

Baroclinic ocean model LSOMG

Libor Šachl, Zdeněk Martinec

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Seminar topic?

- benchmarks of tidal BT models (+2 time-stepping schemes, +1 computational grid, +2 benchmarks)
- modelling of tides (BT and BC)
- computations of wind-driven ocean-induced magnetic fields
- BC ocean model LSOMG, wind- and buoyancy-driven circulation

Outline

- 1 Model description
- 2 Input data
- 3 Benchmarks and realistic runs

Current section

- 1 Model description
- 2 Input data
- 3 Benchmarks and realistic runs

Motivations for the development

- GIA
 - improvement of sea-level equation $\Rightarrow$ paleocean modelling (bathymetry which is evolving in time)
 - long runs ($\approx 20\,000$ years) $\Rightarrow$ LSG ocean model (semi-implicit)
- ESA project “Swarm + Oceans”
 - present-day circulation
 - a few years of Swarm data
 - tides $\Rightarrow$ precludes long time steps

Persistent model requirements

- global primitive-equation ocean model
- fully 3D (not only barotropic) $\Rightarrow$ 3D velocities
- understood on a code level and open for modifications
- usable for geophysical purposes (simplified?)

General characteristics

- primitive-equation 3D ocean model
- global
- z-coordinate
- hydrostatic approximation
 - ⇒ vertical momentum equation reduced to the pressure equation
 - ⇒ vertical velocity computed diagnostically from the continuity equation
- Boussinesq approximation
 - ⇒ reference density is used except for the gravitational force
- shallow ocean (not shallow water!) approximation

LSG vs. LSOMG

	LSG	LSOMG
Horizontal grid	Arakawa E grid	Arakawa C grid
Horizontal coord.	Spherical	Generalized
Vertical grid	Manually generated	Semi-auto generated
Time stepping	no splitting, unstaggered	splitting, staggered
Barotropic part	implicit	explicit (P-C, gen. FB)
Tidal forcing	no	yes (from DEBOT)
Horiz. friction	“rotated” Laplacian	Laplacian, “full” form
Vert. friction	no	yes (explicit, implicit)
Nonlinear terms	no	yes (2 formulations)
Coriolis term	implicit	Adams-Bashforth
Advection scheme	QUICK	QUICK, LW, DST3
State equation	UNESCO (1981)	Jackett et al. (2006)
Programming	F77 fixed format	F90 free format
Parallelization	no	MPI, (OpenMP)

Acronyms

LSG = **L**arge **S**cale **G**eostrophic ocean model

LSOMG = **L**arge **S**cale **O**cean **M**odel for **G**eophysics
= **L**ibor **Š**achl **O**cean **M**odel for **G**eophysics
= **L**ibor **Š**achl? **O**h **M**y **G**od!

Primitive equations

$$\mathbf{u}_{,t} + [\nabla \cdot (\mathbf{v} \otimes \mathbf{v})]_h = -f\mathbf{z} \times \mathbf{v} - \frac{\nabla_h p}{\rho_0} + \mathbf{F}_H + \mathbf{F}_V + \mathbf{F}_{tid},$$

$$p_{,z} = -\rho g,$$

$$\nabla \cdot \mathbf{v} = 0,$$

$$\eta_{,t} = -\nabla_h \cdot \mathbf{U},$$

$$C_{,t} + \nabla \cdot (\mathbf{v}C) = \nabla \cdot \mathbf{F}^C,$$

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

Horizontal grid

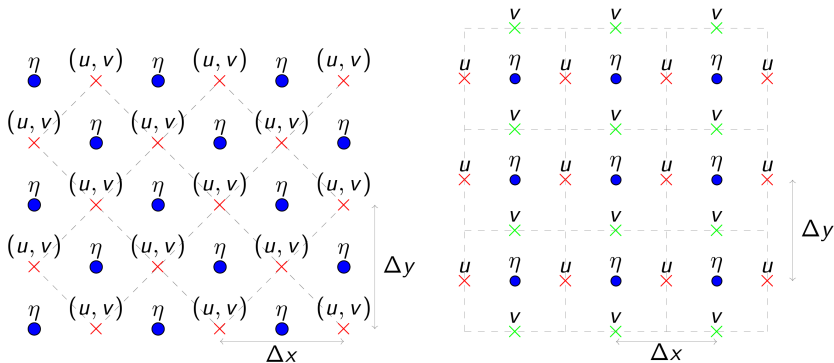


Figure: Original Arakawa E-grid (left) and present C-grid (right).

Perfect E grid?

Grid	Coriolis	Pressure gradient	Divergence
A	no	yes	yes
B	no	yes	yes
C	yes	no	no
D	yes	yes	yes
E	no	no	no

Table: Presence of averaging in the discretization of Coriolis, pressure gradient and divergence terms on Arakawa grids A-E.

Month: 1 Day: 4 Time: 00:00:00

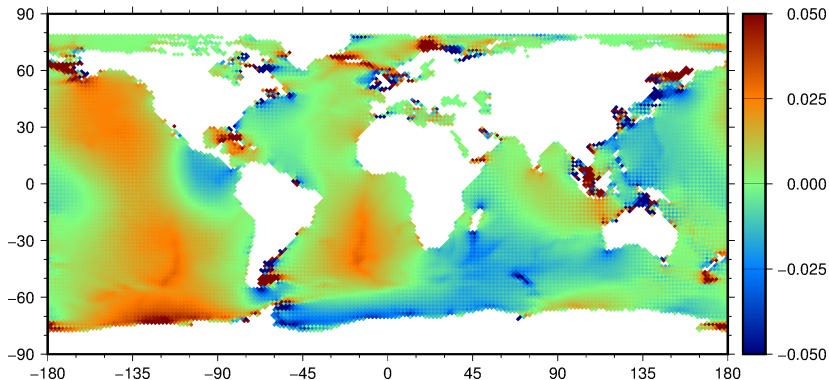


Figure: Horizontal velocity after 3 days of run. Real bathymetry, nonzero horizontal viscosity.

