Numerical simulation of the large-scale ocean circulation on the base of multicomponent splitting method

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Outline

1. The Institute of Numerical Mathematics Ocean Model (INMOM) based on the splitting method used to solve the governing primitive equations is presented.

2. Some results obtained with the INMOM are demonstrated.

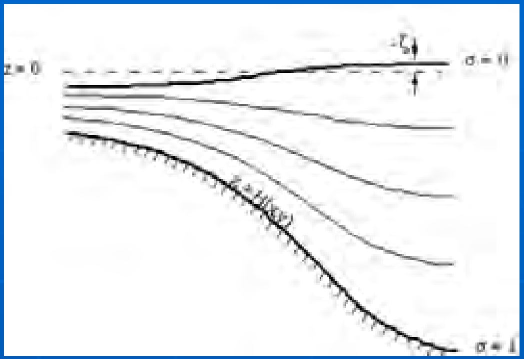
- Characteristics of global ocean climatic circulation from several hundred year simulation are shown.

- The INMOM was used for a simulation of pollutant transport in Pacific Ocean from the shores of Japan.

- The INMOM is also used for the numerical simulation of the Japan/East Sea (JES).

The INMOM vertical coordinate is *σ* (like POM or ROMS), given by the expression:

$$\sigma = \frac{z - \zeta(x,y,t)}{H(x,y) - \zeta(x,y,t)}, \quad \sigma \in [0;1]$$



(x, y, z, t) -coordinates in *z*-system

(x_1, y_1, σ, t_1) -coordinates in *σ*-system

The equations are transformed from z- to σ- coordinate by implementing the transformation:

$$\frac{\partial}{\partial x} = \frac{\partial}{\partial x_1} - \frac{Z_x}{Z_\sigma}\frac{\partial}{\partial \sigma}, \quad \frac{\partial}{\partial y} = \frac{\partial}{\partial y_1} - \frac{Z_y}{Z_\sigma}\frac{\partial}{\partial \sigma},$$

$$\frac{\partial}{\partial z} = \frac{1}{Z_\sigma}\frac{\partial}{\partial \sigma}, \quad \frac{\partial}{\partial t} = \frac{\partial}{\partial t_1} - \frac{Z_t}{Z_\sigma}\frac{\partial}{\partial \sigma}.$$

$Z = \sigma h + \zeta$ - geopotential Z-depth as a function of model coordinates

$h = H - \zeta$ - effective ocean depth

ζ - sea level deviation from undisturbed state

Splitting up technique. Application to the ocean model

(Yanenko, Marchuk, Samarskii et al., 1960 - 2010)

Let the governing equations are represented in operator form as:

$$\frac{\partial \phi}{\partial t} + A\phi = f, \qquad (*)$$

where

$$A = \sum_{i=1}^{I} A_i, \quad A_i \geq 0, \quad f = \sum_{i=1}^{I} f_i \quad (i = 1, 2, 3, ..., I)$$

To solve (*) we reduce the solution of the complex problem to the solution of a set of problems with simpler operators A_i :

$$\frac{\phi^{j+1/I} - \phi^{j}}{\tau} + A_1\left(\alpha \phi^{j+1/I} + (1-\alpha)\phi^{j}\right) = f_1 ,$$

$$\frac{\phi^{j+2/I} - \phi^{j+1/I}}{\tau} + A_2\left(\alpha \phi^{j+2/I} + (1-\alpha)\phi^{j+1/I}\right) = f_2,$$

....

$$\frac{\phi^{j+1} - \phi^{j+(I-1)/I}}{\tau} + A_I\left(\alpha \phi^{j+1} + (1-\alpha)\phi^{j+(I-1)/I}\right) = f_I.$$

All these simple tasks may be solved by effective and stable implicit and semi-implicit methods.

α = 1 - implicit scheme

α = ½ - Crank-Nickolson scheme

Splitting the system of ocean governing equations by physical processes.

Transport-diffusion of tracer (temperature and salinity):

$$D_t\theta = \frac{\partial}{\partial\sigma}\frac{\nu_\theta}{H}\frac{\partial\theta}{\partial\sigma} + D\theta + \frac{\partial R}{\partial\sigma},$$

$$D_t S = \frac{\partial}{\partial\sigma}\frac{\nu_S}{H}\frac{\partial S}{\partial\sigma} + DS.$$

Transport-diffusion of momentum:

$$\tilde{D}_t u - \xi v H = \frac{\partial}{\partial\sigma}\frac{\nu}{H}\frac{\partial u}{\partial\sigma} + Fu,$$

$$\tilde{D}_t v + \xi u H = \frac{\partial}{\partial\sigma}\frac{\nu}{H}\frac{\partial v}{\partial\sigma} + Fv,$$

$$\xi = \frac{1}{r_x r_y}\left(\frac{\partial r_y}{\partial x}v - \frac{\partial r_x}{\partial y}u\right)$$

Adaptation module (adjustment eqation):

$$\begin{cases} \dfrac{\partial u}{\partial t} - fv = -\dfrac{1}{r_x}\left(\frac{1}{\rho_0}P_x + \frac{1}{\rho_0}\frac{\partial p_a}{\partial x} - g\frac{\partial\zeta}{\partial x}\right), \\ \dfrac{\partial v}{\partial t} + fu = -\dfrac{1}{r_y}\left(\frac{1}{\rho_0}P_y + \frac{1}{\rho_0}\frac{\partial p_a}{\partial y} - g\frac{\partial\zeta}{\partial y}\right), \\ \dfrac{\partial\zeta}{\partial t} = \dfrac{1}{r_x r_y}\left(\dfrac{\partial r_y uH}{\partial x} + \dfrac{\partial r_x vH}{\partial y}\right) + \dfrac{\partial\omega}{\partial\sigma}. \end{cases}$$

The transport-diffusion operator may be further split into 3 operators along each of coordinates λ, φ, σ.

Splitting of the adjustment equations

Velocity forced by pressure gradient

$$\frac{\partial u}{\partial t} = -\frac{1}{\rho_0 r_x}P_x,$$

$$\frac{\partial v}{\partial t} = -\frac{1}{\rho_0 r_y}P_y.$$

Spltting velocities into baroclinic and barotropic components

$$u = \bar{u} + u', \quad v = \bar{v} + v',$$

$$\omega = \int_1^\sigma \frac{1}{r_x r_y}\left(\frac{\partial u' r_y H}{\partial x} + \frac{\partial v' r_x H}{\partial y}\right)d\sigma.$$

The inertia adjustment

$$\begin{cases} \dfrac{\partial u'}{\partial t} - fv' = 0, \\ \dfrac{\partial v'}{\partial t} + fu' = 0, \end{cases}$$

The barotropic adjustment (shallow water equations).

$$\begin{cases} \dfrac{\partial\bar{u}}{\partial t} - f\bar{v} + r\bar{u} = \dfrac{1}{r_x}\left(g\dfrac{\partial\zeta}{\partial x} - \dfrac{1}{\rho_0}\dfrac{\partial p_a}{\partial x}\right), \\ \dfrac{\partial\bar{v}}{\partial t} + f\bar{u} + r\bar{v} = \dfrac{1}{r_y}\left(g\dfrac{\partial\zeta}{\partial y} - \dfrac{1}{\rho_0}\dfrac{\partial p_a}{\partial y}\right), \\ \dfrac{\partial\zeta}{\partial t} = \dfrac{1}{r_x r_y}\left(\dfrac{\partial r_y \bar{u} H}{\partial x} + \dfrac{\partial r_x \bar{v} H}{\partial y}\right), \end{cases}$$

INMOM multicomponent splitting includes

- Symmetrized form of governing equations for energy conservation low keeping in numerical dicretization on energy conserving space approximations using Arakawa C grid.
- Multicomponent splitting into series of nonnegative subsystems.
- It allows to use implicit and semi-implicit schemes for time integration of these subsystems with long time step.
- Each separate subsystem has its adjoint analog. The adjoint model consists of the respective subsystems adjoint to the split subsystems of the forward model. This technique simplifies the construction a full adjoint model required for 4D-var data assimilation.

