EGU General Assembly 2019, 07-12 April 2019, Vienna, Austria

11 April, Thursday
Section: **Recent Developments in Numerical Earth System Modelling**
Co-organized as BG1.62/CL5.08/NP1.3/OS4.23

Photography encouraged

A full free surface ocean general circulation model in sigma-coordinates for simulation of the World Ocean circulation and its variability

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Outline

1) Some aspects of the climate system modelling.

2) Review of the INM RAS climate model complex.

3) OGCM INMOM: structure, implementation, application

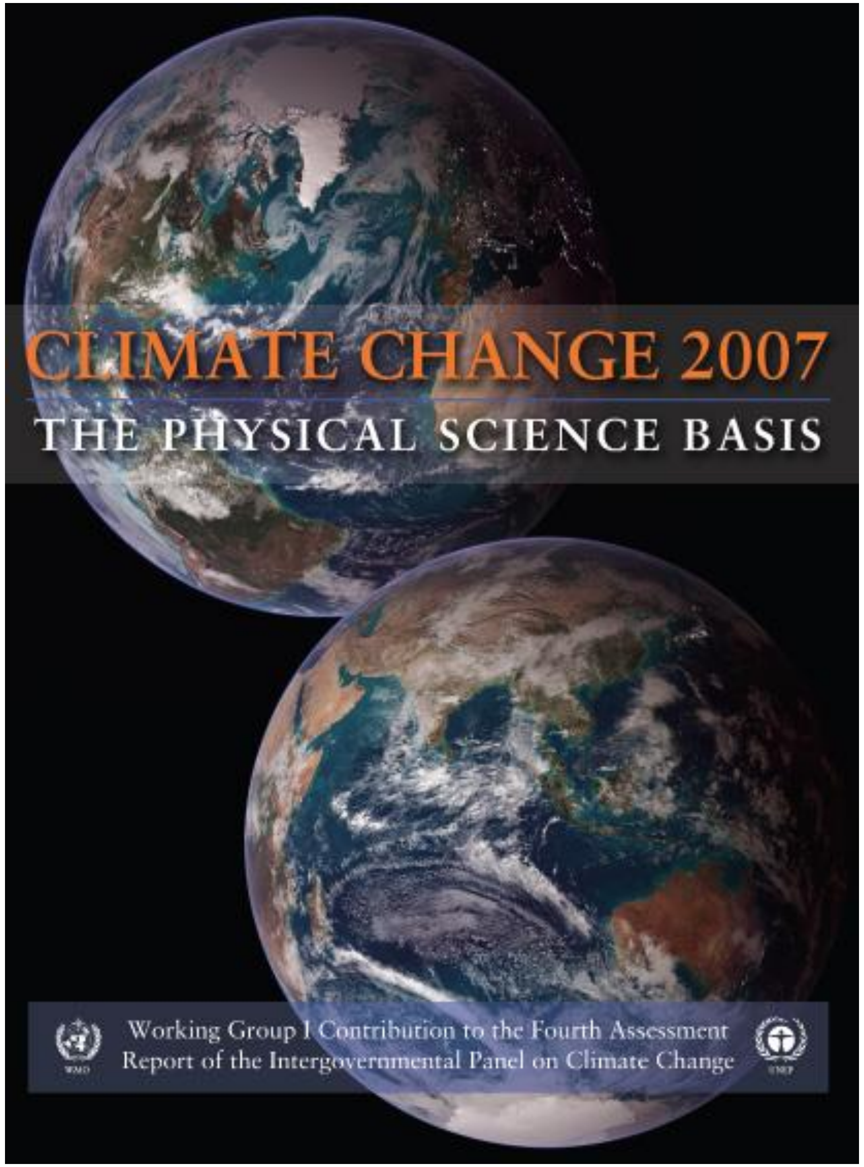
4) Ways for further improvements of the INMOM.

Earth climate model components

These components are developed separately and need to be coupled in some way.
Each of them must be separately validated before including them in the coupled model

INMCM – the only Russian climate model series presented in the IPCC Reports

INMCM3:
Atmosphere: 5x4 deg. x 21 levs
Ocean: 2.5x2 deg. x 33 levs



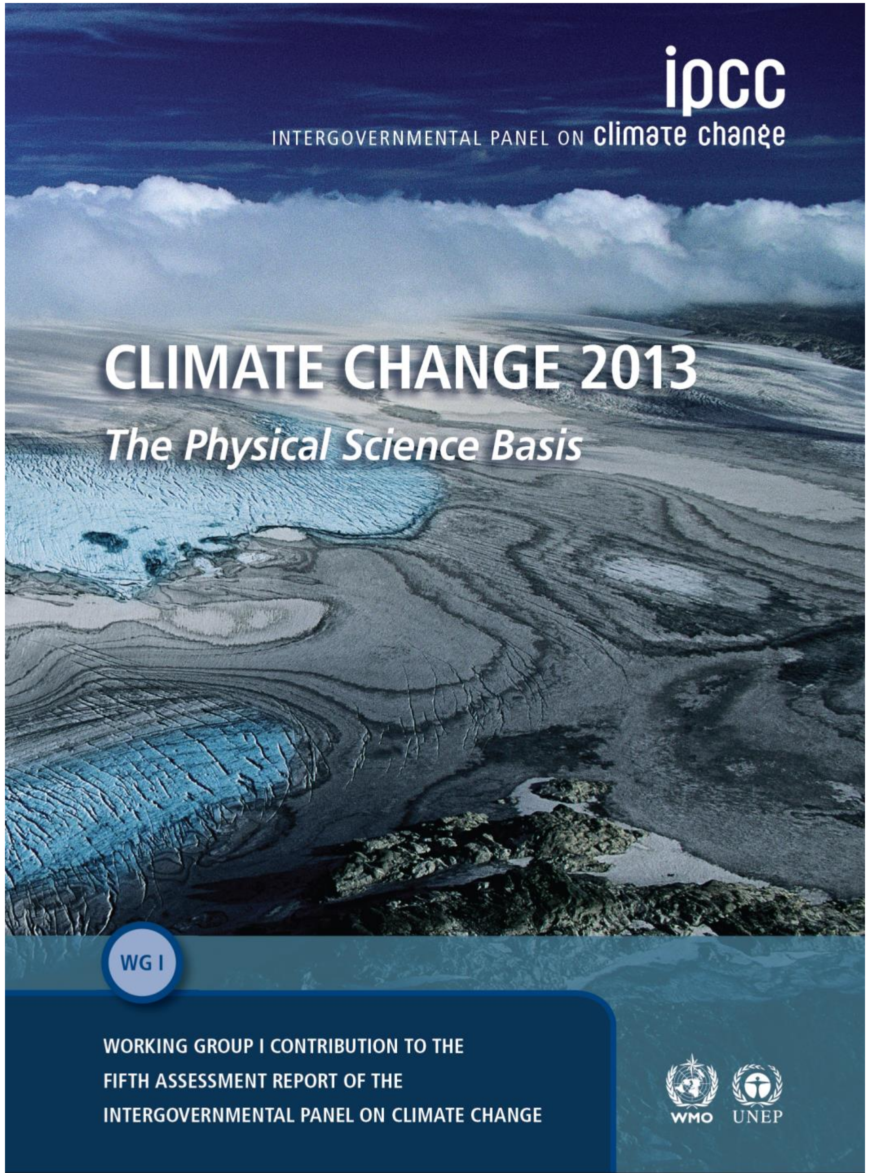
N. A. Diansky and E. M. Volodin, "Simulation of present-day climate with a coupled atmosphere–ocean general circulation model," Izv., Atmos. Ocean. Phys. **38** (6), 732–747 (2002).

