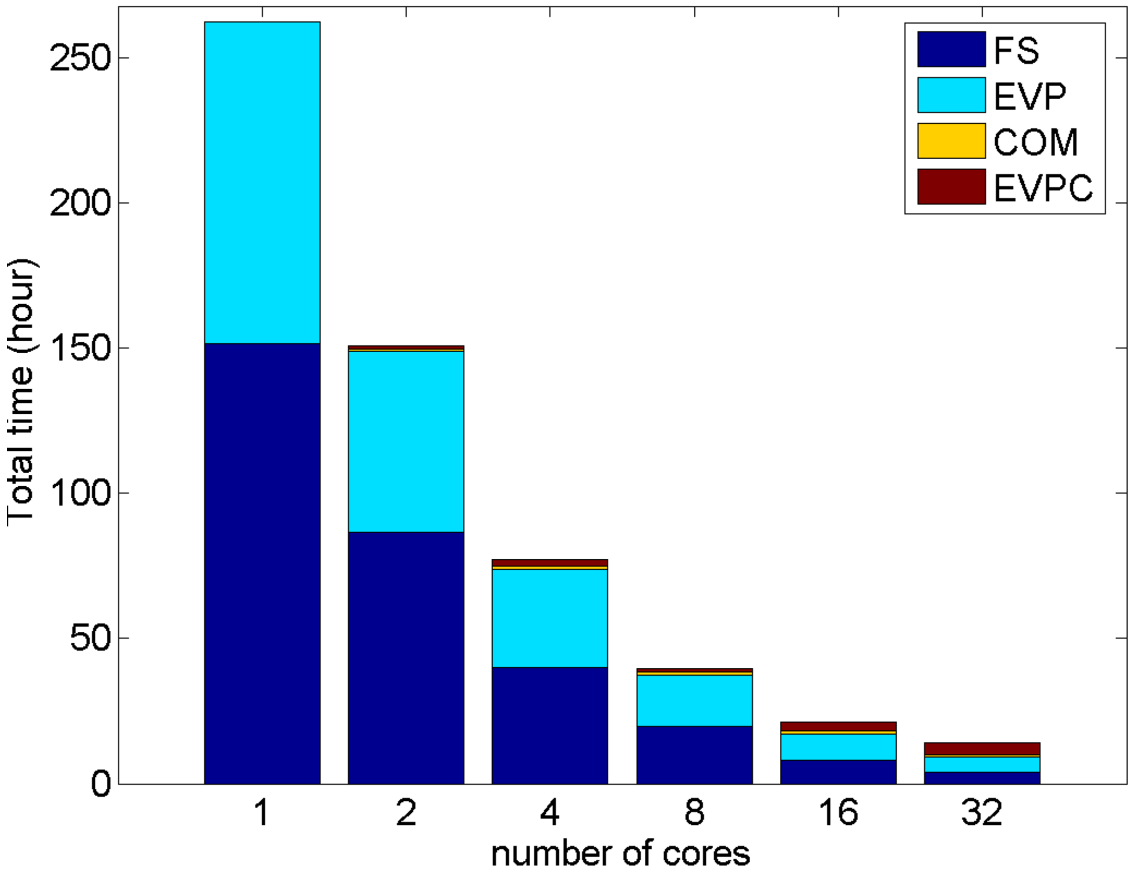


Platforms for parallel performance test

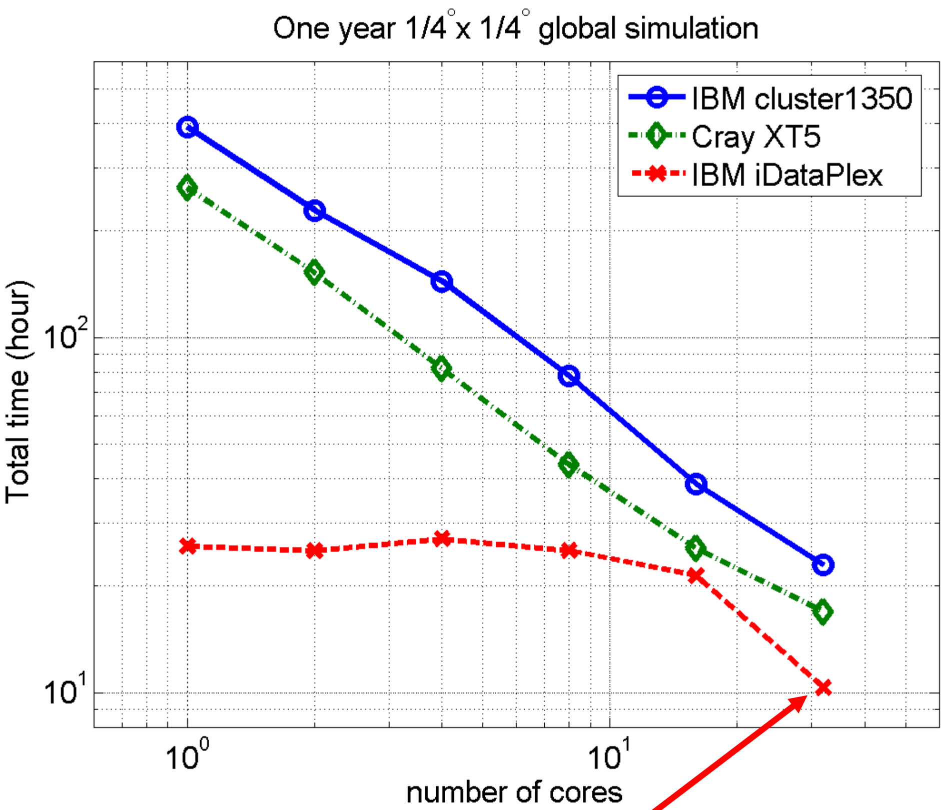
Platform	CPU	Total cores	Network
IBM C1350	Woodcrest 3.0GHz (dual-core x2)	4096	InfiniBand
Cray XT5	Opteron 2.4GHz (quad-core x2)	5312	SeaStar
IBM iData Plex	Intel Nehalem 2.67GHz (quad-core x2)	3200	InfiniBand

Parallel performance

FS: simulation time
EVP: pressure solver time
COM: Other Communication
EVPC: Communication in EVP solver