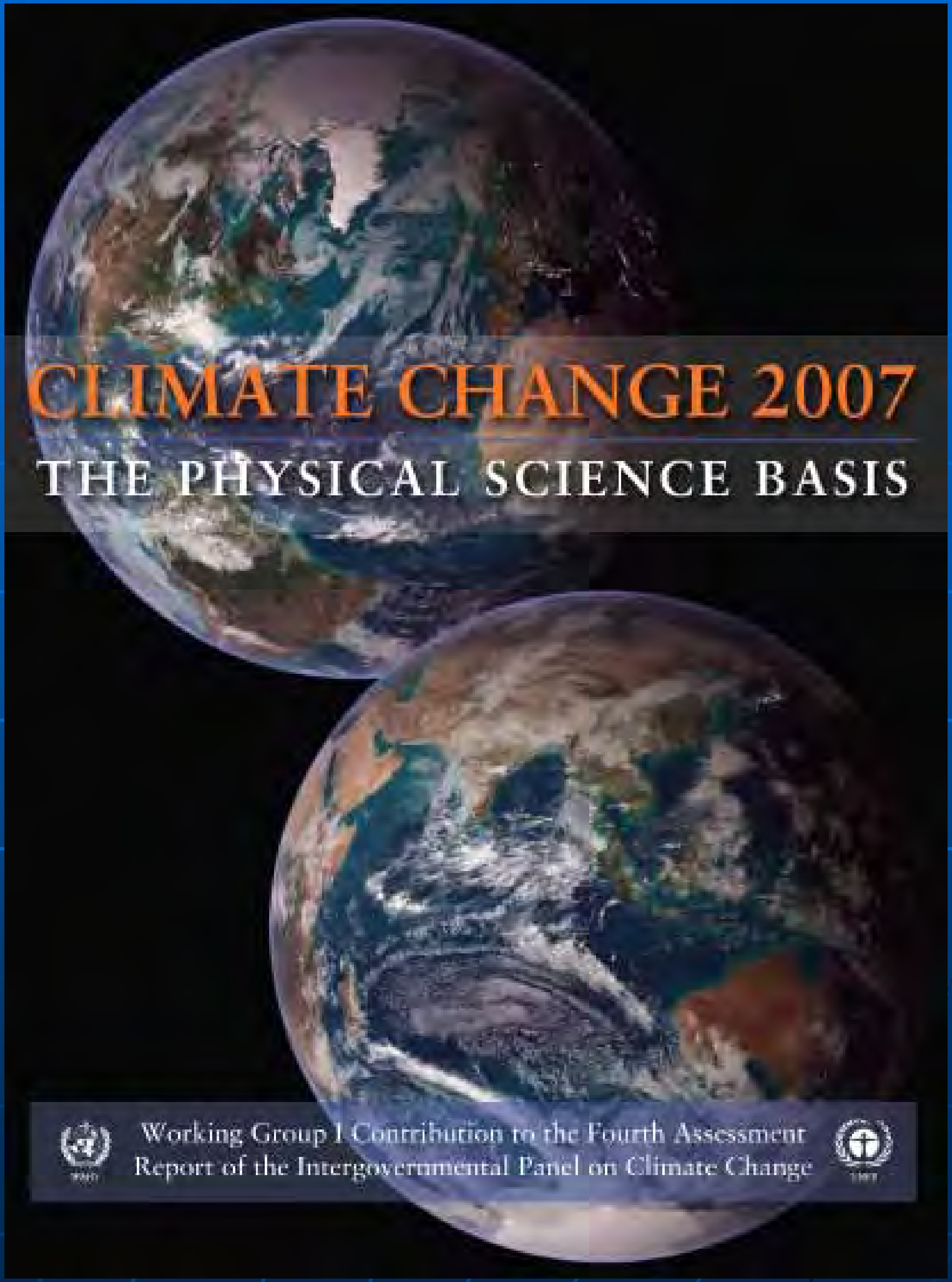
Physical parametrizations

- The EVP (elastic- viscous- plastic) dynamic - thermodynamic sea ice model (Hunke, 2001) is embedded.
- Philander-Pakanovsky or Monin-Obukhov parameterization of vertical mixing are used.
- A Laplacian operator along the geopotential surface is used for the lateral diffusion on the tracers and a bilaplacian operator along sigma-surface is used for the lateral viscosity on momentum.

The global version of the INMOM is used as the oceanic component of the IPCC climate model INMCM (Institute of Numerical Mathematics Climate Model).

INMCM3 with INMOM of 2x2.5 deg. resolution is presented in the IPCC Fourth Assessment Report (2007).

INMCM4 with INMOM of 0.5x1 deg. resolution will be presented in the IPCC AR-5.



The global version of the INMOM is realized on curvilinear orthogonal grid to avoid problems near North Pole.

Moebius transformation:

$$\eta = \frac{1 + A\xi}{\xi + A}$$

$$\xi = \tan\left(\frac{\pi}{4} + \frac{y}{2}\right)\exp(i(x - x_0)),$$

$$\eta = \tan\left(\frac{\pi}{4} + \frac{\varphi}{2}\right)\exp(i(\lambda - \lambda_0)),$$

$$A = \tan\left(\frac{\pi}{4} + \frac{\varphi_0}{2}\right).$$

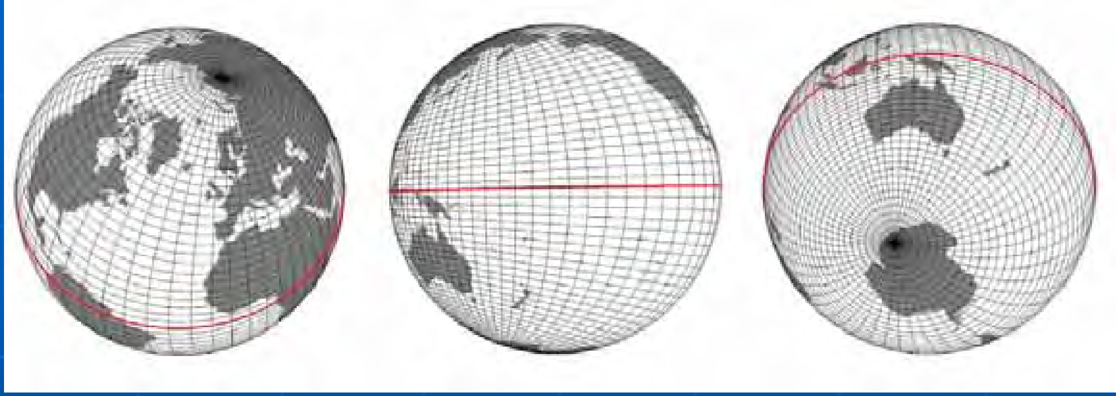
$x_0, \lambda_0, \varphi_0$ -transformation parameters

$$r_x = R\sqrt{\left(\frac{\partial\lambda}{\partial x}\cos\varphi\right)^2 + \left(\frac{\partial\varphi}{\partial x}\right)^2},$$