Vertical grid

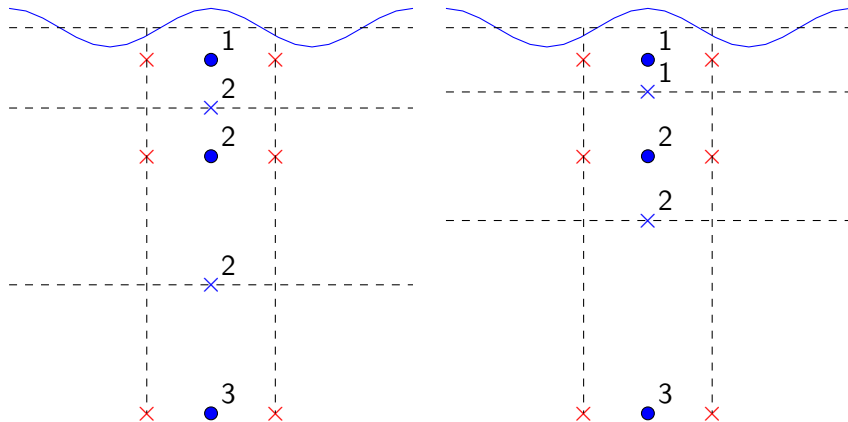


Figure: Two available distributions of grid points in the vertical.

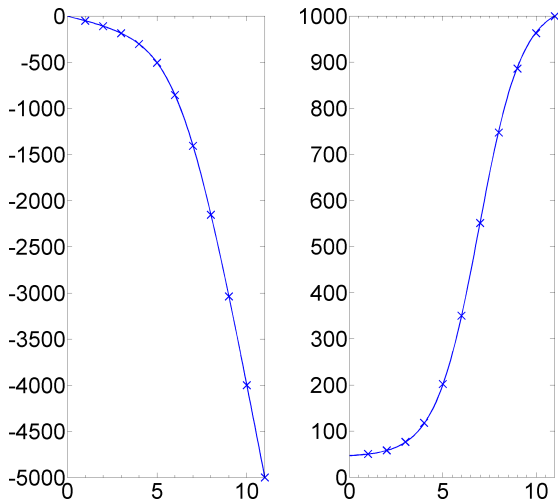


Figure: Depths (left) and thicknesses (right), 11 layers, analytic form of Madec (2012).

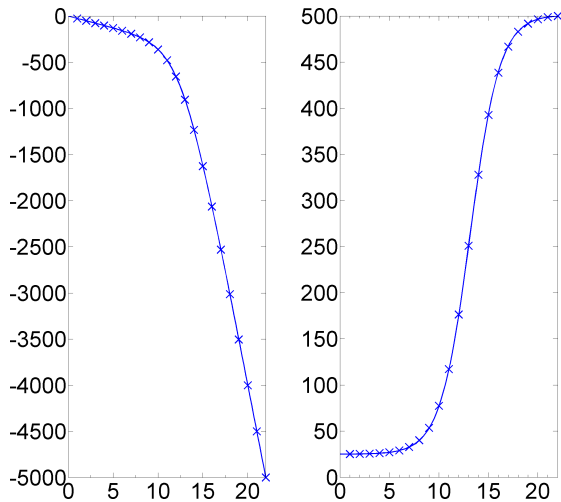


Figure: Depths (left) and thicknesses (right), 22 layers, analytic form of Madec (2012).

Original LSG time stepping

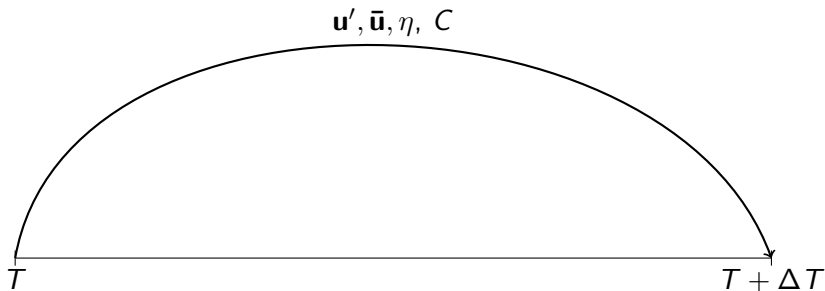


Figure: Unstagged two level time stepping.

Time stepping in LSOMG

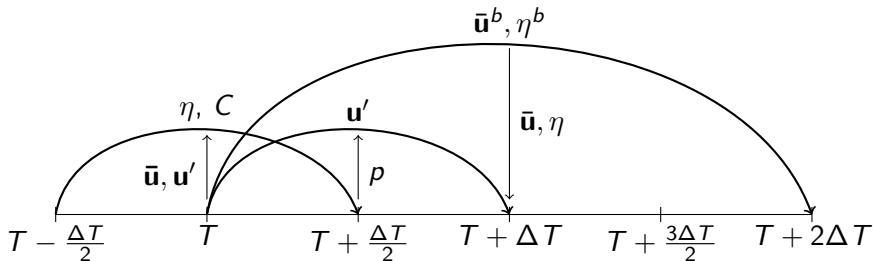


Figure: Staggered time stepping method of Griffies (2004).