E. M. Volodin and N. A. Diansky, "Response of a coupled atmosphere–ocean general circulation model to increased carbon dioxide," Izv., Atmos. Ocean. Phys. **39** (2), 170–186 (2003).

E. M. Volodin and N. A. Diansky, "Reproduction of El-Nino in a coupled atmosphere–ocean general circulation model," Russ. Meteorol. Hydrol. **29** (12), 5–14 (2004)

E. M. Volodin and N. A. Diansky, "Simulation of climate changes in the 20th–22nd centuries with a coupled atmosphere–ocean general circulation model," Izv., Atmos. Ocean. Phys. **42** (3), 267–281 (2006).

INMCM4
Atmosphere: 2x1.5 deg. x 21 levs
Ocean: 1x0.5 deg. x 40 levs



N.A. Dianskii, V.Ya. Galin, A.V. Gusev, S.P. Smyshlyaev, E.M. Volodin, N.G. Iakovlev. The model of the Earth system developed at the INM RAS. *Russian Journal of Numerical Analysis and Mathematical Modelling*. 2010. V. **25**, N. 5, P. 419–429.

E. M. Volodin, N. A. Diansky, and A. V. Gusev, “Simulating present-day climate with the INMCM4.0 coupled model of the atmospheric and oceanic general circulations,” *Izv., Atmos. Ocean. Phys.* **46** (4), 414–431 (2010).

E. M. Volodin, N. A. Diansky, and A. V. Gusev, “Simulation and prediction of climate changes in the 19th to 21st centuries with the Institute of Numerical Mathematics, Russian Academy of Sciences, model of the Earth’s climate system,” *Izv., Atmos. Ocean. Phys.* **49** (4), 347–366 (2013).

INMCM5
Atmosphere: 2x1.5 deg. x 73 levs
Ocean: 0.5x0.25 deg. x 40 levs

1. E.M. Volodin, E.V. Mortikov, S.V. Kostrykin, V.Ya. Galin, V.N. Lykossov, A.S. Gritsun, N.A. Diansky, A.V. Gusev, N.G. Iakovlev. Simulation of the present-day climate with the climate model INMCM5 // *Clim. Dyn*. 2017. V. **49**. P. 3715–3734.
2. E.M. Volodin, E.V. Mortikov, S.V. Kostrykin, V.Ya. Galin, V.N. Lykosov, A.S. Gritsun, N.A. Diansky, A.V. Gusev, N.G. Yakovlev. Simulation of modern climate with the new version of the INM RAS climate model. *Izvestiya, Atmospheric and Oceanic Physics*, 2017, V. **53**, № 2, P. 142–155
3. Volodin, E., Mortikov, E., Kostrykin, S., Galin, V., Lykossov, V., Gritsun, A., Diansky, N., Gusev, A., Iakovlev, N., Shestakova, A., Emelina, S. Simulation of the modern climate using the INM-CM48 climate model. *Russian Journal of Numerical Analysis and Mathematical Modelling*, 2018, **33**(6), pp. 367-374

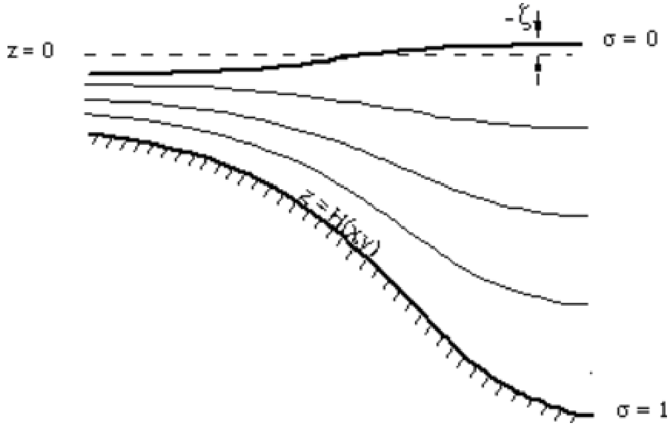
The ocean is the climate system component with the great heat capacity. It must proceed the validation processes before including it into the CSM.

The subject of this presentation is INMOM: the oceanic component of the INMCM series.

The INMOM characteristics

1) Basis: Primitive equations of the ocean hydro- and thermodynamics, Boussinesq and hydrostatic approximations are used.

2) Vertical coordinate is σ (like POM or ROMS): $\sigma = \dfrac{z+\zeta(x,y,t)}{H(x,y)+\zeta(x,y,t)}, \quad \sigma \in [0;1]$



3) Arbitrary orthogonal coordinates in horizontal subspace.