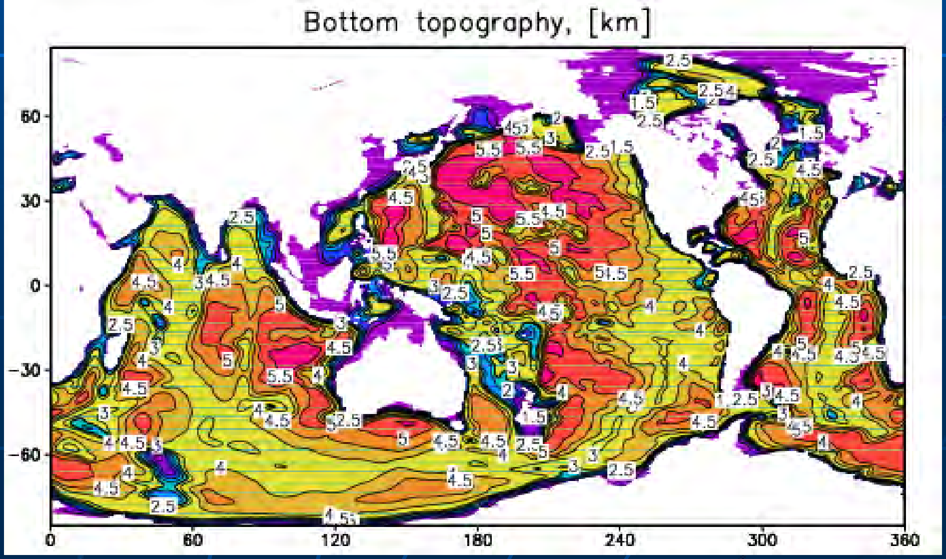
$$r_y = R\sqrt{\left(\frac{\partial\lambda}{\partial y}\cos\varphi\right)^2 + \left(\frac{\partial\varphi}{\partial y}\right)^2}.$$

- Metrical coefficients in curvilinear system

New north pole is placed to 100°E, 70°N (Taimyr peninsula) and new south pole is symmetrically placed to 100°E, 70°S (Antarctica)



Global ocean bottom topography in the curvilinear coordinates



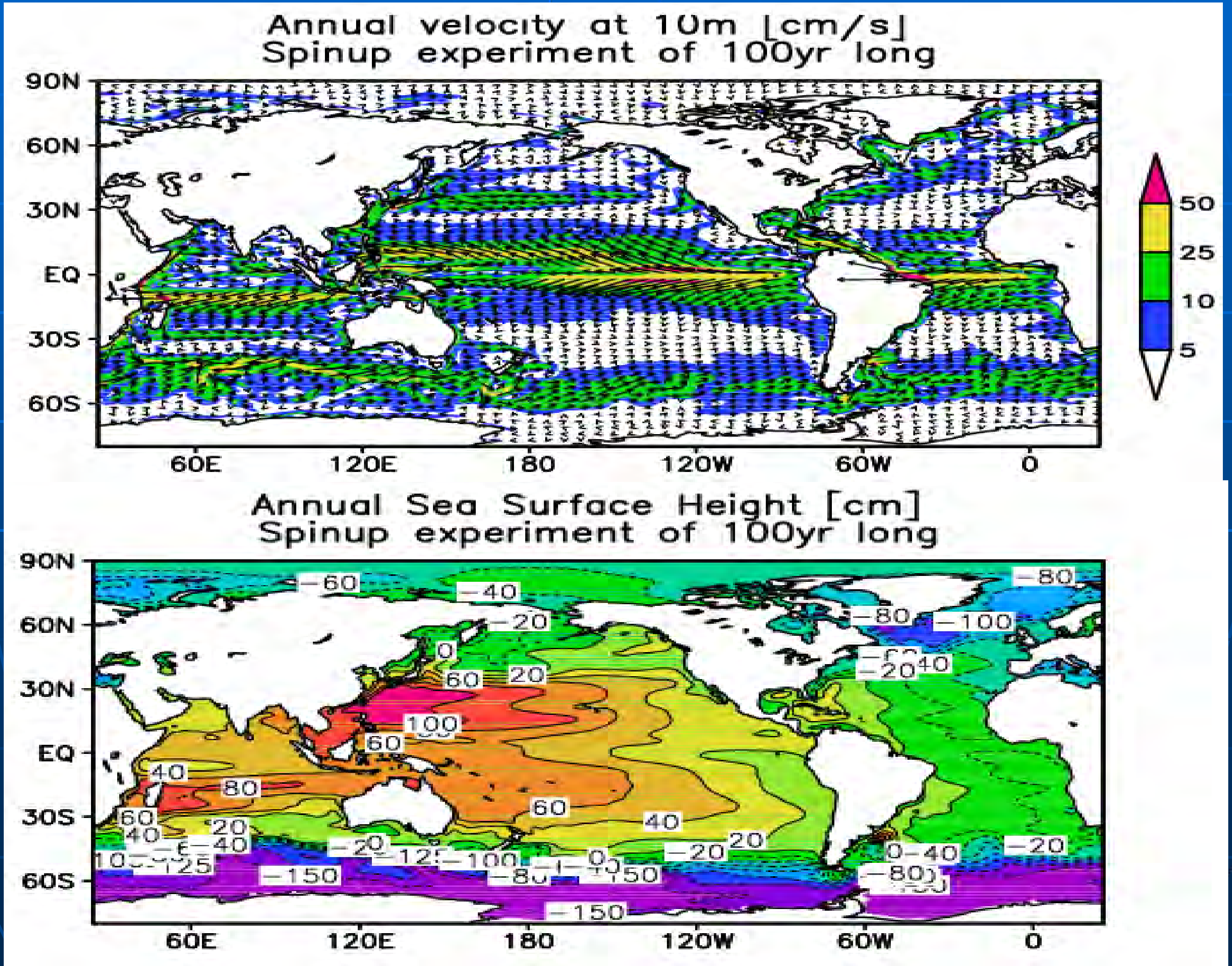
Grid properties:

1) Orthogonality (in horizontal coordinates)
2) Analytical transformation from geographical system
3) Singularities beyond the ocean area
4) Preserved geographical equator position

The model was integrated for 100 years starting from the Levitus January climatology with atmospheric forcing prescribed from CORE datasets (forcing for Common Ocean-ice Reference Experiments) [Griffies et al 2004].

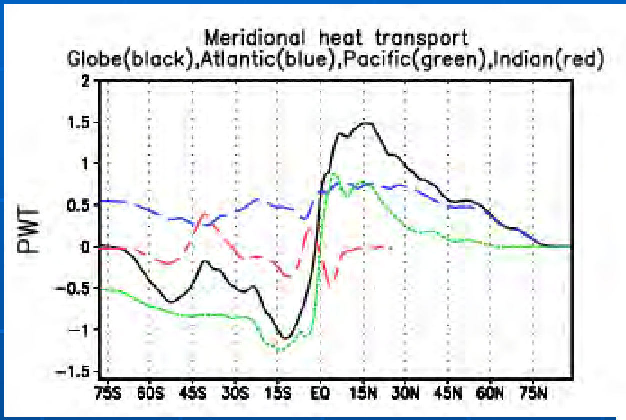
Results of experiments

(resulting fields are interpolated on the conventional geographical grid)

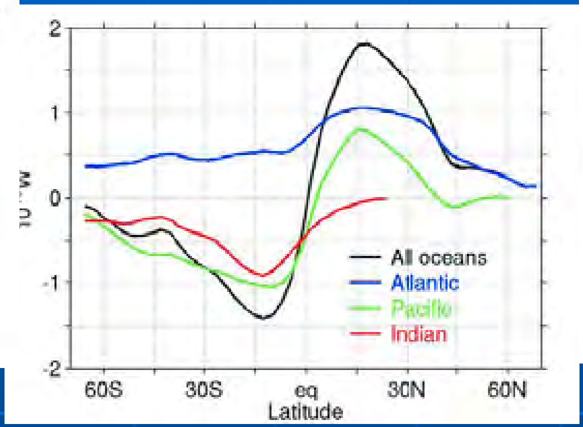


Annual mean Meridional Heat Transport (MHT) is very important characteristic for climatic OGC