Order: $\eta, C, \bar{u}, u'$

Friction in ocean models

Griffies (2004):

- dissipation of E_k is small in the real ocean but huge in models
- 2 central roles of friction
 - parametrization of the effect unresolved scales on the resolved scales
 - ad-hoc numerical closure
 - as low as possible keeping the model stable
 - tuning

Stress-strain rate relation

- generalized Hooke's law + symmetries

$$\frac{\boldsymbol{\sigma}}{\rho} = \mathbf{A} : \mathbf{e}$$

- transverse isotropy ($\Rightarrow$ 5 coefficients)
- $\nabla \cdot \mathbf{v} = 0$
- $Tr(\boldsymbol{\sigma}) = 0$
- quasi-hydrostatic approximation (stable stratification or close to it)

Horizontal friction

$$F_{H1} = \nabla_h \cdot (A_H \nabla_h u) + \left(M_1 \frac{\partial v}{\partial \xi_1} - M_2 \frac{\partial v}{\partial \xi_2} \right) + (N_1 u + N_2 v)$$

$$F_{H2} = \nabla_h \cdot (A_H \nabla_h v) - \left(M_1 \frac{\partial u}{\partial \xi_1} - M_2 \frac{\partial u}{\partial \xi_2} \right) + (N_1 v - N_2 u)$$

(Murray and Reason, 2001)

Horizontal friction

$$F_{H1} = \frac{1}{h_1 h_2 h_3} \left[\frac{1}{h_2} \frac{\partial}{\partial \xi_1} (h_2^2 h_3 A_H D_T) + \frac{1}{h_1} \frac{\partial}{\partial \xi_2} (h_1^2 h_3 A_H D_S) \right]$$
$$F_{H2} = \frac{1}{h_1 h_2 h_3} \left[\frac{1}{h_2} \frac{\partial}{\partial \xi_1} (h_2^2 h_3 A_H D_S) - \frac{1}{h_1} \frac{\partial}{\partial \xi_2} (h_1^2 h_3 A_H D_T) \right]$$

$$D_T = \frac{h_2}{h_1} \frac{\partial}{\partial \xi_1} \left(\frac{u}{h_2} \right) - \frac{h_1}{h_2} \frac{\partial}{\partial \xi_2} \left(\frac{v}{h_1} \right)$$
$$D_S = \frac{h_2}{h_1} \frac{\partial}{\partial \xi_1} \left(\frac{v}{h_2} \right) + \frac{h_1}{h_2} \frac{\partial}{\partial \xi_2} \left(\frac{u}{h_1} \right)$$

(Murray and Reason, 2001; Einspigel and Martinec, 2015)

Smagorinsky viscosity

$$A_H = \left(k_H \frac{d}{\pi} \right)^2 \sqrt{D_T^2 + D_S^2}$$

where

$$d = \min(\Delta x, \Delta y)$$

Griffies and Hallberg (2000):

$$k_H \in \langle 3, 4 \rangle$$

Our settings:

$$k_H = 4$$

Smagorinsky viscosity

$$\text{CFL: } A_H < \frac{d^2}{4\Delta t}$$

$$\text{grid Reynolds number: } A_H > \frac{Ud}{2} \quad (\text{Bryan et al., 1975})$$

$$\text{Munk layer: } A_H > \beta \left(\frac{\sqrt{3}}{\pi} d \right)^3 \quad (\text{Munk, 1950})$$

where

$$\beta = \frac{1}{R} \frac{\partial f}{\partial \phi} = \frac{2\Omega \cos \phi}{R}$$

Our settings:

$$U = 0.4 \text{ m/s}$$

Vertical friction

$$\mathbf{F}_V = \frac{\partial}{\partial z} \left(A_V \frac{\partial \mathbf{u}}{\partial z} \right)$$

Boundary conditions:

$$A_V \frac{\partial \mathbf{u}}{\partial z} = \frac{\boldsymbol{\tau}_{wind}}{\rho_0} \quad \text{at the surface}$$

$$A_V \frac{\partial \mathbf{u}}{\partial z} = \boldsymbol{\tau}_{bottom} \quad \text{at the bottom}$$

where

$$\boldsymbol{\tau}_{wind} = \rho_{air} C_D |\mathbf{u}_{10}| \mathbf{u}_{10}$$

$$\boldsymbol{\tau}_{bottom} = C_g |\mathbf{u}| \mathbf{u}$$

Chosen values

$$\rho_{air} = 1.3 \text{ kg/m}^3,$$

$$C_g = 2.5 \times 10^{-3}$$

Drag coefficient C_D :

- constant, e.g.: 1×10^{-3} (Timmermann et al., 2009)
- dependent on the wind speed, e.g.:

$$6 \leq |\mathbf{u}_{10}| \leq 26 \text{ m/s} \Rightarrow C_D = (0.60 + 0.071 |\mathbf{u}_{10}|) / 1000$$

$$3 \leq |\mathbf{u}_{10}| \leq 6 \text{ m/s} \Rightarrow C_D = \left(0.29 + \frac{3.1}{|\mathbf{u}_{10}|} + \frac{7.7}{|\mathbf{u}_{10}|^2} \right) / 1000,$$

$$|\mathbf{u}_{10}| \leq 3 \text{ m/s} \Rightarrow C_D = C_D(3\text{m/s})$$

(Yelland and Taylor, 1996)

Nonlinear terms

$$\frac{\partial \mathbf{u}}{\partial t} = -f \mathbf{k} \times \mathbf{v} - [\nabla \cdot (\mathbf{v} \otimes \mathbf{v})]_h$$