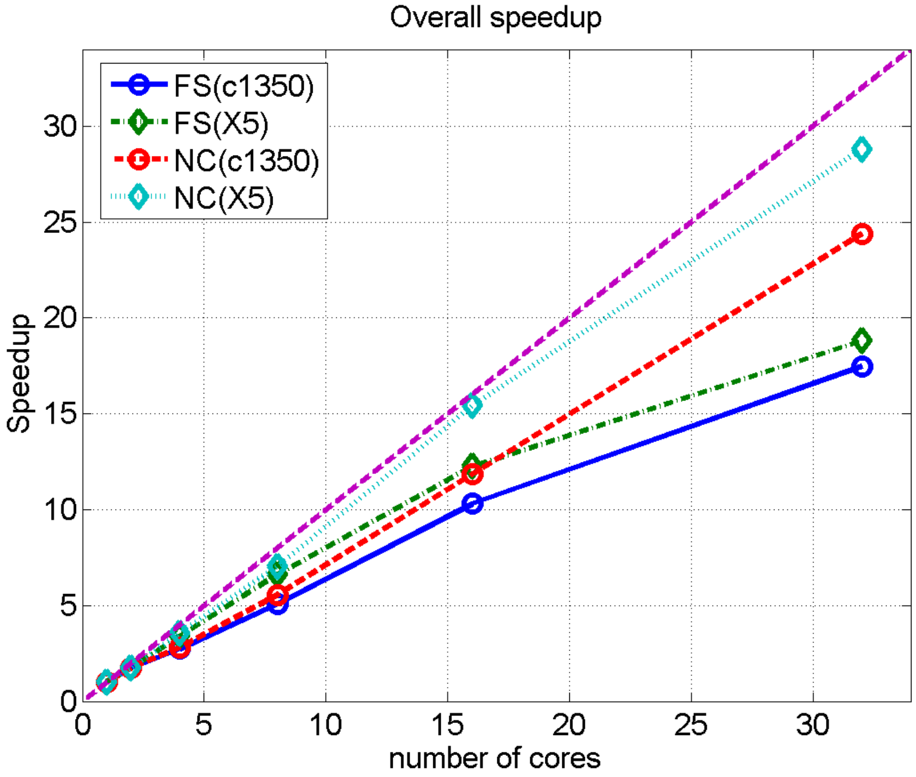


Parallel speedup

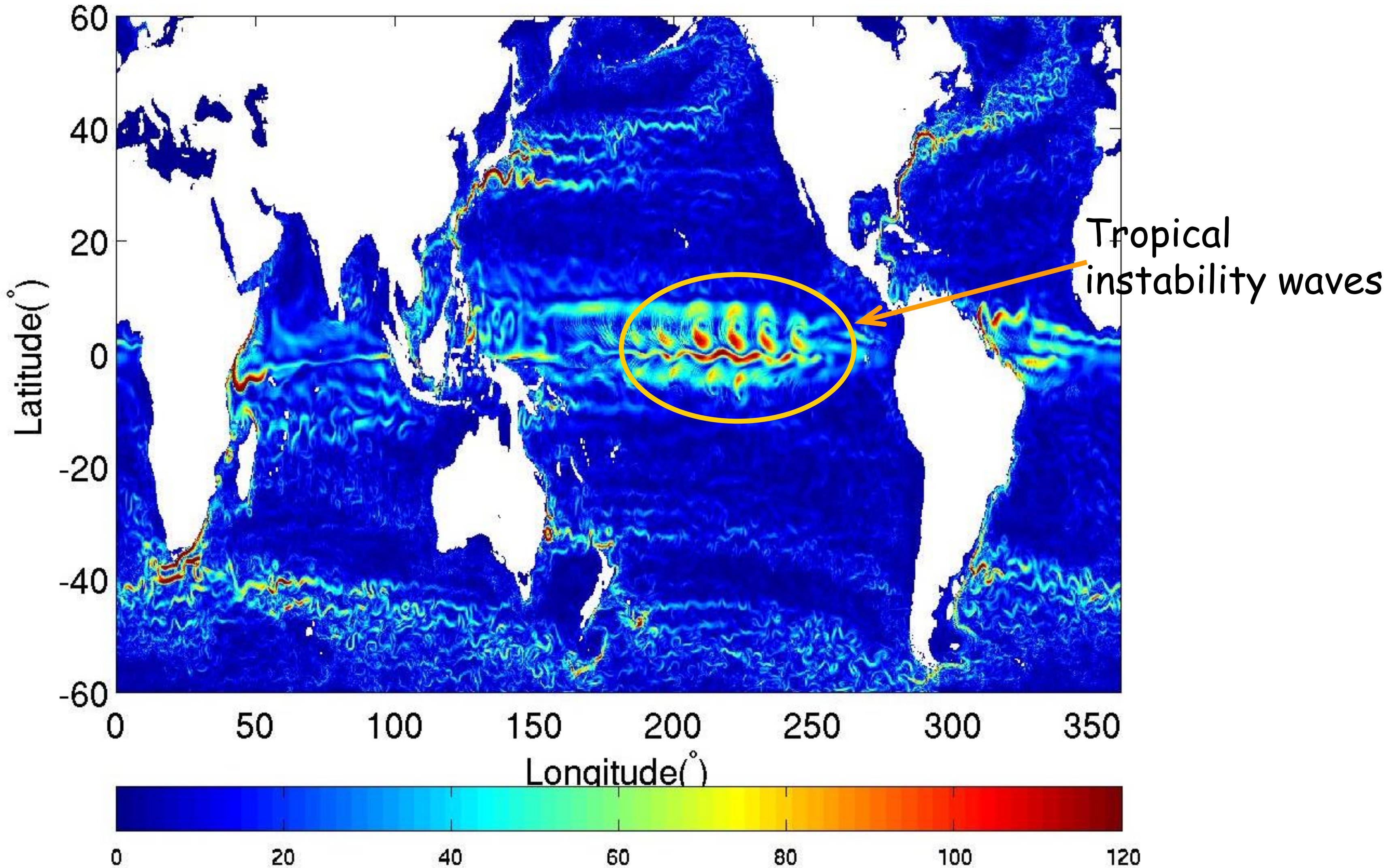


Roughly 10 CPU hrs/per simulation year

FS: all computation
NC: full computation without the communication

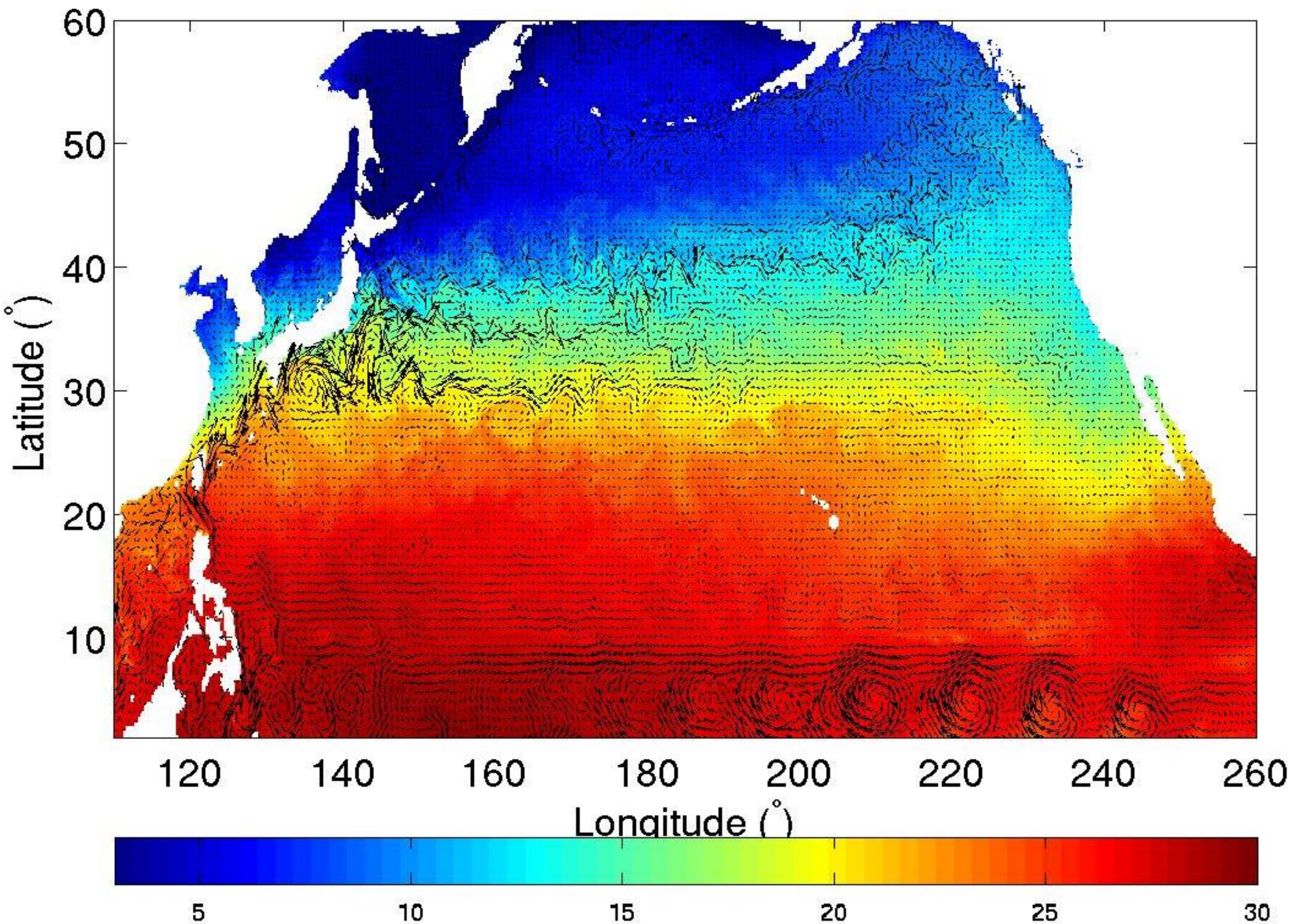