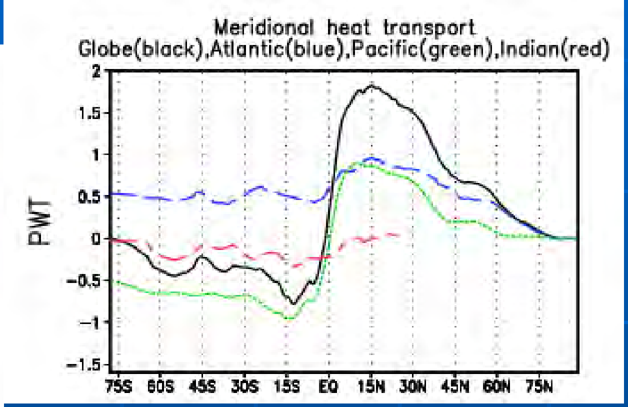
INMOM with prescribed CORE atmospheric forcing



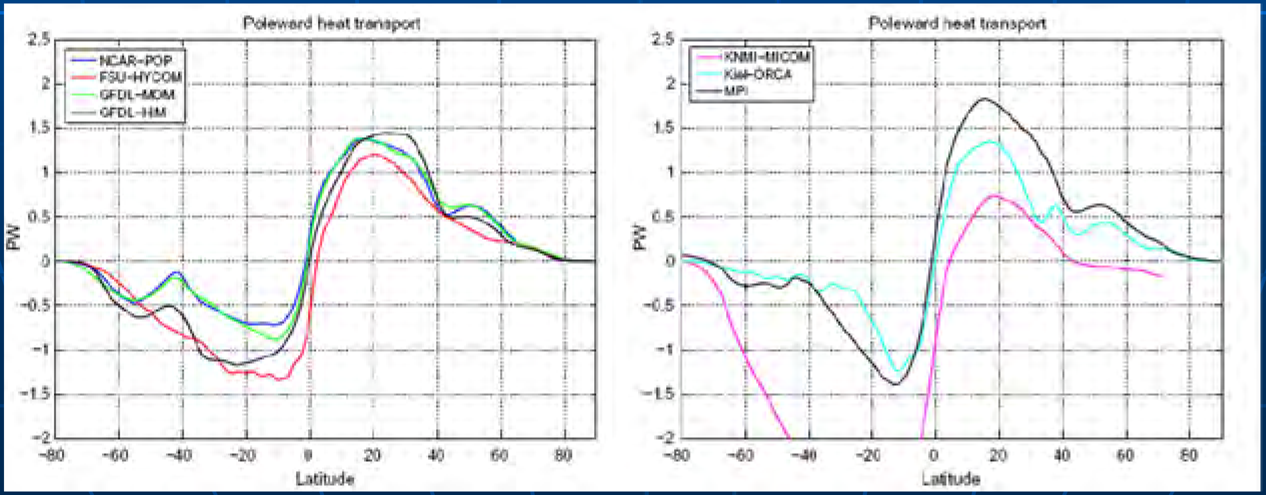
Estimation from observations (Trenberth and Caron, 2001)