4) Isopycnal mixing using.

5) Implicit free surface method

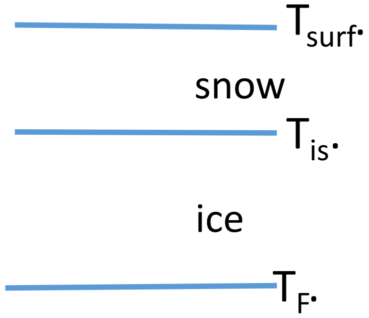
Remark: INMOM is the only s-model in the world used for climate simulations

Embeddded sea ice dynamics-transport-thermodynamics module.

1) Thermodymamics – 0-layer model (Yakovlev)

2) Transport – MPDATA (Smolarkiewicz)

3) Dynamics – EVP-rheology (Hunke and Dukowicz)



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

Moebius transformation:

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

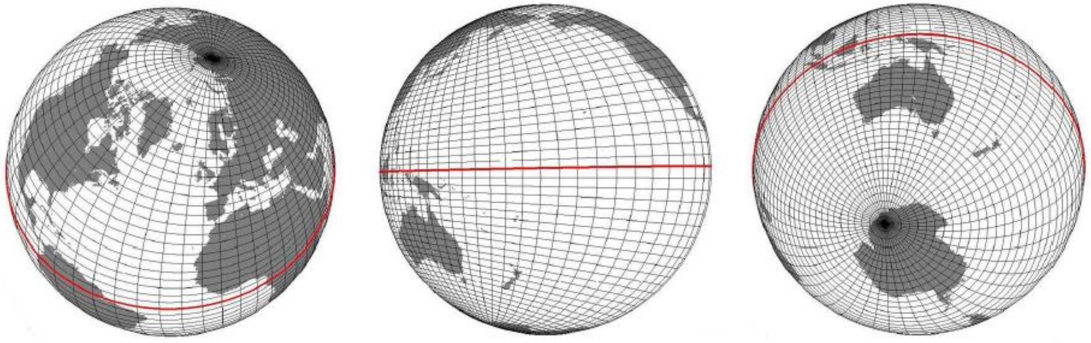
$$\xi = \tan\left(\frac{\pi}{4} + \frac{y}{2}\right)\exp(i(x - x_0)),$$

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

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

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

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)

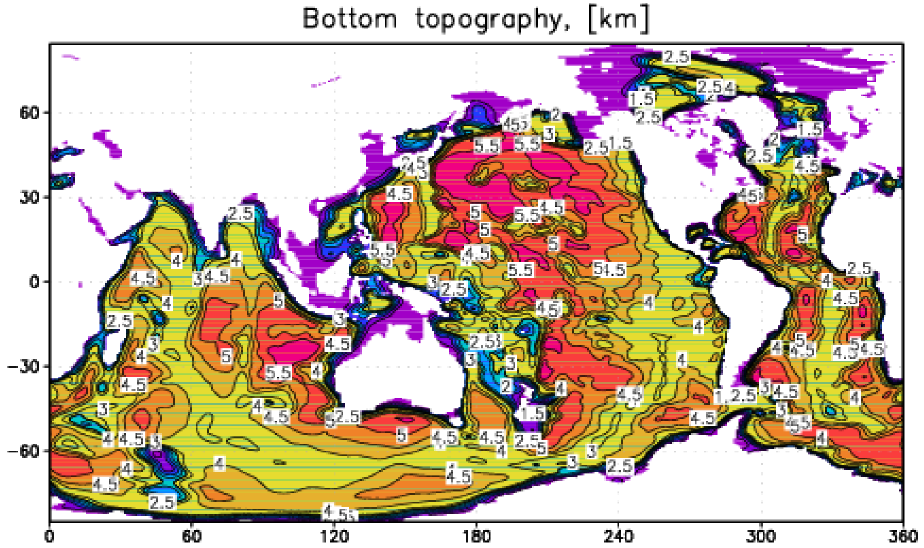


$$r_x = R\sqrt{\left(\frac{\partial\lambda}{\partial x}\cos\varphi\right)^2 + \left(\frac{\partial\varphi}{\partial x}\right)^2},$$