Flux form:

$$\begin{aligned} \frac{\partial u}{\partial t} &= + \left[f + \frac{1}{h_1 h_2} \left(v \frac{\partial h_2}{\partial \xi_1} - u \frac{\partial h_1}{\partial \xi_2} \right) \right] v - \nabla \cdot (\mathbf{v} u) \\ \frac{\partial v}{\partial t} &= - \left[f + \frac{1}{h_1 h_2} \left(v \frac{\partial h_2}{\partial \xi_1} - u \frac{\partial h_1}{\partial \xi_2} \right) \right] u - \nabla \cdot (\mathbf{v} v) \end{aligned}$$

Vector invariant form:

$$\frac{\partial \mathbf{u}}{\partial t} = -(\zeta + f) \mathbf{k} \times \mathbf{v} - \frac{1}{2} \nabla_h (\mathbf{u} \cdot \mathbf{u}) - w \frac{1}{h_3} \frac{\partial \mathbf{u}}{\partial \xi_3}$$

Coriolis term

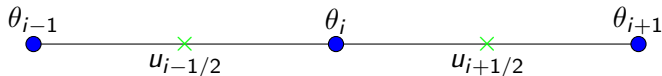
- energy conserving scheme (available: enstrophy conserving, energy+enstrophy conserving, 4-point average)
- all points not only wet points
- 3rd order Adams-Bashforth extrapolation
- noise $\Rightarrow$ divergence damping

$$\frac{\partial \mathbf{u}}{\partial t} = \dots + \nabla_h (\lambda \nabla_h \cdot \mathbf{u})$$

- vorticity dynamics unaffected (rotational motions unaffected)
- divergence equation has an additional diffusion term

Advection schemes

$$\begin{aligned}\partial_t \theta + \nabla_h \cdot (\mathbf{u} \theta) + \partial_z (w \theta) &= \nabla \cdot \mathbf{F}^\theta, \\ \partial_t S + \nabla_h \cdot (\mathbf{u} S) + \partial_z (w S) &= \nabla \cdot \mathbf{F}^S,\end{aligned}$$



Advection schemes

- QUICK scheme: Quadratic Upstream Interpolation for Convective Kinematics (Leonard, 1979), adaption of Farrow and Stevens (1995)
- Lax-Wendroff scheme of Smith et al. (2010)
- Lax-Wendroff scheme with flux limiters
- DST3 with flux limiters

Flux limiters

- combine the best of both the 1st order and higher order methods
- smooth parts of the solution $\Rightarrow$ higher order (2nd, 3rd) advection
- jump or a sudden gradient $\Rightarrow$ switch to the 1st order
- TVD (total-variation diminishing)

$$TV(\theta) = \int_a^b \left| \frac{\partial \theta}{\partial x} \right| dx \rightarrow TV(\theta) = \sum_{i=1}^N |\theta_i - \theta_{i-1}|$$

Splitting method of Adcroft et al. (2014)

$$\frac{\partial \theta}{\partial t} = -\frac{1}{h_1 h_2 h_3} \left[\frac{\partial (h_2 h_3 u \theta)}{\partial \xi_1} + \frac{\partial (h_1 h_3 v \theta)}{\partial \xi_2} + \frac{\partial (h_1 h_2 w \theta)}{\partial \xi_3} \right]$$

$$\frac{\partial \theta}{\partial t} = -\partial_x(u\theta) + \theta \partial_x u$$

$$\theta^{n+1/3} = \theta^n - \Delta t [\partial_x F_x(\theta^n) + \theta^n \partial_x u]$$

$$\theta^{n+2/3} = \theta^{n+1/3} - \Delta t [\partial_y F_y(\theta^{n+1/3}) + \theta^n \partial_y v]$$

$$\theta^{n+3/3} = \theta^{n+2/3} - \Delta t [\partial_z F_z(\theta^{n+2/3}) + \theta^n \partial_z w]$$

Equation of state of sea water

- UNESCO formula (UNESCO, 1981)

$$\rho(S, T, p) = \frac{\rho(S, T, 0)}{1 - \frac{p}{K(S, T, p)}}$$

- state equation of Jackett et al. (2006)

$$\rho(S, \theta, p) = \frac{P_1(S, \theta, p)}{P_2(S, \theta, p)},$$

	UNESCO (1981)	Jackett et al. (2006)
$\rho =$	$\rho(S, T, p)$	$\rho(S, \theta, p)$
Coefficients	41	25
Accuracy		improved

Conversion of T to θ with Jackett et al. (2006)

$$\sigma(S, \theta, p_r) = \sigma(S, T, p),$$

where σ is a specific entropy

Solution:

- iterative Newton-Raphson technique
- initial guess θ_0 :

$$\theta_0(S, T, p, p_r) = T + (p - p_r)P(S, T, [p + p_r]),$$

where P is a given polynomial

- pressure p unknown but required $\Rightarrow p_0 = \text{hydrostatic} \rightarrow$ apply repeatedly, refine p

What did I skip?

- barotropic system
- generalized horizontal coordinates
- tripolar grid
- partial bottom cells
- isopycnal mixing
- GM stirring
- convective adjustments
- sea ice
- values of vertical diffusivities/viscosities
- tides

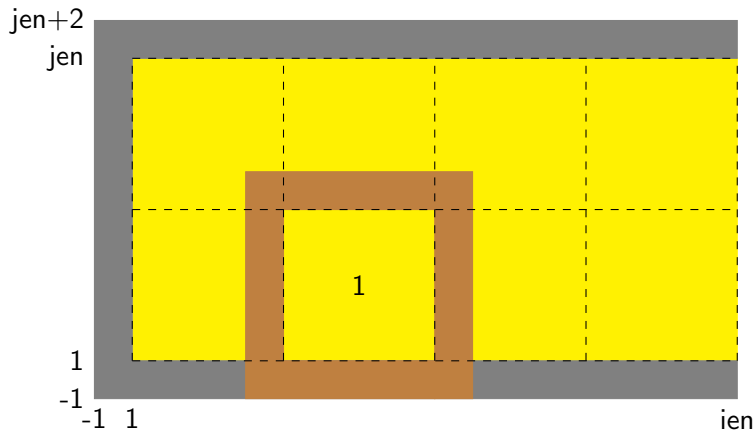


Figure: Inner domain and **halo region** for the thread number 1 and the halo region for the thread number 0 (master thread).