INMOM from Coupled Model INMCM4

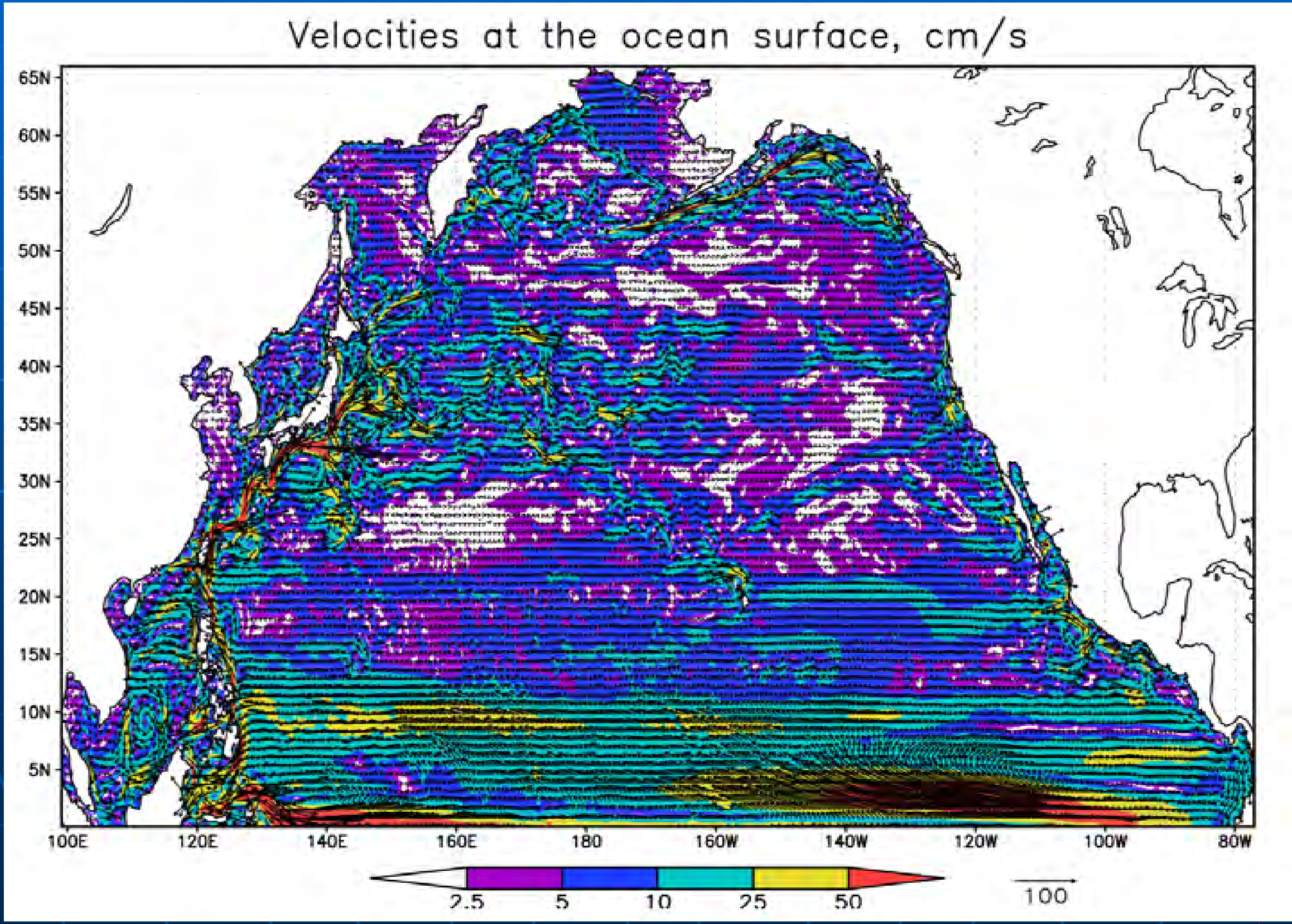


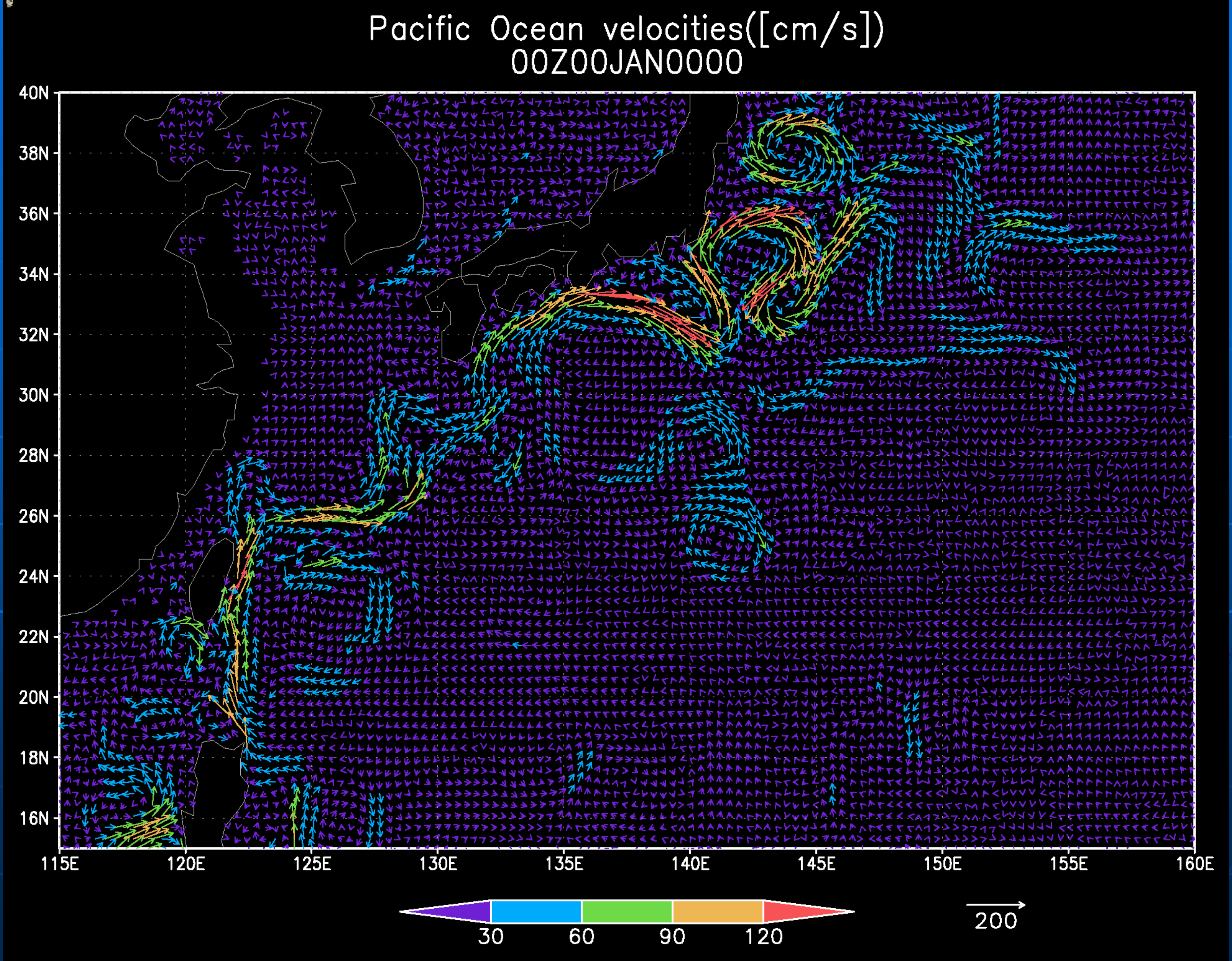
From CORE OGCMs [Griffies et al. 2009]



Simulation of North Pacific circulation using INMOM.

Spatial resolution is 1/8 degree and 33 unevenly spaced vertical sigma-levels. Atmospheric forcing is prescribed from CORE database for normalized year. Initial temperature and salinity is from World Ocean Database 2009.





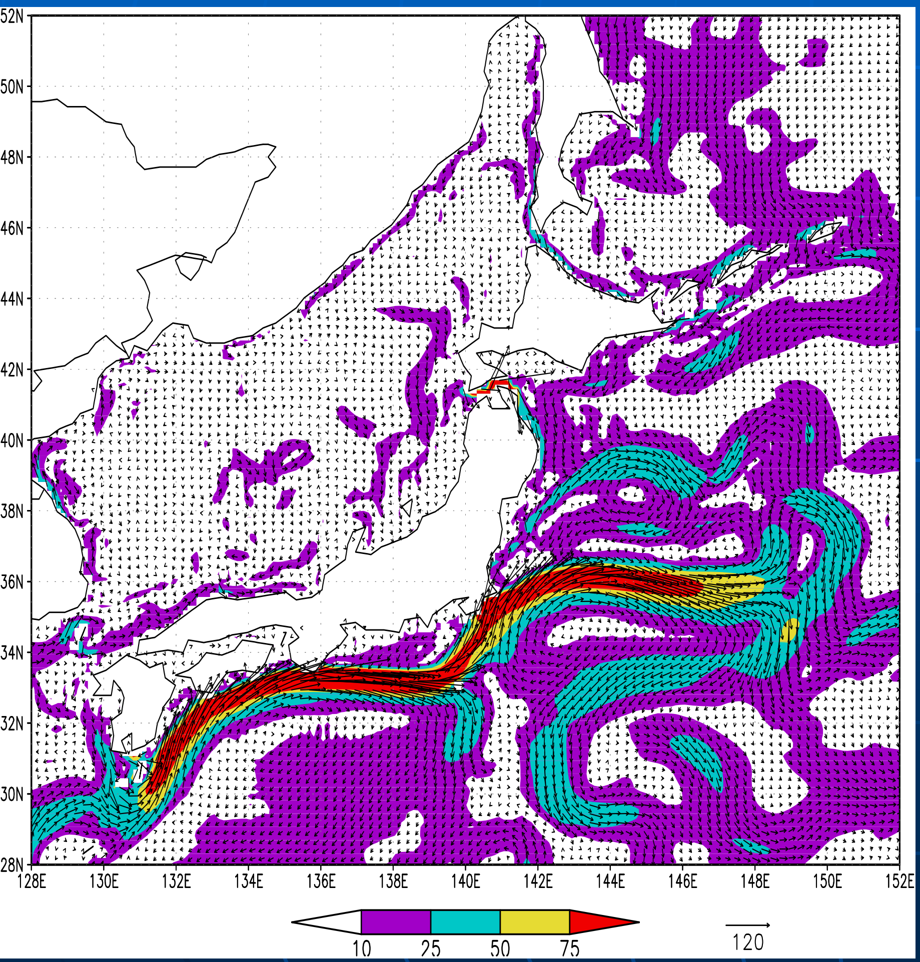
Pacific Ocean velocities([cm/s])
00Z00JAN0000
40N
38N
36N
34N
32N
30N
28N
26N
24N
22N
20N
18N
16N
115E
120E
125E
130E
135E
140E
145E
150E
155E
160E
30
60
90
120
200