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

- Metrical coefficients in curvilinear system

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

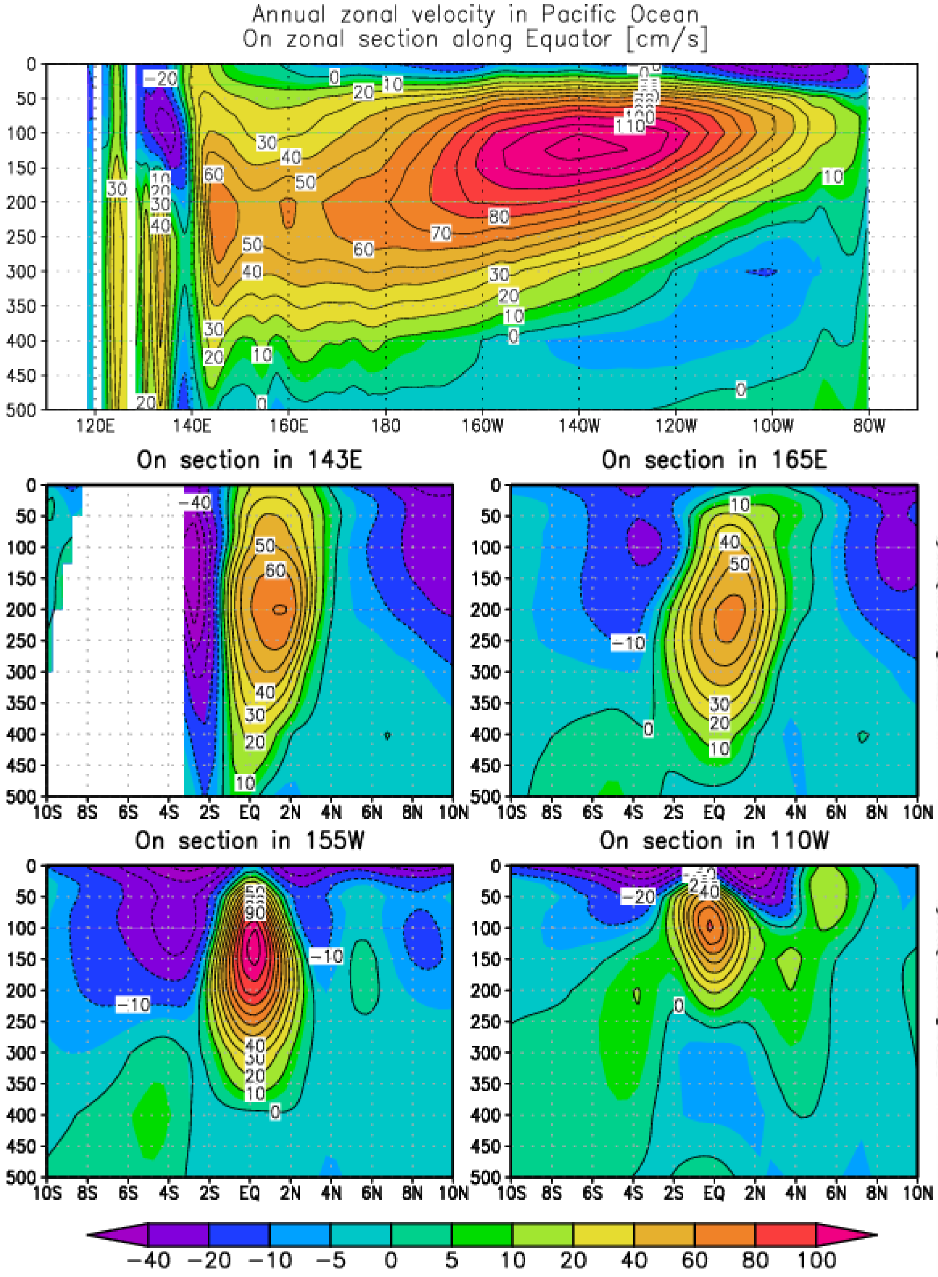
Coordinated Ocean-ice Reference Experiments (CORE) Phase II (CORE-II) with INMOM (Institute of Numerical Mathematics Ocean Model)

1. Interannual CORE(Common Ocean Research Experiment) real atmospheric forcing is used for the period 1948-2007 (later extended to 2009).
2. Spinup- 240 years (4x60 yr), analysis - 241-300 years (60yr).
3. Resolution is 1.0°x0.5° (360x340 nodes on horizontal grid and 40 σ-levels along depth) on the curvilinear grid with displaced poles (North pole is placed at 100°E 70°N).
4. Time step is 1 hour.
5. Initial conditions are rest state, January Levitus T and S, ice null.
6. Sea ice dynamics-thermodynamics model (Yakovlev; Hunke, et. al) was used.
7. Vertical mix is Pacanowski & Philander with simple wind wave breaking parameterization added.
8. SSS restoring of 50m/2yr is applied.

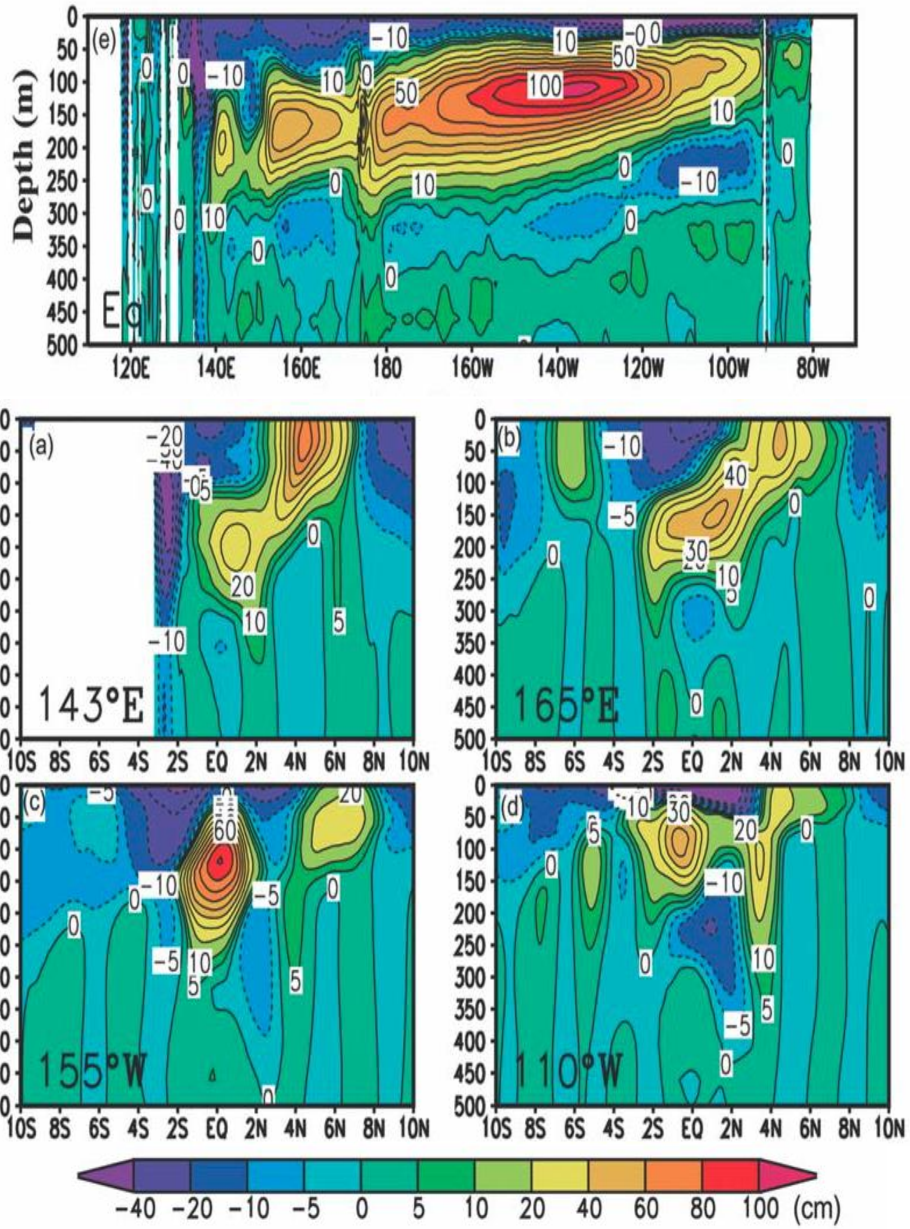
1. A.V. Gusev and N.A. Diansky. Numerical simulation of the World ocean circulation and its climatic variability for 1948–2007 using the INMOM. *Izvestiya, Atmospheric and Oceanic Physics*, 2014, Vol. **50**, No. 1, pp. 1–12
2. Danabasoglu, G., S. G. Yeager et al., 2014: North Atlantic simulations in Coordinated Ocean-ice Reference Experiments phase II (CORE-II). Part I: Mean states. *Ocean Modelling*, **73**, 76-107
3. S.M. Downes, R. Farneti et al. An assessment of Southern Ocean water masses and sea ice during 1988–2007 in a suite of interannual CORE-II simulations. *Ocean Modelling* (2015), **94**, 67–94
4. R. Farneti, S.M. Downes et al. An assessment of Antarctic Circumpolar Current and Southern Ocean Meridional Overturning Circulation during 1958–2007 in a suite of interannual CORE-II simulations, *Ocean Modelling* (2015), **93**, 84-120
5. Danabasoglu, G., S. G. Yeager et al., 2016: North Atlantic simulations in Coordinated Ocean-ice Reference Experiments phase II (CORE-II). Part II: Inter-annual to decadal variability. *Ocean Modelling*, **97**, 65-90