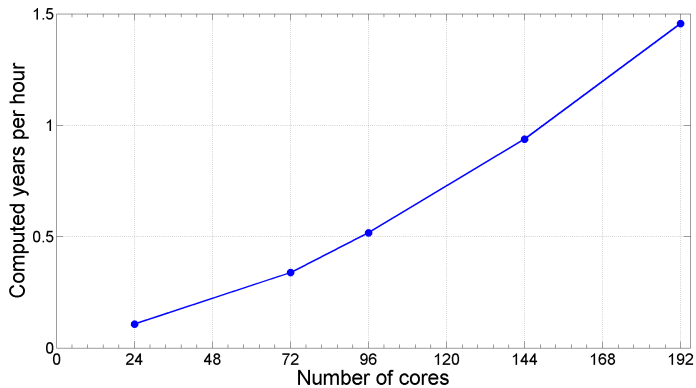


Figure: Performance of the 0.25° BT tidally-driven version.

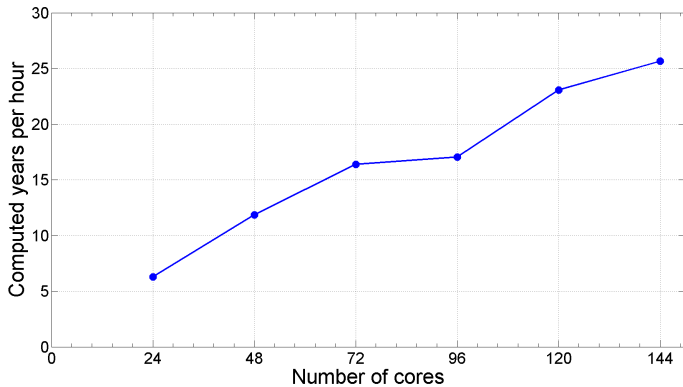


Figure: Performance of the 1° BC wind-driven version.

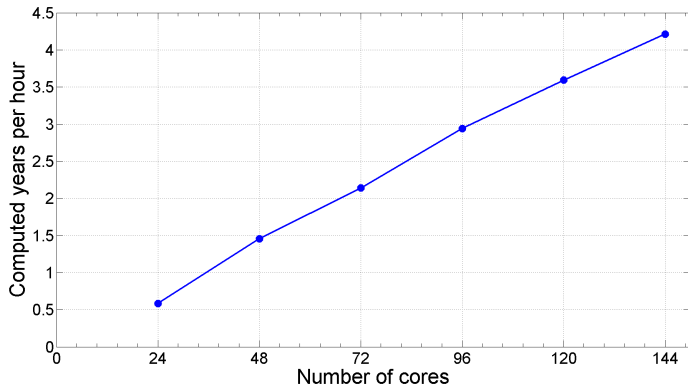


Figure: Performance of the 0.5° BC wind-driven version.

Current section

- 1 Model description
- 2 Input data**
- 3 Benchmarks and realistic runs

Input data

- bathymetry data
 - GEBCO or ETOPO1 data
 - resolution 1'
- temperature and salinity data
 - WOA 2013 data
 - horizontal resolution: 0.5° (1440×720 data points)
 - vertical resolution:

Climatology	Number of depth levels
annual	102 (0–5500 m)
seasonal	102 (0–5500 m)
monthly	57 (0–1500 m)

Input data

- horizontal wind speed
 - NCEP/NCAR Reanalysis 1
 - resolution in time: 4-times daily, daily and monthly mean values for 1948/01/01 to present
 - horizontal resolution: 2.5°
 - ERA interim data
 - resolution in time: 4-times daily and monthly mean values for 1979/01/01 to present
 - horizontal resolution: 0.75°

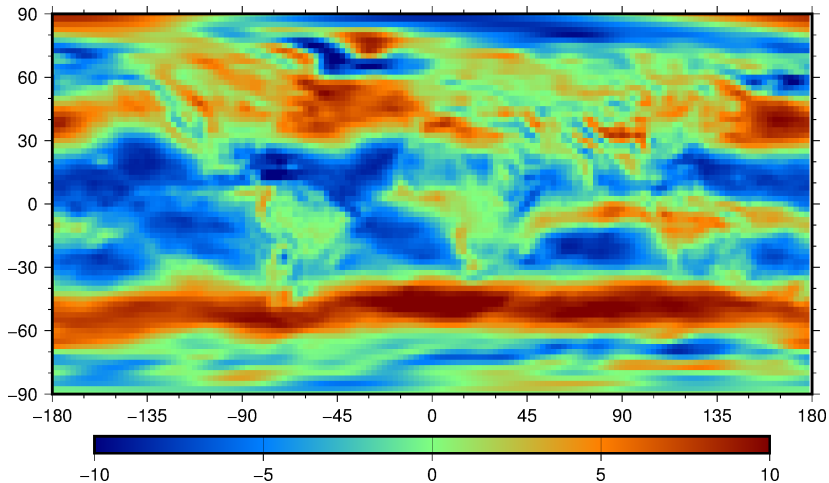


Figure: NCEP/NCAR zonal wind [m/s], monthly mean for January.