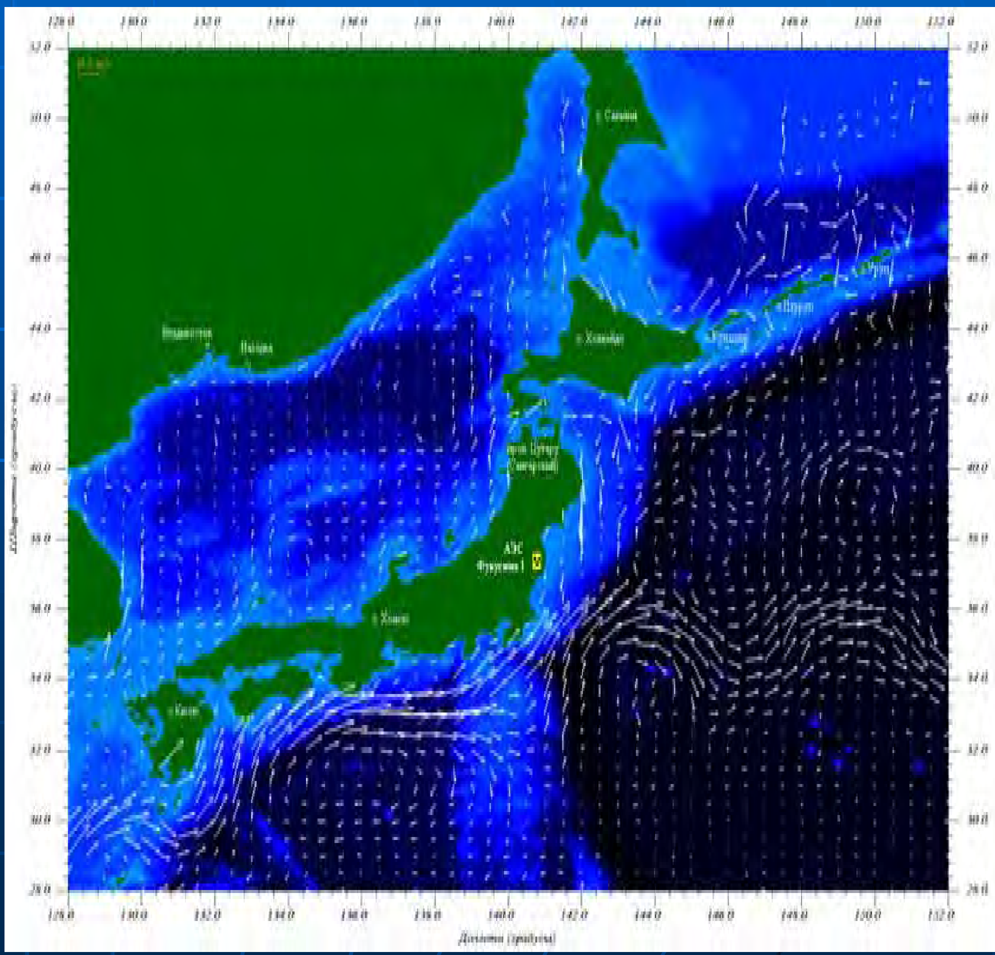
This version of INMOM is used for a simulation of pollutant transport (PT) in Pacific Ocean from the NPP Fukushima-1. Here ¼ degree atmospheric forcing of from NCEP analyses is used. The simulation of PT from March 11 to 28, 2011 is performed. In a model grid cell, next to the location of NPP Fukushima-1, the constant concentration of neutral buoyancy PT is given with the value equal to the 10000 MPC (Maximum Permissible Concentration)

Fields of surface currents in North-West Pacific Ocean

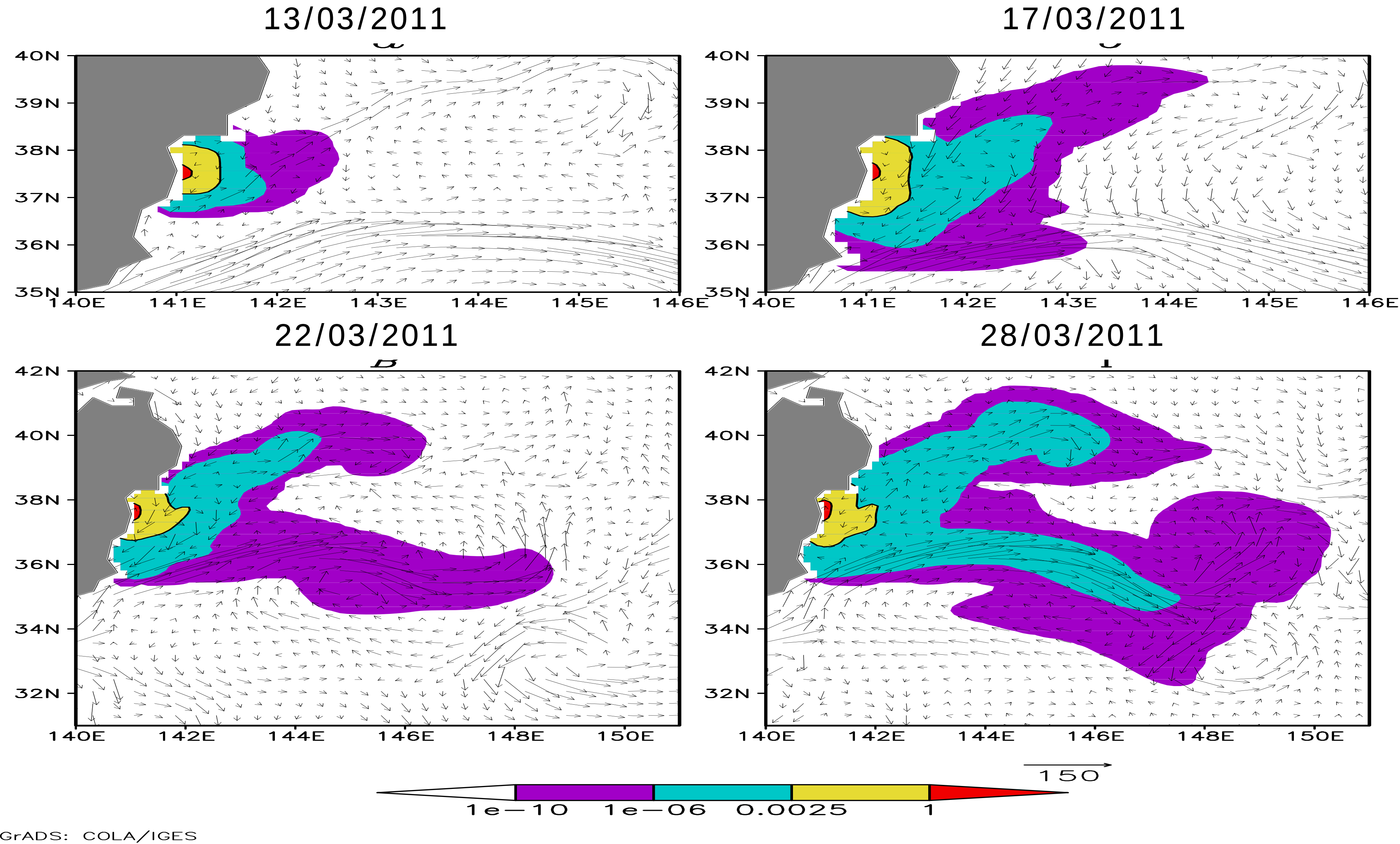
Model results averaged for April – March 2011. Simple SST assimilation is used.

Drifter data from NOAA (USA) и IFREMER (France) averaged for April-March from 1989 to 2011





The concentration of PT (colored) vs surface currents (arrows) for March 13, 17, 22 and 28 of 2011. Red shows concentration greater then MPC (Maximum Permissible Concentration). So there is not any dangerous concentration of radioactive with exception of very small area near Fukushima-1.



STUDY OF THE LOW-FREQUENCY VARIABILITY OF THE JES CIRCULATION BY NUMERICAL SIMULATIONS

Dmitry V. Stepanov and Nikolay A. Diansky

W4 Workshop Posters, 7635 PICES 2011

Low-frequency variability of the circulation in the central part of the Japan/East Sea on the 500 and 800 m depths and in layer is investigated based on numerical simulations. The large-scale three-dimensional circulation of the Japan/East Sea is reconstructed by using the Institute of Numerical Mathematics Ocean Model (INMOM).