1/4° x 1/4° global resolution (domain 1442x720x26)



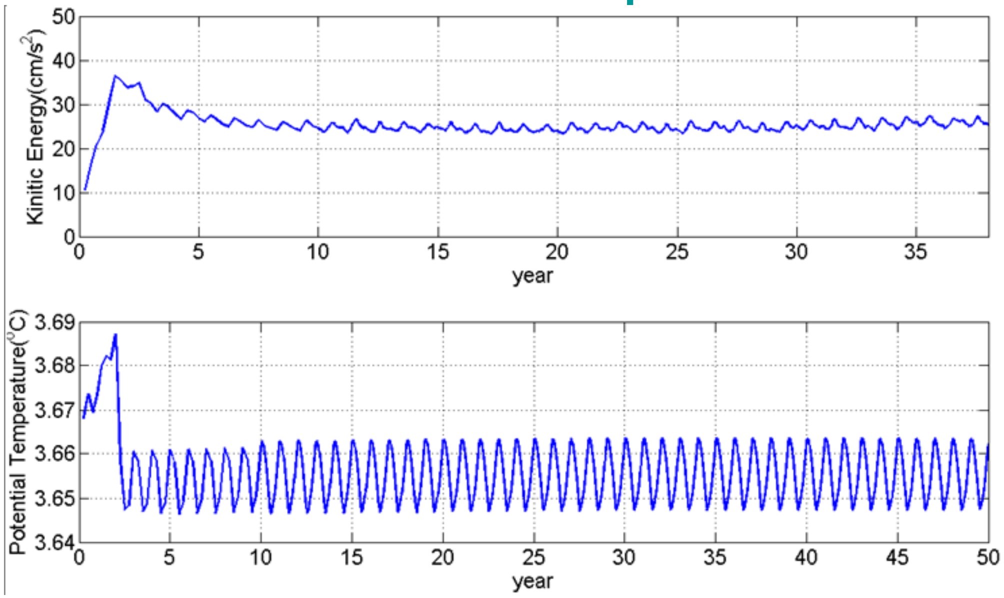
Global velocity speed field (day 5, Year 49)

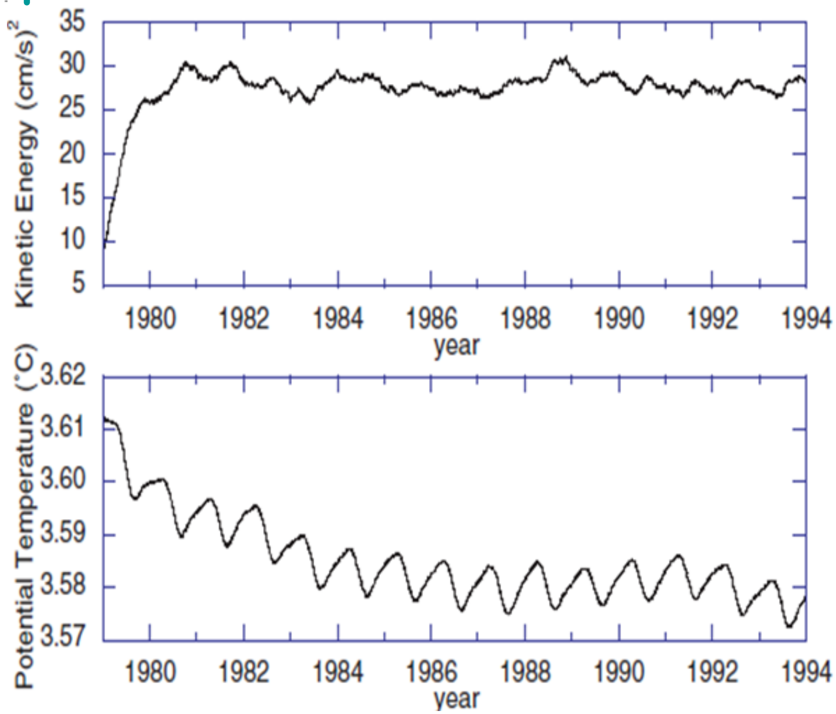
1/4° x 1/4° global resolution (domain 1442x720x26)