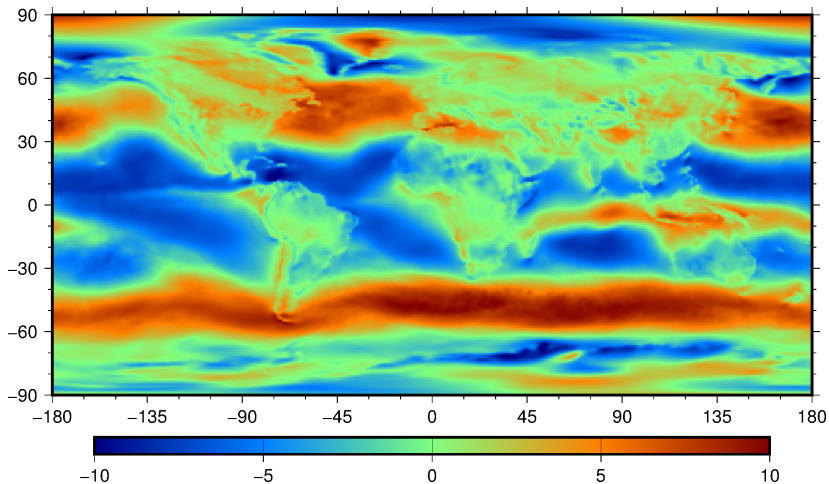


Figure: ERA Interim zonal wind [m/s], monthly mean for January.

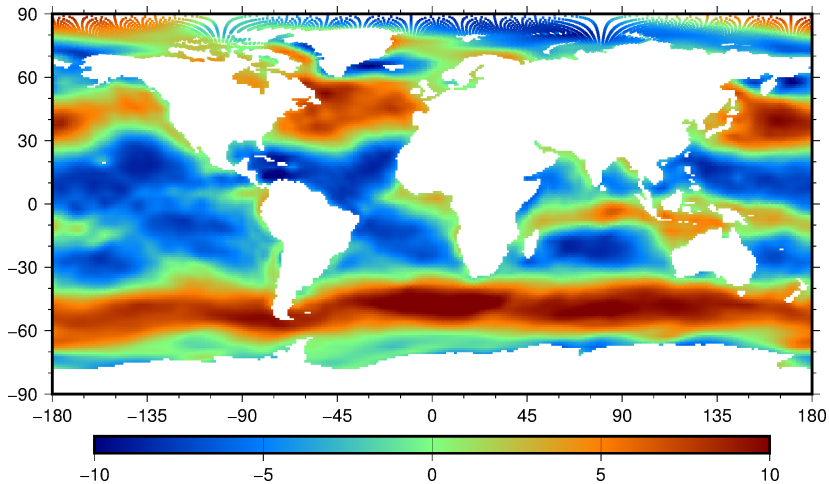


Figure: NCEP/NCAR zonal wind [m/s], LSOMG grid.

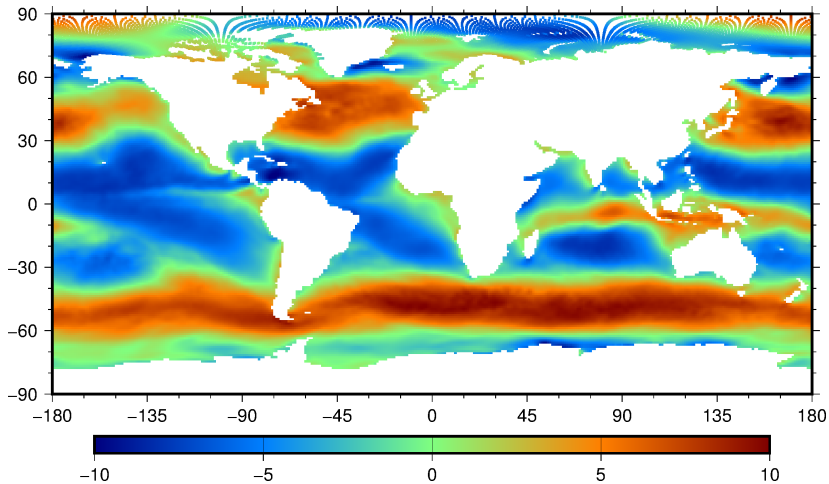


Figure: ERA Interim zonal wind [m/s], LSOMG grid.

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Munk problem

- BT geostrophic equations (homogeneous fluid, nonlinearities neglected)

$$f\mathbf{k} \times \mathbf{U} + gh\nabla_h\eta = A_H\Delta_h\mathbf{U} + \boldsymbol{\tau},$$
$$\nabla_h \cdot \mathbf{U} = 0$$

- harmonic friction
- ocean bottom is flat

Barotropic stream function

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0$$

$$\Rightarrow \exists \psi : U = \frac{\partial \psi}{\partial y}, \quad V = -\frac{\partial \psi}{\partial x}$$

More general case:

$$\nabla_h \cdot \mathbf{U} = -\eta_{,t} \approx 0$$

$$\Rightarrow \exists \psi : \mathbf{U} = \nabla \times (\psi \mathbf{k}) = -\mathbf{k} \times \nabla \psi$$