Relative vorticity (z/f and f - Coriolis parameter at 40N) and the average area relative vorticity in the central region (38.4N 133E; 41N 137E) of the Japan/East Sea on are analyzed to reveal low-frequency variability of the velocity field on the 100, 500 and 800 m depths.

TYPE OF COMPUTATION / CONFIGURATION

The model's resolution is 1/10 degree and 15 sigma-levels.
The model's topography is from ETOPO2
Initial Temperature and Salinity World Ocean Database 2009.

Atmosphere Forcing

Database CORE (forcing for Common Ocean-ice Reference Experiments) 1958-2006 contains the following fields on a horizontal grid of 192 longitude points and 94 latitude points

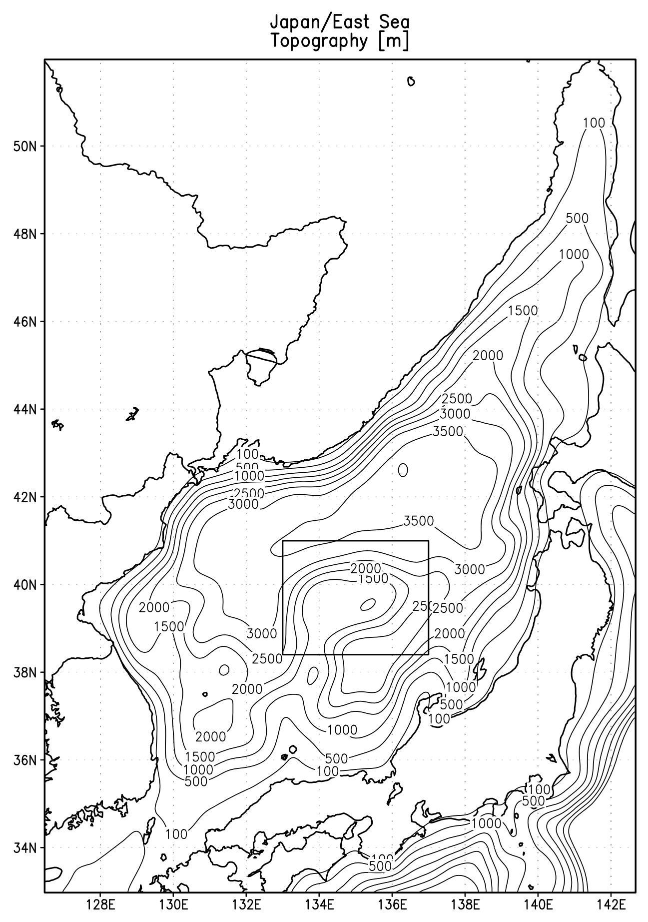
- monthly varying precipitation (12 time steps)
- daily varying shortwave and longwave (365 time steps–no diurnal cycle and no leap years),
- six-hourly varying 10m temperature, humidity, zonal velocity, meridional velocity, and sea level pressure (4 × 365 × 43 time steps–no leap years for the interannual data).

Experiment

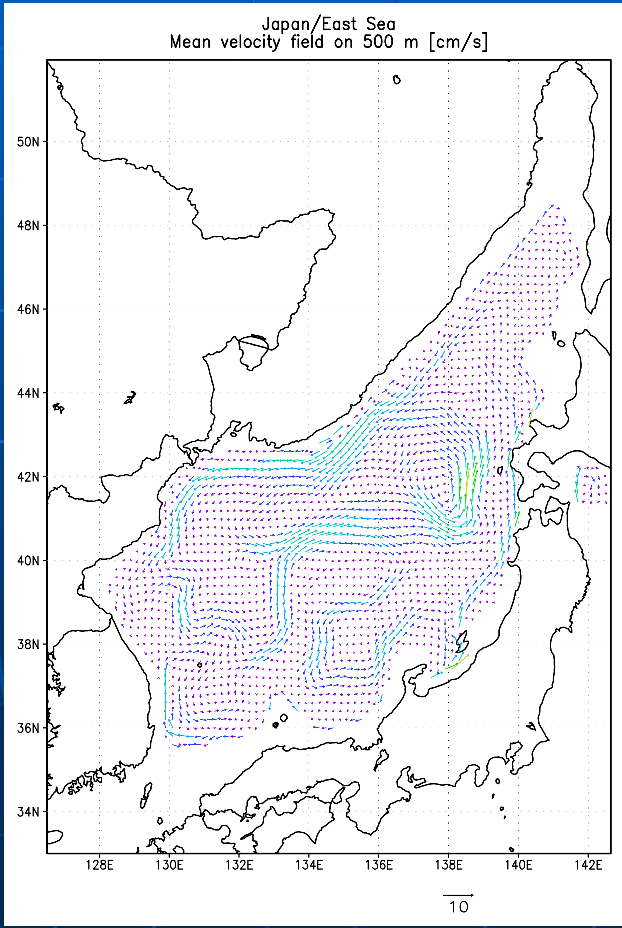
The vertical viscosity and diffusion coefficients are calculated by Monin-Obukhov parameterization. The coefficient of horizontal viscosity and diffusivity are set up equal to 20 m^2/s and to 400 m^2/s, respectively. CORE data from 1958 to 2006 is used.

LOW-FREQUENCY VARIABILITY RELATIVE VORTICITY AND THE AVERAGE AREA RELATIVE VORTICITY IN THE CENTRAL REGION (38.4N 133E; 41N 137E) OF THE JAPAN/EAST SEA

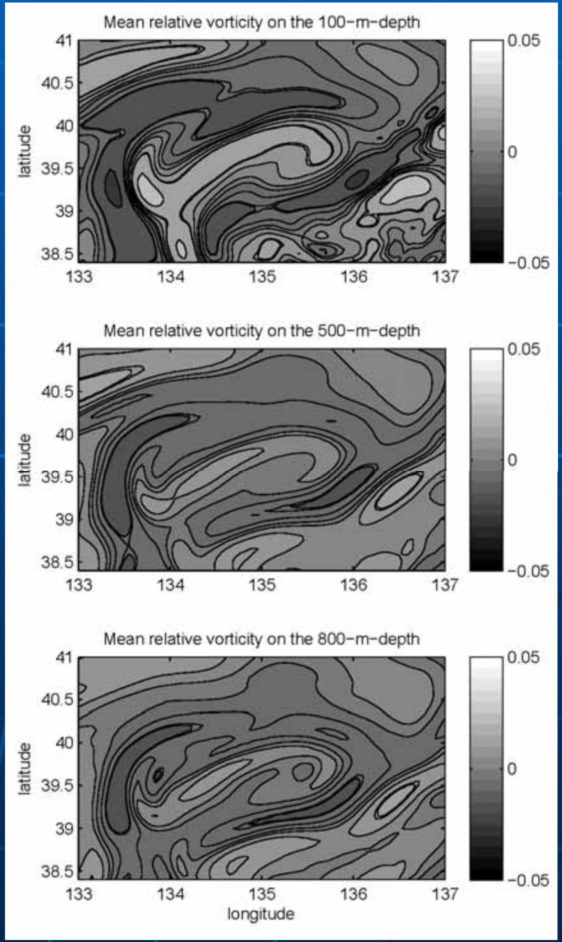
Topography [m]



Mean velocity field [cm/s]