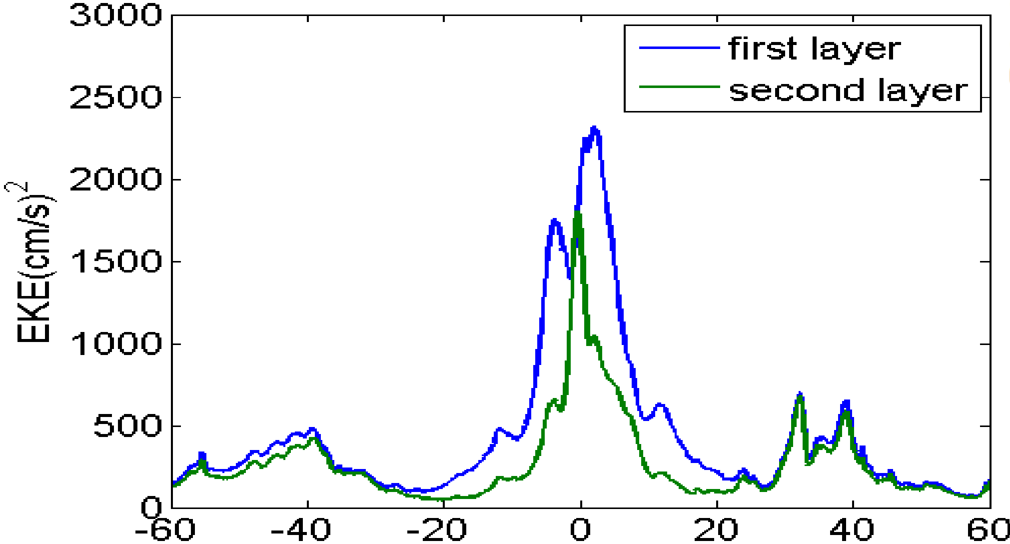
North Pacific temperature and velocity field (day 5, Year 49)

Time evolution of globally averaged Total Kinetic Energy and potential temperature



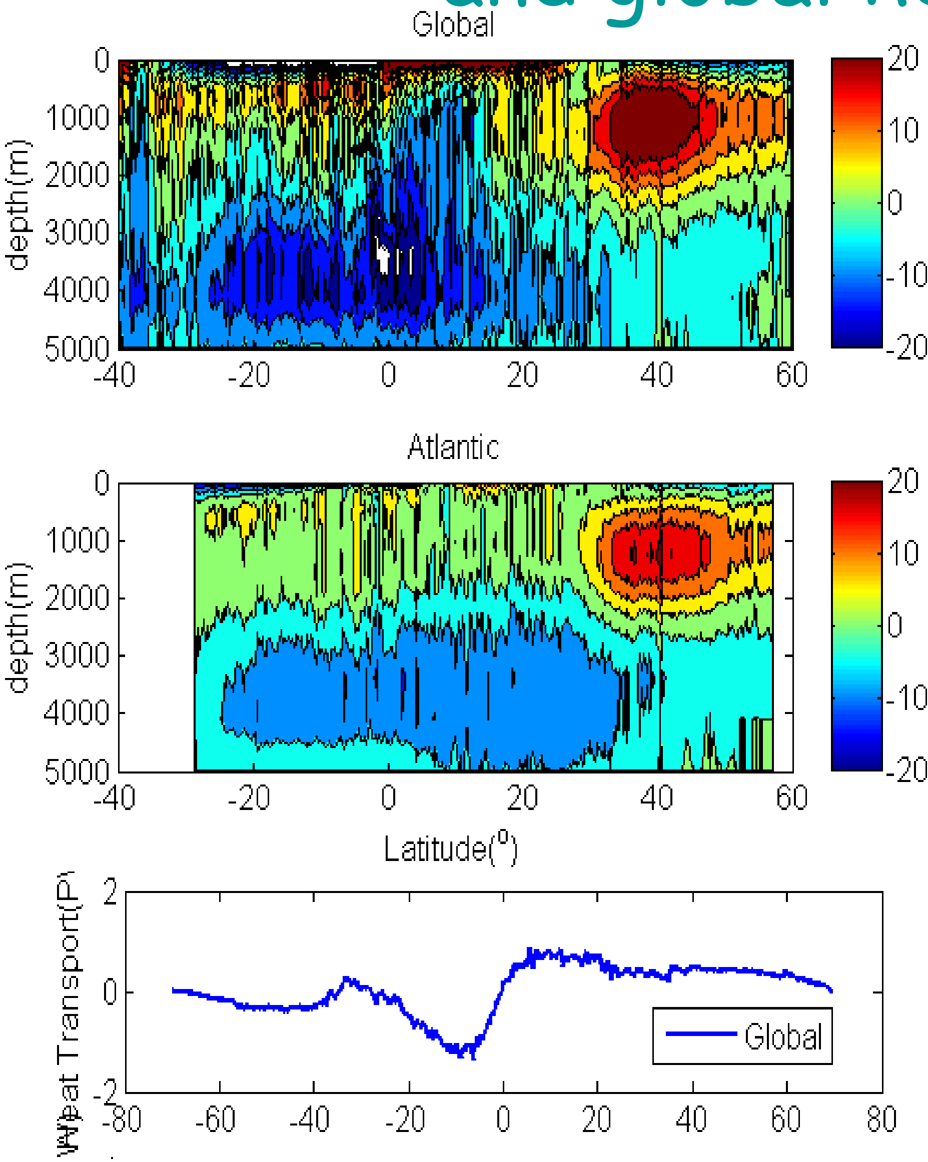


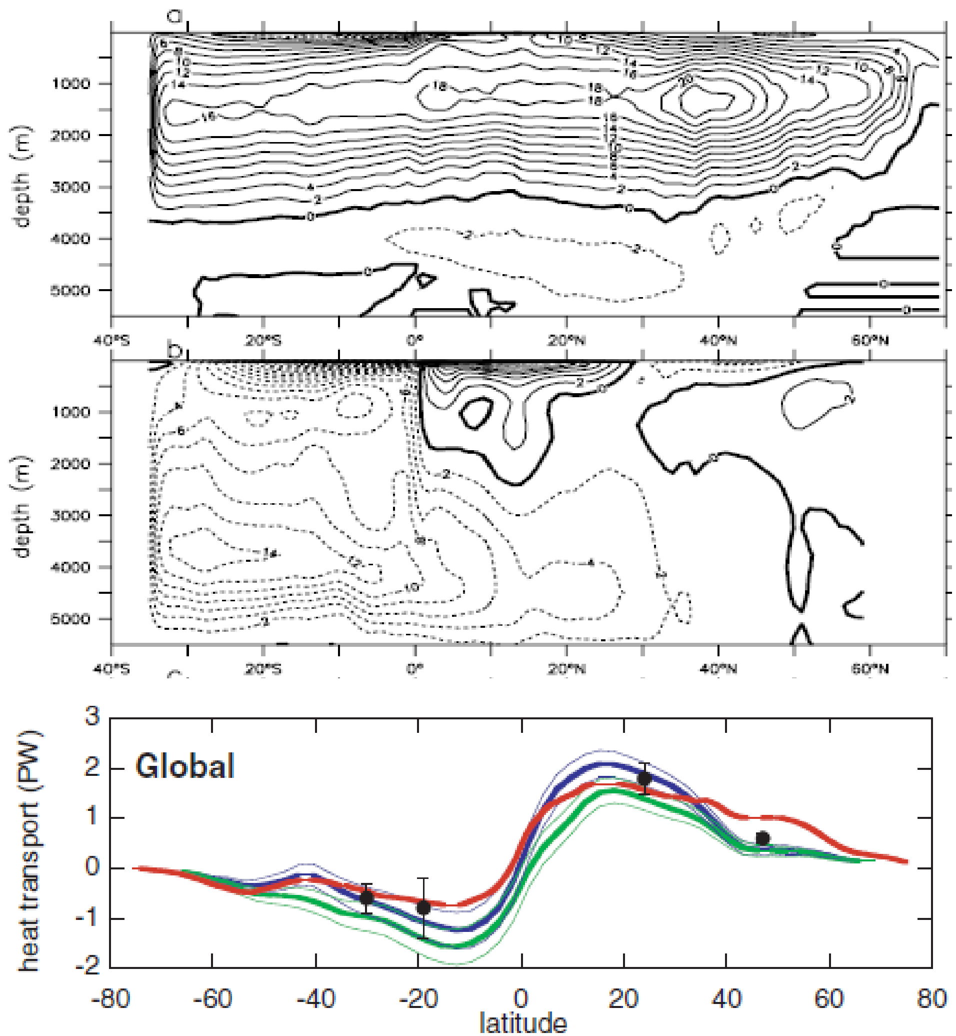
Maltrud and McClean (2005)