Equatorial circulation

INMOM (average for 1948-2007)



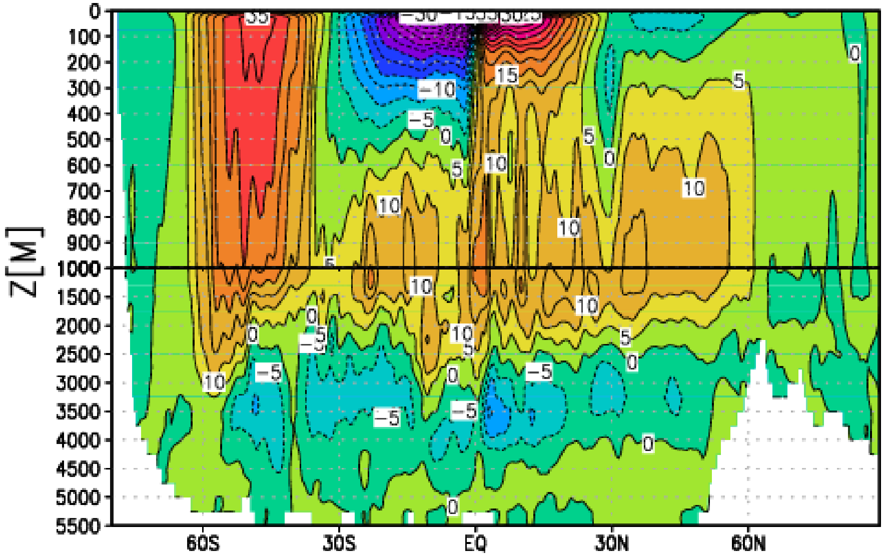
OFES(Masumoto et._al., 2004) -high-resolution MOM



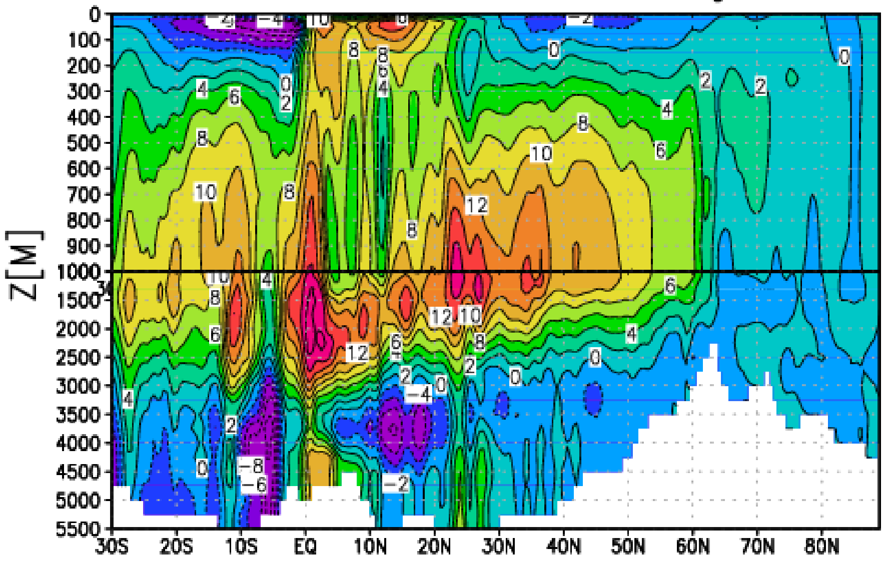
MOC streamfunction

INMOM (average for 1948-2007)