Mean relative vorticity

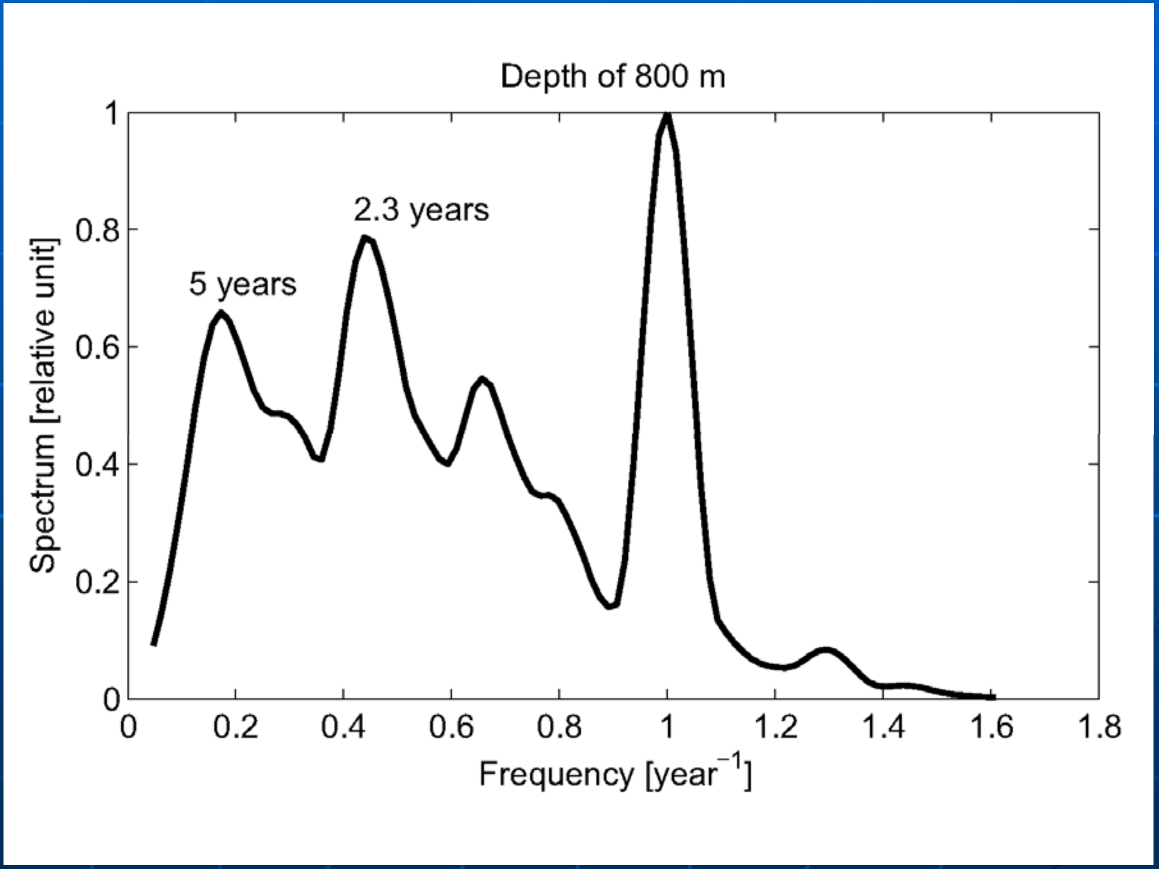


CONCLUSION from JES climatic circulation modelling

Spectrum of area averaged relative vorticity shows the picks on quasi-biennial and five year periods.

Possibly they are generated by atmospheric forcing. This suggestion will be proved in neer future study.

Quasi-biennial oscillation is also manifested in SSH observations (e.g. Trusenkova, 2011).

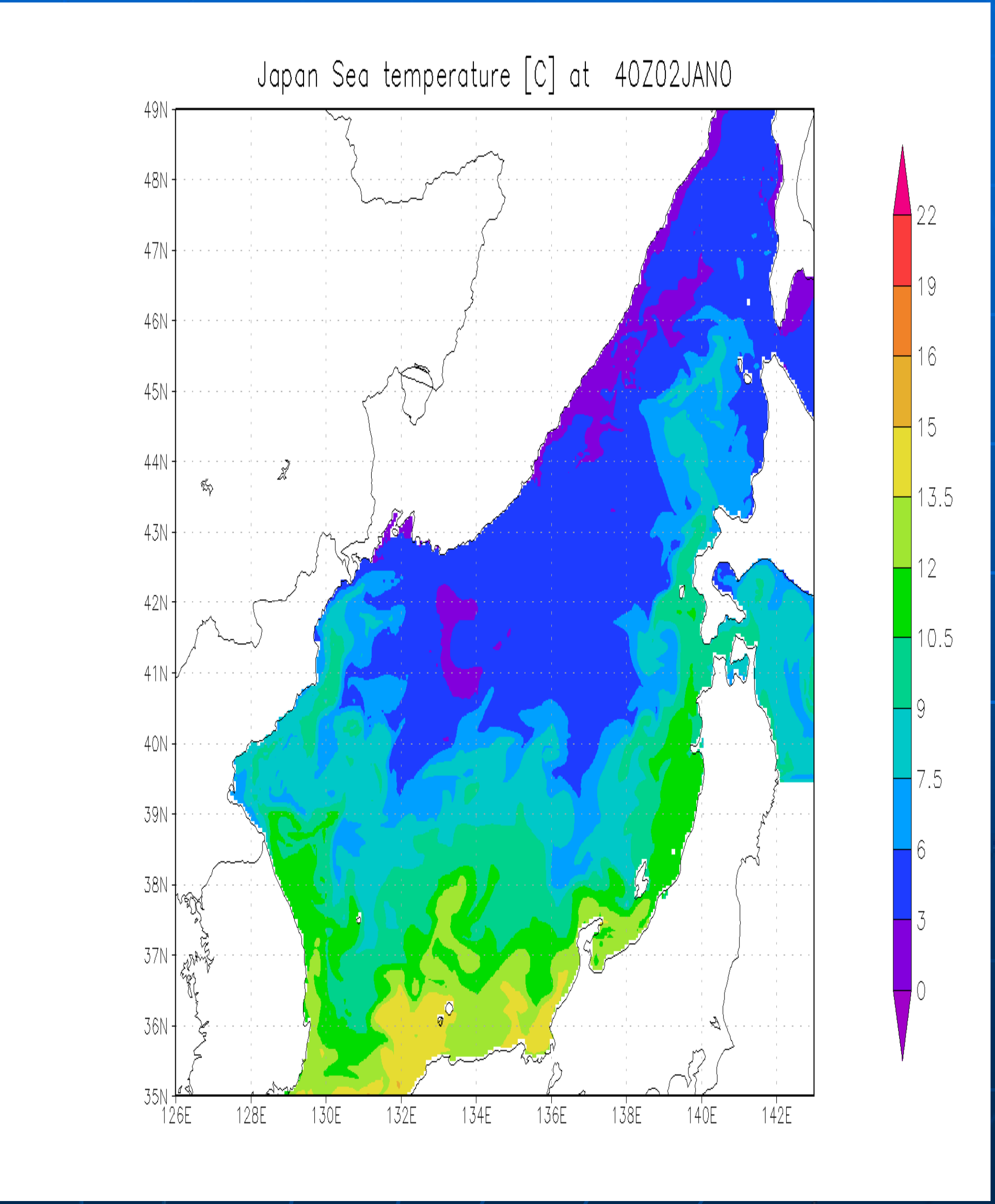


FIRST RESULTS OF NEW VERSION INMON FOR JES CIRCULATION

Time evolution of JES temperature field on 50 m obtained using
new version INMOM.

Spatial resolution is 1/20 degree and 40 sigma-levels. Atmospheric forcing is from CORE database for normalized year. Initial temperature and salinity is from World Ocean Database 2009.

Time integration is carried out for 2 years. Sub-mesoscale and mesoscale variability are shown against the background on annual cycle



Conclusions

The INMOM may be used for simulation some aspects of ocean circulation.

For future improving of the INMOM better physical paramerizations are needed especially for vertical mixing.

We need any observed data for comparison but there is a problem to get these data on appropriate time and spatial model grids.