Near-surface Eddy Kinetic Energy

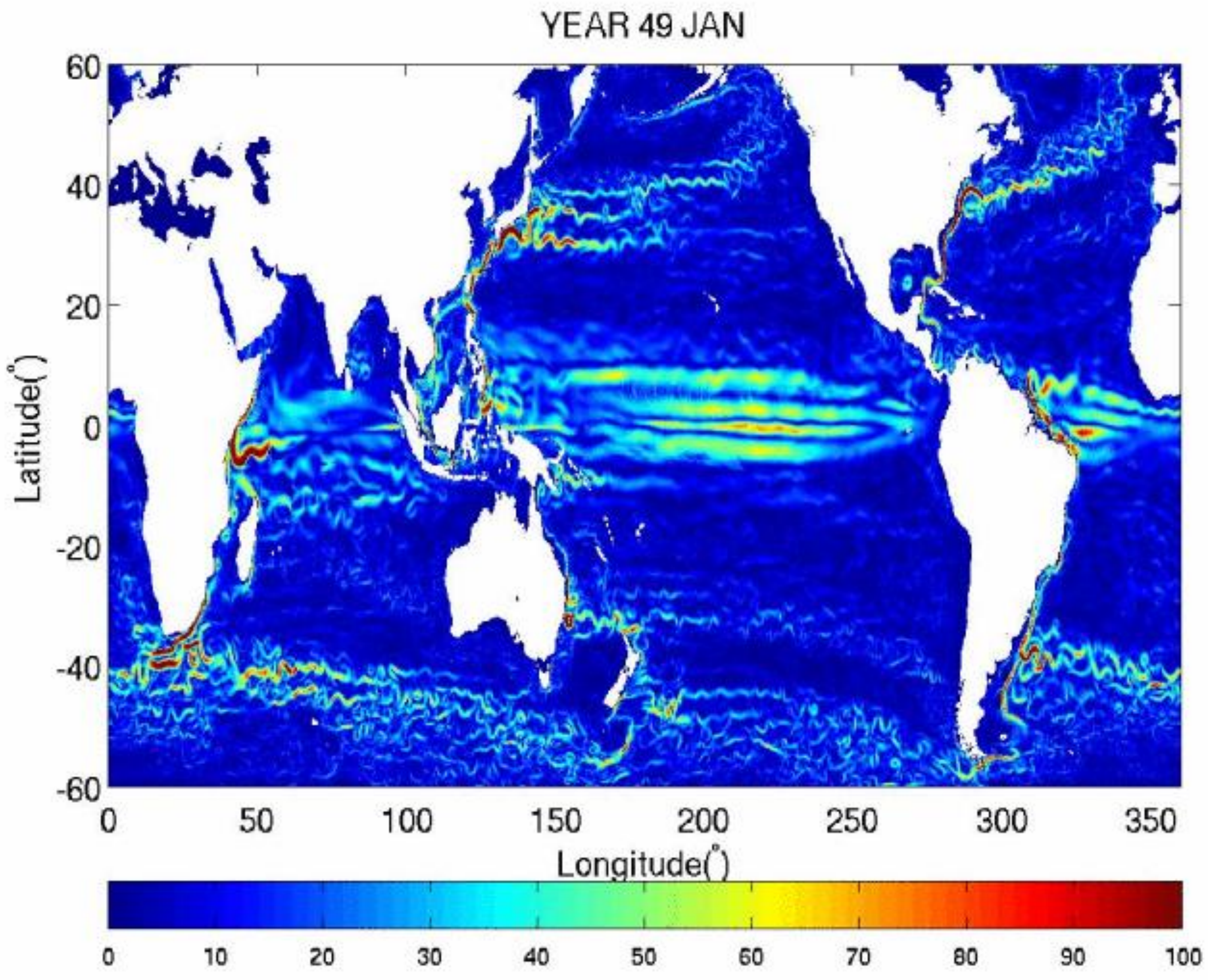
Meridional overturning streamfunction and global heat transport





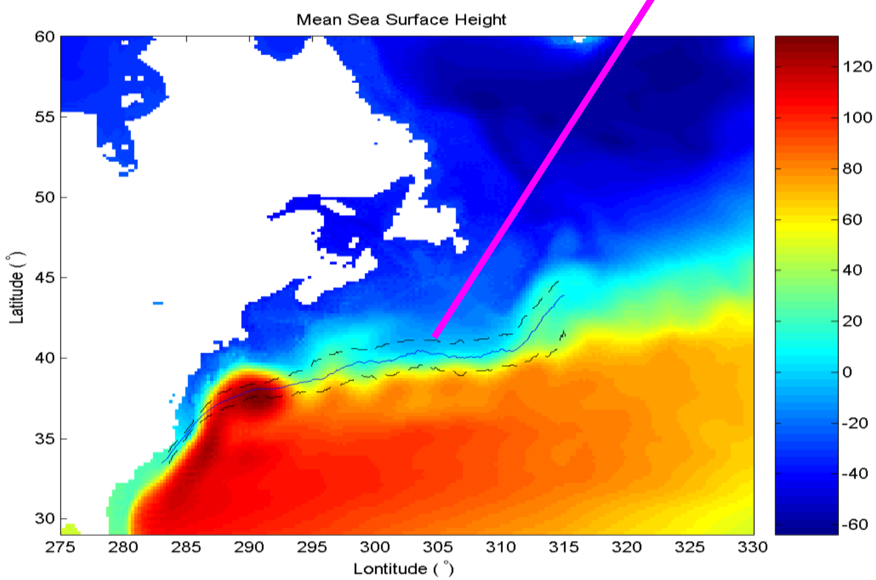
Maltrud and McClean (2005)

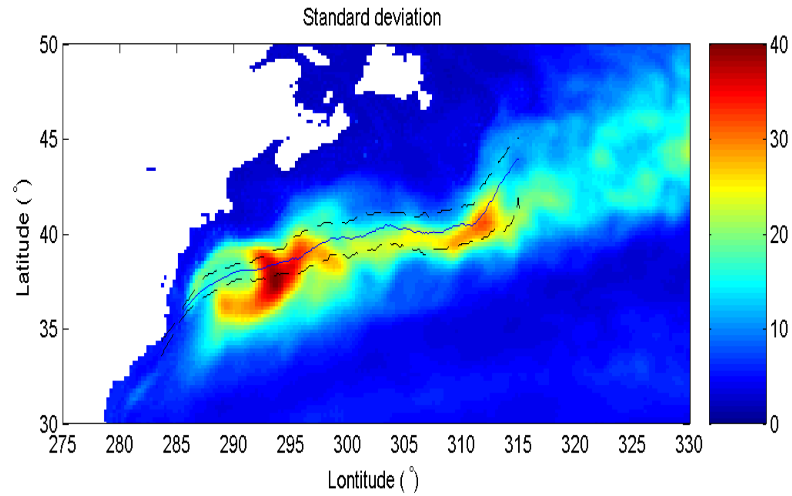
Animation of global surface velocity speed