Munk problem, analytic solution

$$\psi = \frac{\mathbf{k} \cdot (\nabla \times \boldsymbol{\tau})}{\beta \rho_0} (\psi_I + \psi_E + \psi_W)$$

$$\psi_I = d_B - d$$

$$\psi_E = d_M e^{\frac{d-d_B}{d_M}}$$

$$\psi_W = -d_B e^{-\frac{d}{2d_M}} \left[\cos \left(\frac{\sqrt{3}d}{2d_M} \right) + \frac{1}{\sqrt{3}} \sin \left(\frac{\sqrt{3}d}{2d_M} \right) \right]$$

where

$$d_M = \left(\frac{A_H}{\beta} \right)^{1/3}$$

$$\beta = \frac{1}{R} \frac{\partial f}{\partial \phi} = \frac{2\Omega \cos \phi}{R}$$

Munk problem, settings

Frisius et al. (2009):

- idealized basin: $\lambda \in \langle -90^\circ, 90^\circ \rangle$, $\phi \in \langle -85^\circ, 85^\circ \rangle$
- flat bottom: $H = 5000$ m
- wind stress: $\tau_\lambda = -0.1 \cos(3\phi) \text{ Nm}^{-2}$

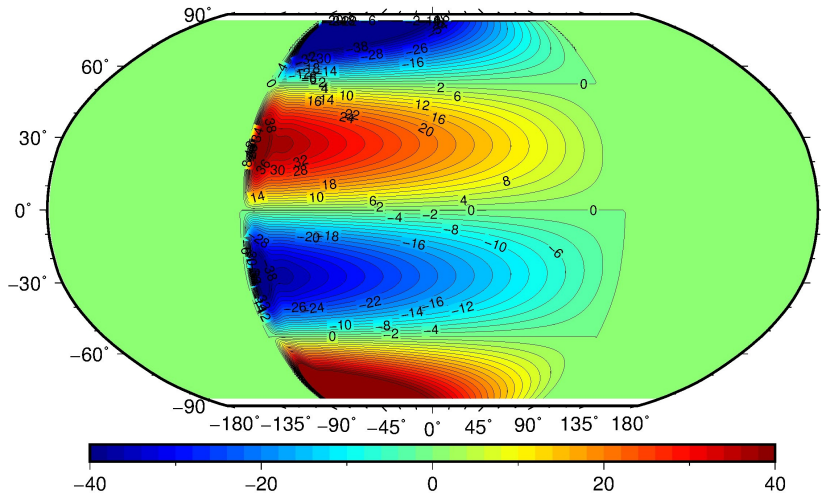


Figure: Theoretical stream function [Sv].

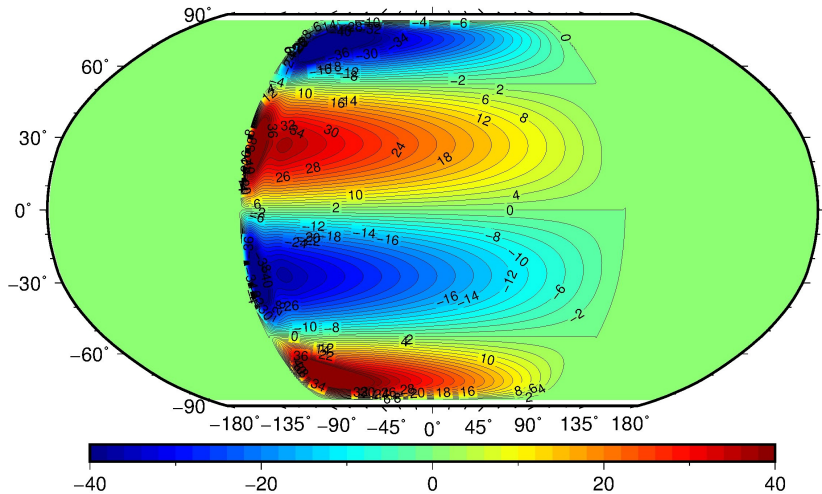


Figure: LSOMG stream function [Sv].

Ekman layer benchmark, theory

Simplified governing equations

$$\begin{aligned}fv + A_V \frac{\partial^2 u}{\partial z^2} &= 0, \\ -fu + A_V \frac{\partial^2 v}{\partial z^2} &= 0,\end{aligned}$$

with surface boundary conditions

$$\begin{aligned}A_V \frac{\partial u}{\partial z} &= \frac{\tau_x}{\rho_0}, \\ A_V \frac{\partial v}{\partial z} &= \frac{\tau_y}{\rho_0}.\end{aligned}$$

Ekman layer benchmark, theory

Solution:

$$\begin{aligned}u &= V_0 e^{az} \sin\left(\frac{\pi}{4} - az\right), \\v &= V_0 e^{az} \cos\left(\frac{\pi}{4} - az\right).\end{aligned}$$

where

$$a = \sqrt{\frac{f}{2A_V}}.$$

Specially, $z = 0$:

$$\begin{aligned}u &= V_0 \sin\left(\frac{\pi}{4}\right), \\v &= V_0 \cos\left(\frac{\pi}{4}\right).\end{aligned}$$