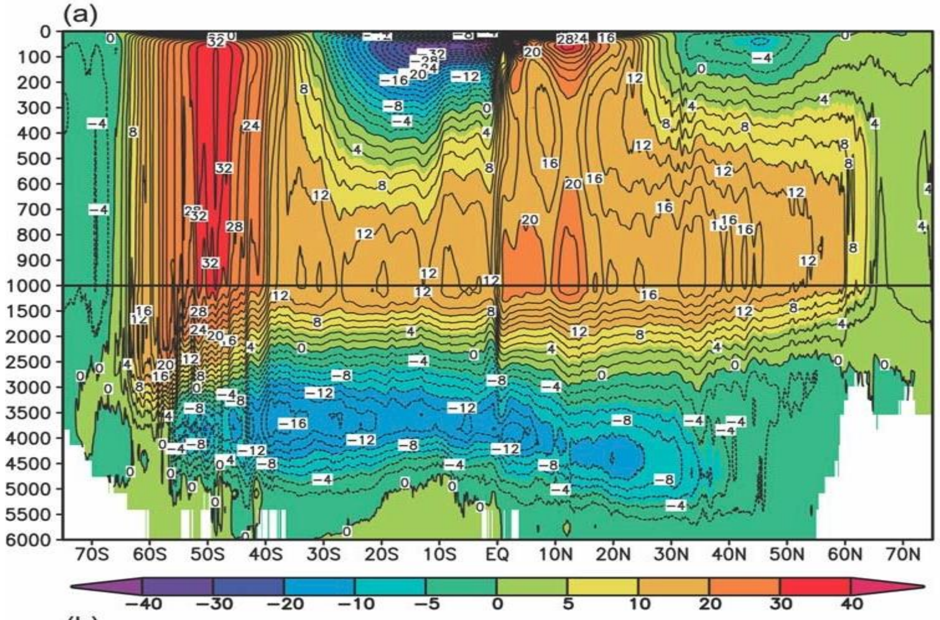
Annual mean global meridional overturning ciculation, Sv

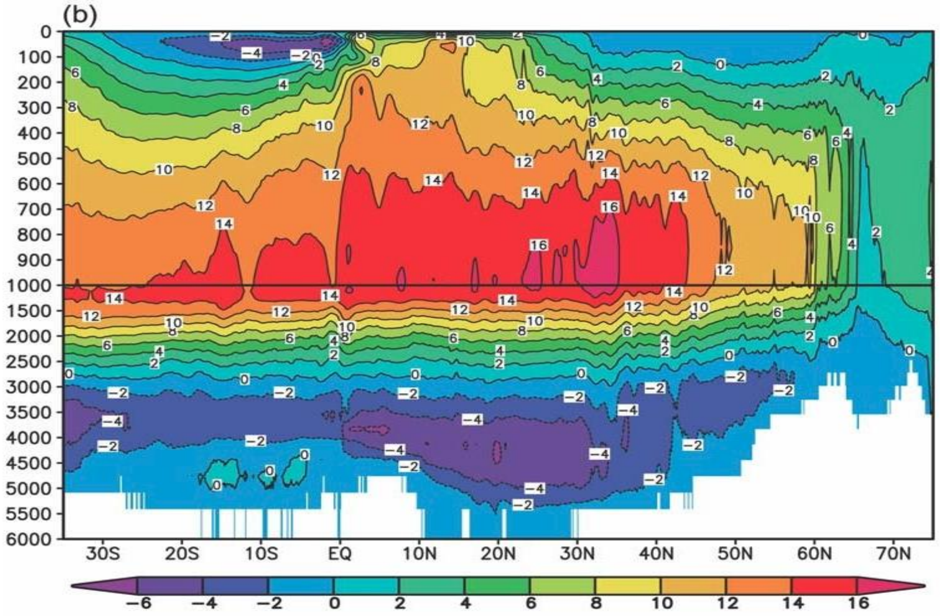


Annual mean Atlantic meridional overturning ciculation, Sv



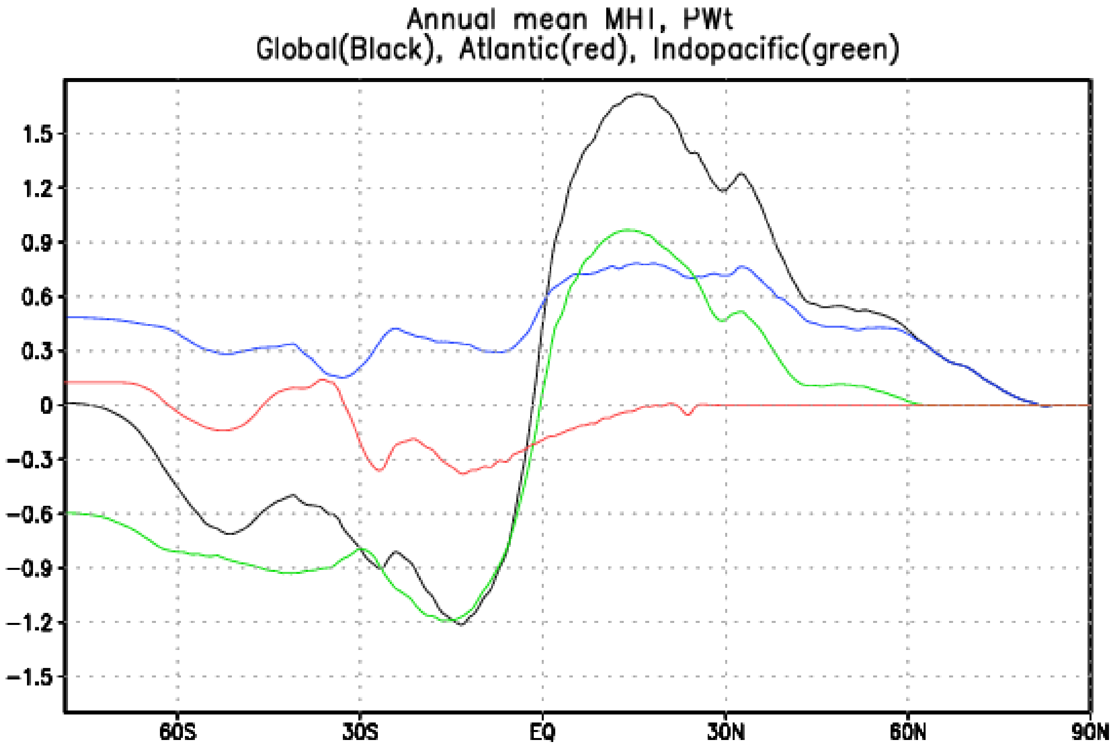
OFES(Masumoto et._al., 2004) -high-resolution MOM