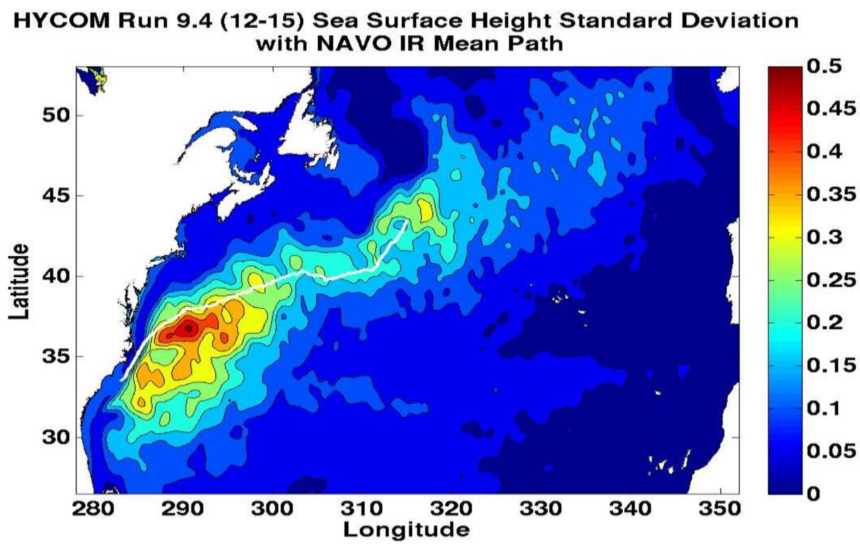


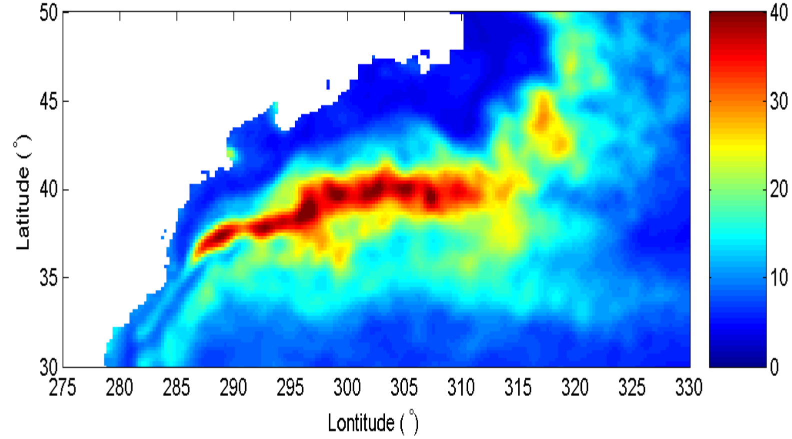
Gulf Stream

The mean Gulf Stream IR northwall pathway $\pm 1\sigma$ (standard deviation) by Cornillon and Sirkes





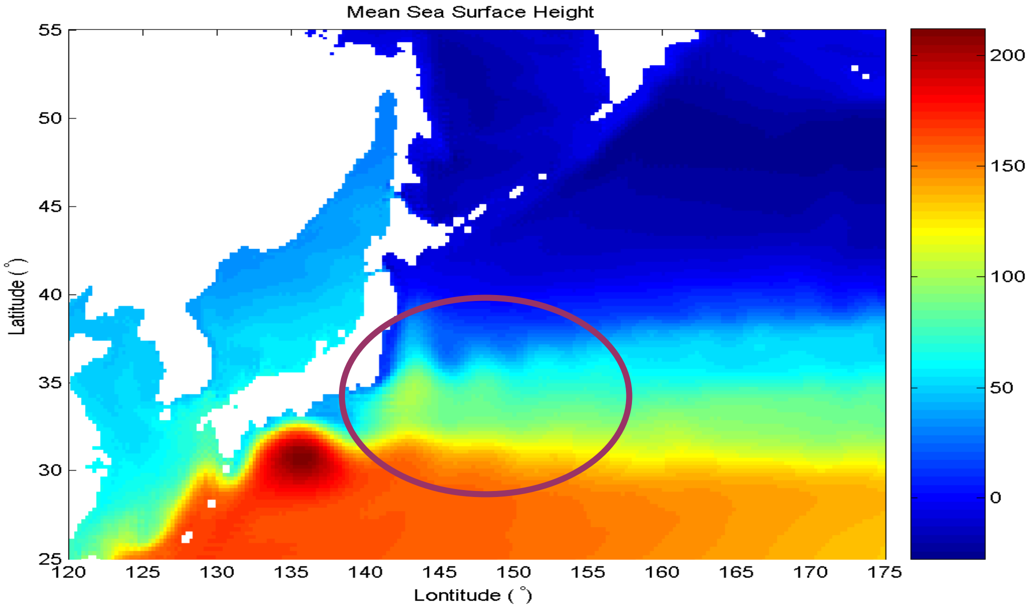


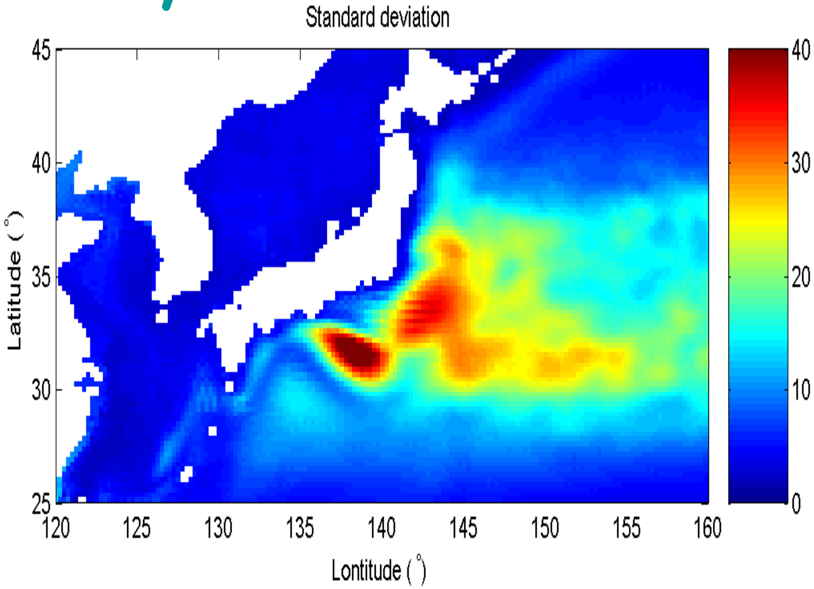


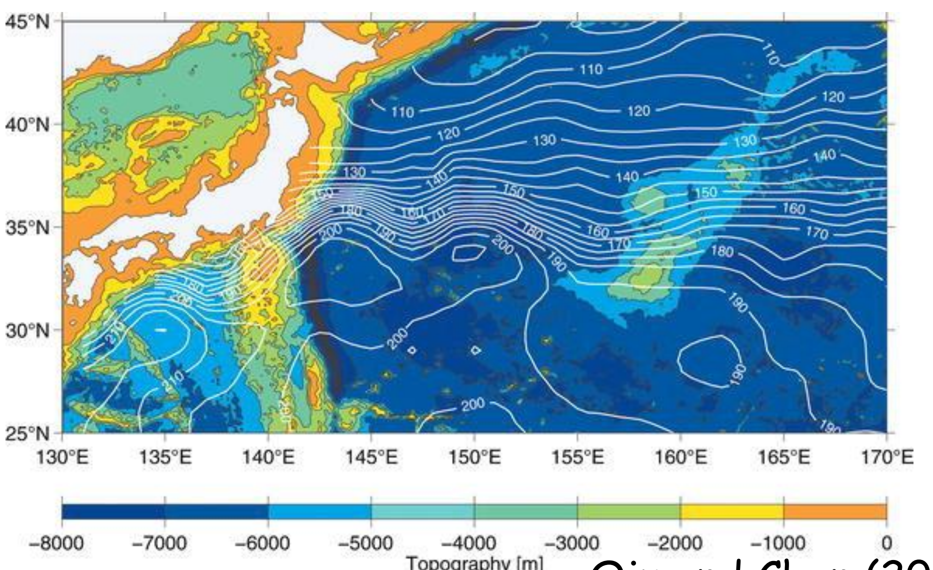
modelled ten-year standard deviation (year 41-50) of equivalent sea surface height (in cm)

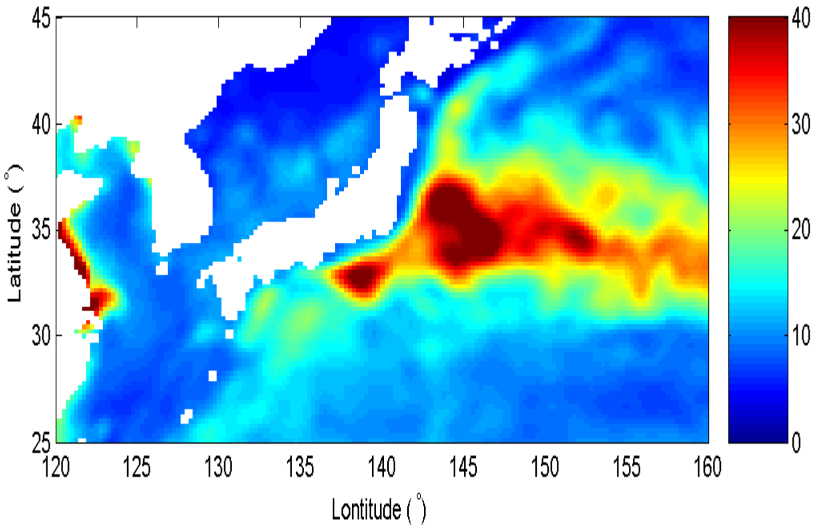
Courtesy of Jim Richman (NRL)