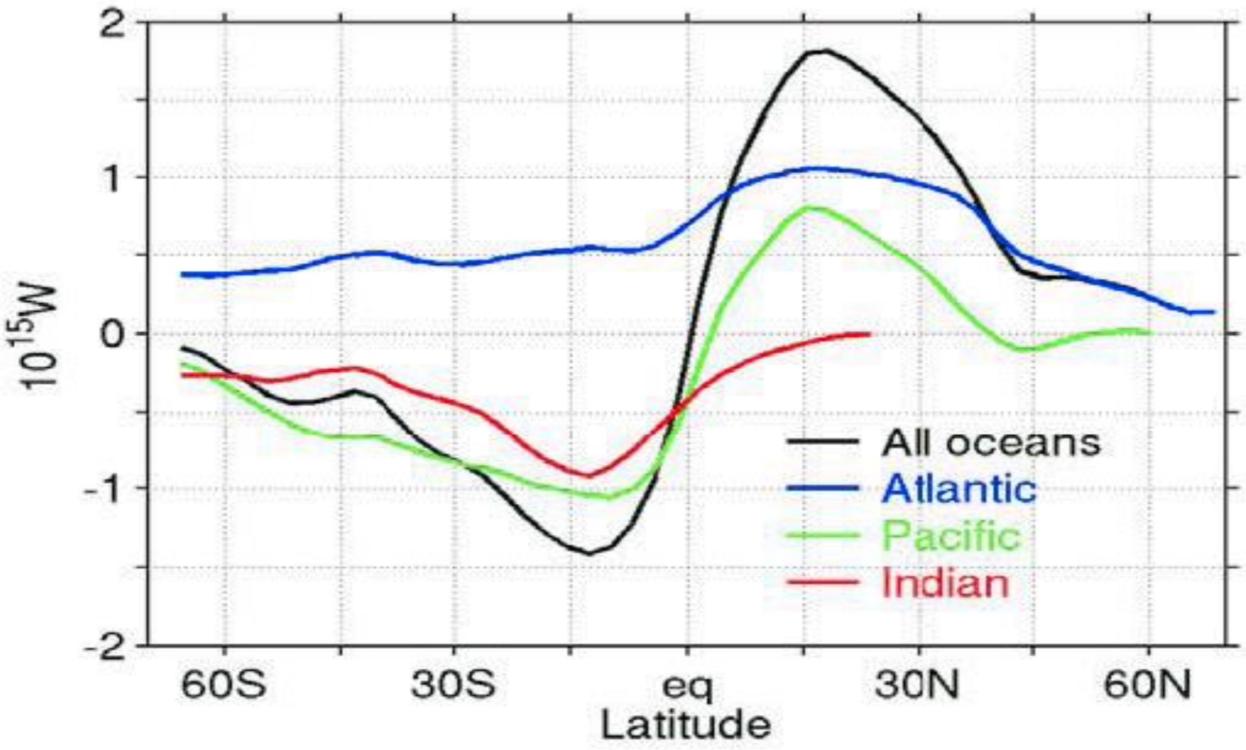


Meridional Heat Transport (MHT)

INMOM (average for 1948-2007)



Estimations
(Trenberth and Carron, 2001)



Further development of the INMOM

1) Implementation of the ocean dynamics block in terms of full free surface (h – time variable total depth, changed due to dynamic and volume budget change: precipitation, evaporation, river runoff, ice volume change.

$$\frac{\partial hS}{\partial t}+\frac{1}{r_x r_y}\left(\frac{\partial u r_y hS}{\partial x}+\frac{\partial v r_x hS}{\partial y}\right)+\frac{\partial \omega S}{\partial \sigma}=D_L(S)+D_V(S).$$

$$\frac{\partial h}{\partial t}+\frac{1}{r_x r_y}\left(\frac{\partial u r_y h}{\partial x}+\frac{\partial v r_x h}{\partial y}\right)+\frac{\partial \omega}{\partial \sigma}=0.$$

Consequences:

2) More correct statement of surface boundary conditions (e.g. no need to introduce artificial salt fluxes):

$$\omega S-\frac{\nu_S}{h}\frac{\partial S}{\partial \sigma}=q_s$$

$$\omega\big|_{\sigma=0}=Q$$

3) No need to use “levitating ice” approximation

4) Using a simple ice salt evolution

Further development of the INMOM

Modification of dissipation processes.

1) Lateral diffusion-viscosity:

a) formulation of lateral viscosity operator in the tensor form:

b) using Smagorinsky algorithm to compute lateral viscosity and diffusion coefficients (proportional to stress tensor magnitude);

c) Inplementation of isopycnal diffusion including Gent-McWilliams eddy-induced transport

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

$$D_S = \frac{r_x}{r_y}\frac{\partial}{\partial y}\left(\frac{u}{r_x}\right) + \frac{r_y}{r_x}\frac{\partial}{\partial x}\left(\frac{v}{r_y}\right).$$

$$D_u(u,v) = \frac{1}{r_y}\frac{\partial}{\partial x}\left(r_y{}^2 K D_T\right) + \frac{1}{r_x}\frac{\partial}{\partial y}\left(r_x{}^2 K D_S\right),$$

$$D_v(u,v) = -\frac{1}{r_x}\frac{\partial}{\partial y}\left(r_x{}^2 K D_T\right) + \frac{1}{r_y}\frac{\partial}{\partial x}\left(r_y{}^2 K D_S\right).$$

$$K_{smag} = K_{ref} + \kappa\sqrt{D_T^2 + D_S^2},$$

$$\frac{\partial hS}{\partial t} + \frac{1}{r_x r_y}\left(\frac{\partial u r_y hS}{\partial x} + \frac{\partial v r_x hS}{\partial y}\right) + \frac{\partial \omega S}{\partial \sigma} = D_L(S) + D_V(S), \quad D(S) = \mathrm{div}(\widehat{\mathrm{K}}\,\mathrm{grad}\, S),$$

$$\widehat{\mathrm{K}} = \begin{pmatrix} \mu & 0 & -\mu\alpha_x \\ 0 & \mu & -\mu\alpha_y \\ -\mu\alpha_x & -\mu\alpha_y & \mu(\alpha_x^2 + \alpha_y^2) \end{pmatrix} + \begin{pmatrix} 0 & 0 & \gamma\mu(\alpha_x - Z_x) \\ 0 & 0 & \gamma\mu(\alpha_y - Z_y) \\ -\gamma\mu(\alpha_x - Z_x) & -\gamma\mu(\alpha_y - Z_y) & 0 \end{pmatrix}$$

$$U_{gm} = \frac{\partial}{\partial z}\left(\gamma\mu(\alpha_x - Z_x)\right), \quad V_{gm} = \frac{\partial}{\partial z}\left(\gamma\mu(\alpha_y - Z_y)\right), \quad W_{gm} = -div_h\left(\gamma\mu(\alpha_x - Z_x), \gamma\mu(\alpha_y - Z_y)\right).$$

$$Z = (H + \zeta)\sigma - \zeta$$

Remark. GM eddy-induced transport is possibly relevant only for coarse resolution, while Smagorinsky, vice versa, for high enough one.