Kuroshio Current System



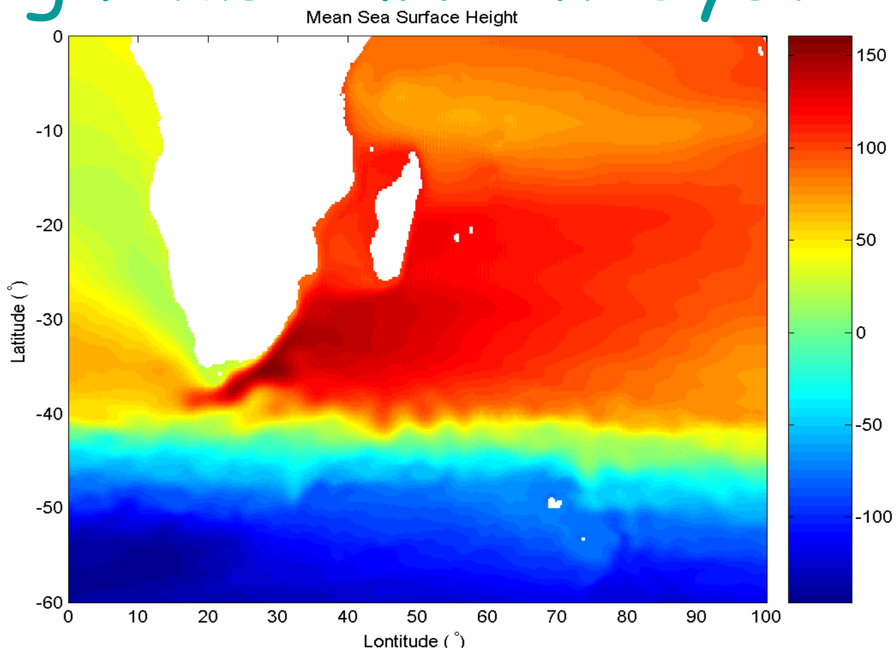


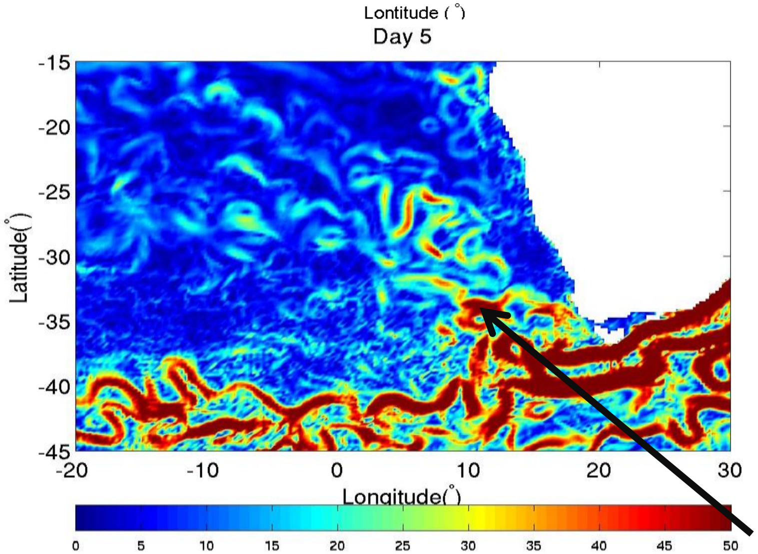


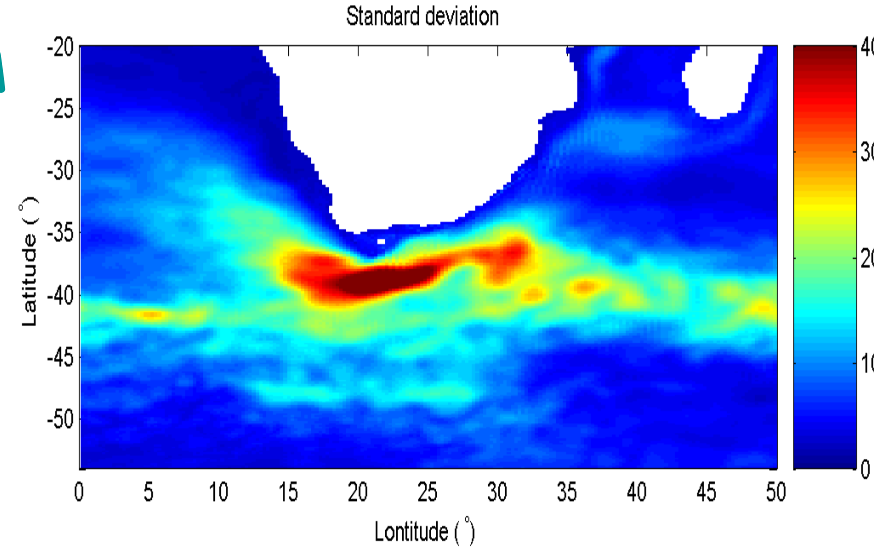


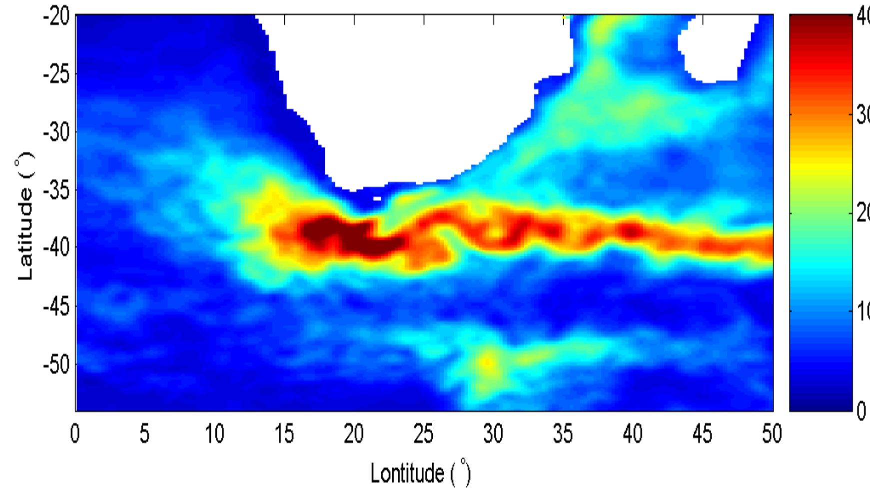
Qiu and Chen (2005)

Agulhas Current System









5-day averaged surface current speed (cm/s) in Cape Basin

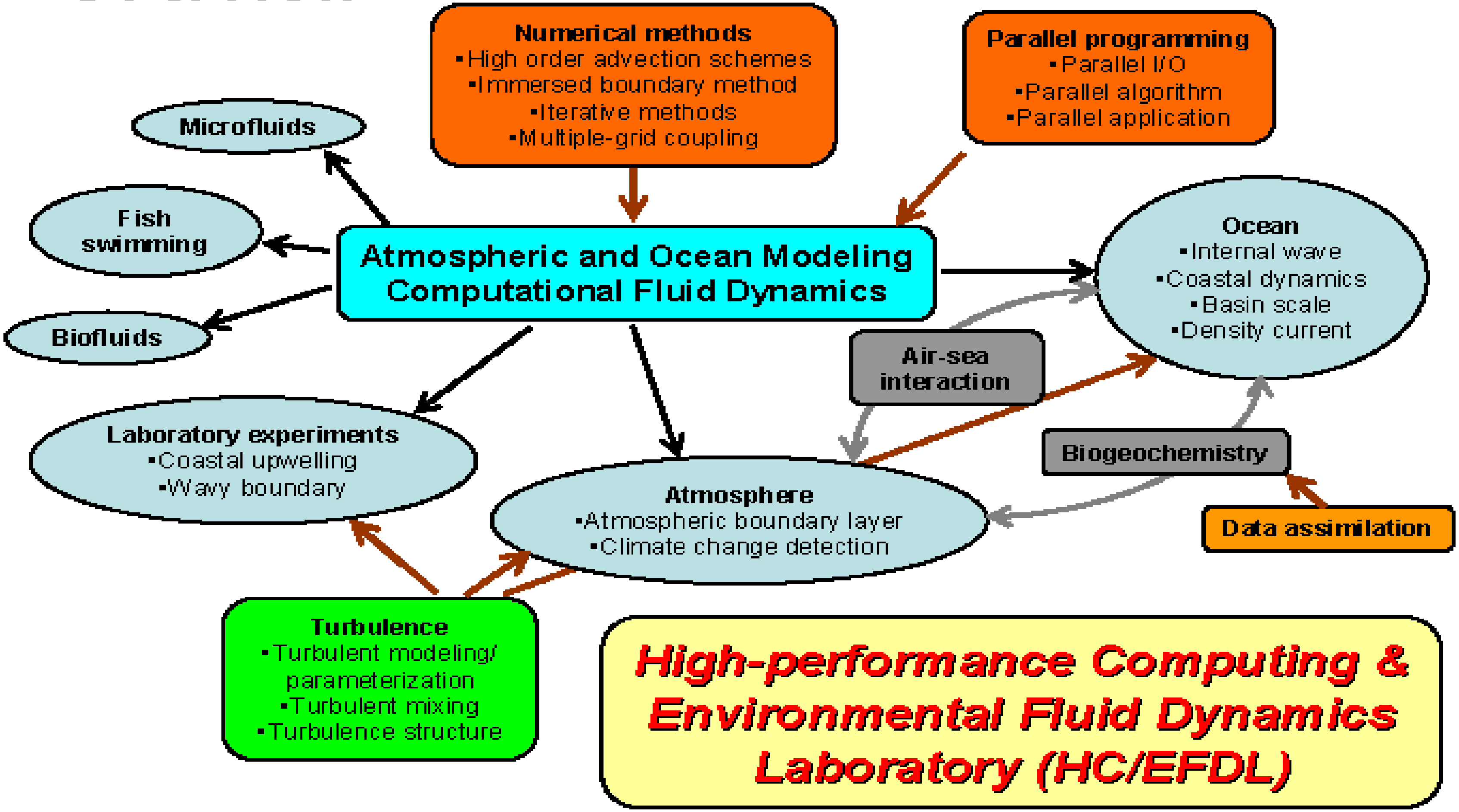
Retroflection of the Agulhas Current

Summary

- High-resolution Parallel Domain-decomposed TaIwan Multi-scale Community Ocean Model (PD-TIMCOM) is developed
  - Based on TIMCOM
  - Based on an efficient parallel EVP solver
  - Ideal (scalable) for parallel domain-decomposition
- Reasonable mean, standard deviation and skewness states
- Eddy-resolving global circulation patterns
- Fifty year simulation is almost completed
- Further validations and extremely high-resolution (1/16°) in Global Oceans and investigate the global ocean climate

Overview

高速計算與環境流體動力實驗室



Questions……?