Further development of the INMOM

Vertical turbulent exchange parameterization with the two-equation algorithm (e.g. Mellor-Yamada)

$$\frac{dq^2}{dt} - \frac{\partial}{\partial z}\left[\nu_q \frac{\partial q^2}{\partial z}\right] = 2\left[P_s - P_b - \frac{q^3}{B_1 l}\right] + D(q^2),$$

1st equation – for turbulent kinetic energy

$$\frac{d\left(q^2 l\right)}{dt} - \frac{\partial}{\partial z}\left[\nu_q \frac{\partial q^2 l}{\partial z}\right] = lE_1\left[P_s - P_b\right] - \frac{q^3}{B_1}\left[1 + E_2\left(\frac{l}{\kappa L}\right)^2 + D(q^2 l)\right],$$

2nd equation – for a certain turbulence scale (length if Mellor-Yamada algorithm is applied.)

$$P_s = \nu_v\left(\frac{\partial u}{\partial z}\right)^2 + \nu_v\left(\frac{\partial v}{\partial z}\right)^2$$

$$P_b = \frac{g}{\rho_0}\nu_T \frac{\partial \rho}{\partial z}$$

$$L^{-1} = \frac{1}{z} + \frac{1}{H - z}$$

$$q^2 = B_1^{2/3}(u^*)^2, \quad q^2 l = 0, \quad \sigma = 0{,}1$$

$$u^* = \frac{1}{\rho_0}\sqrt{\left(\tau^x\right)^2 + \left(\tau^y\right)^2}$$

$$\nu_T = lqS_T, \quad \nu_v = lqS_v,$$

Further development of the INMOM

Unfortunately, pressure gradient problem in the s-coordinates has not been fully solved yet.

$$\frac{\partial u}{\partial t} = -\frac{1}{\rho_0 r_x}\left(\frac{\partial p}{\partial x} - \frac{\partial Z/\partial x}{\partial Z/\partial \sigma}\frac{\partial p}{\partial \sigma}\right),$$

$$\frac{\partial p}{\partial \sigma} = \rho g \, \partial Z/\partial \sigma,$$

$$Z = (H+\zeta)\sigma - \zeta$$

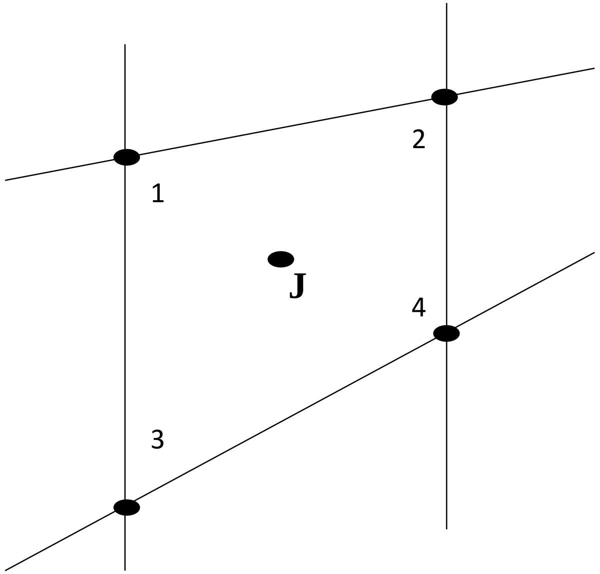
We can present the total density as a sum of the background one and deviation and exclude the pressure.

$$\rho = \rho_0 + \rho'$$

$$\frac{\partial u}{\partial t} = -\frac{g}{r_x}\frac{\partial \zeta}{\partial x} - \frac{1}{\rho_0 r_x}\left(g\frac{\partial \zeta}{\partial x}\rho'\Big|_{\sigma=0} + \int_0^{\sigma}\left(\frac{\partial \rho'}{\partial x}\frac{\partial Z}{\partial \sigma} - \frac{\partial \rho'}{\partial \sigma}\frac{\partial Z}{\partial x}\right)d\sigma\right).$$

$$J = \frac{\partial \rho'}{\partial x}\frac{\partial Z}{\partial \sigma} - \frac{\partial \rho'}{\partial \sigma}\frac{\partial Z}{\partial x}$$

$$2\hat{J}\Delta x \Delta \sigma = (\rho_4 - \rho_1)(Z_3 - Z_2) - (Z_4 - Z_1)(\rho_3 - \rho_2).$$



1) If density is a linear function of Z, there is no motion generated.
2) In the case of quadratic function (as in state equations) artificial currents appear. The greatest error is near the Equator.
3) We can apply non-linear approximations of the Jacobian, but this will require to modify the temperature and salinity transport schemes.

Conclusions

1) The OGCM INMOM is presented which is an oceanic component of the CSMs INMCM developed in the INM RAS. The INMCM results are presented in the IPCC reports and other publications.

2) The description and results of INMOM validation are reviewed at the example of the past simulation by the scenario CORE-II. The main characteristics responsible for the climate formation are acceptably reproduced.

3) The improvements are presented performed in the new INMOM model version, and problems are formulated arising by using sigma-coordinates.

P.S. Unfortunately, the presentation time is limited, however, there are many various aspects to discuss. If someone is interested, I’d be glad to continue the discussion beyond the oral session, as well, via e-mail.

That’s all !!!