Ekman layer benchmark, settings

- Depth of the bottom: $H = 200$ m
- Vertical resolution: 20 equally thick layers $\Rightarrow$ layer thickness is 10 m
- Vertical viscosity: $A_V = 0.05$ m²/s
- Predicted thicknesses D_E of the Ekman layer:

$$D_E = \frac{\pi}{a} = \pi \sqrt{\frac{2A_V}{f}}$$

$$\Rightarrow D_E \approx 98 \text{ m at } \phi = 45^\circ$$

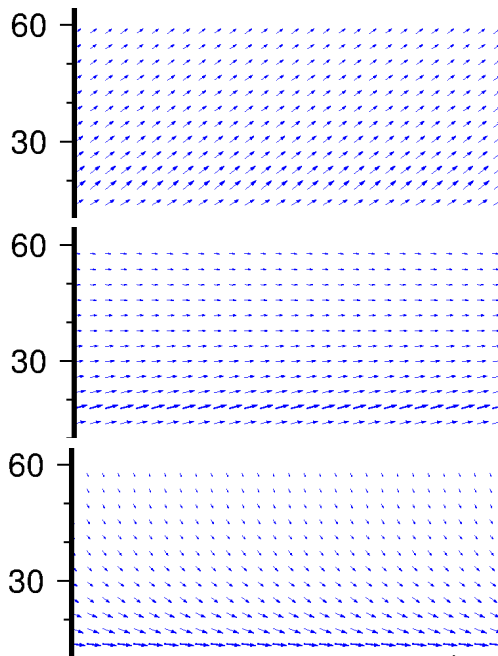


Figure: Horizontal velocities in 5 m, 25 m and 55 m (from top) depth.

Benchmark of horizontal advection of tracers

- Gaussian-shape and box distribution of tracers
- Resolution: 1°
- Horizontal velocity: $\mathbf{u} = 1.1 \text{ m/s}$
- Vertical velocity: $w = 0 \text{ m/s}$
- Time step: 1800 s
- Computation time: 420 days $\Rightarrow$ 1 period

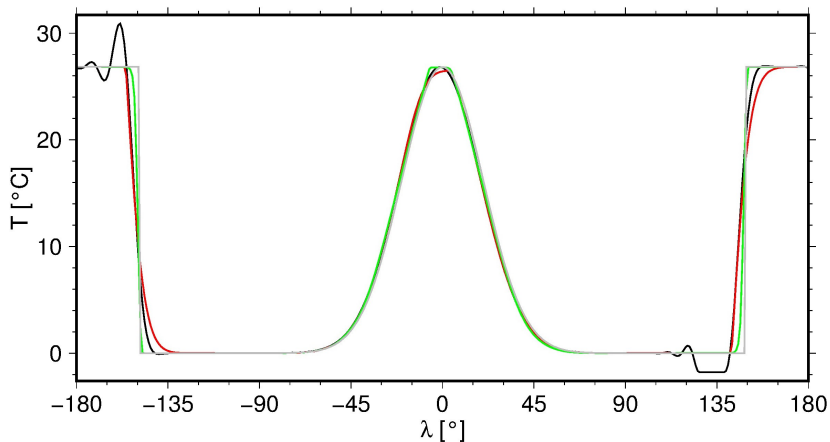


Figure: Tracer field advected by Quick schemes, Lax-Wendroff scheme of Smith et al. (2010) and Lax-Wendroff scheme with Superbee flux limiters.

Benchmark of vertical advection of tracers

- Gaussian-shape distribution of tracers
- 22 layers
- Horizontal velocity: $\mathbf{u} = 0$
- Vertical velocity: $w = 2 \times 10^{-3}$ m/s
- Time step: 1800 s
- Computation time: 10 days

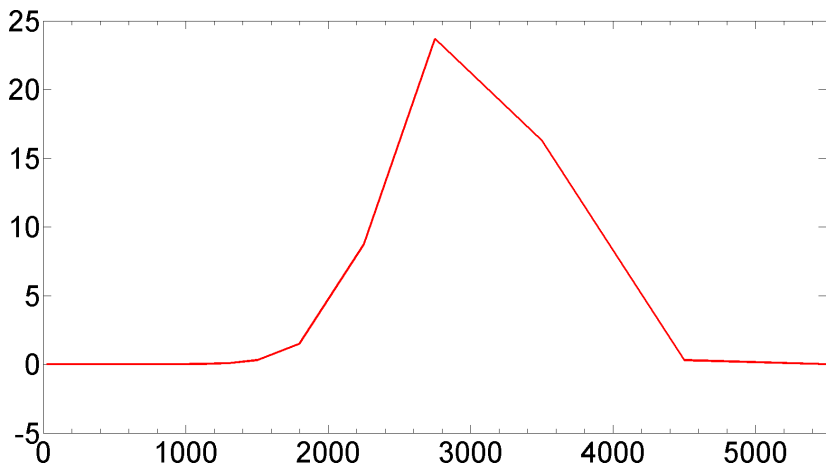


Figure: Initial tracer field.

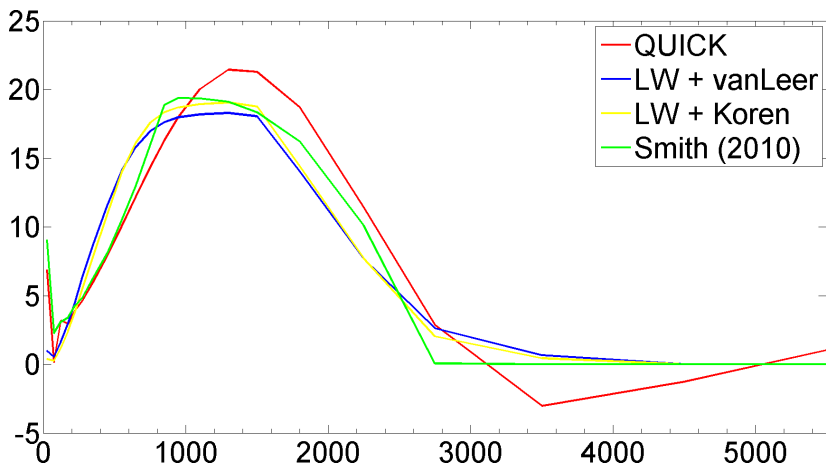


Figure: Advected tracer fields after 10 days of computations.

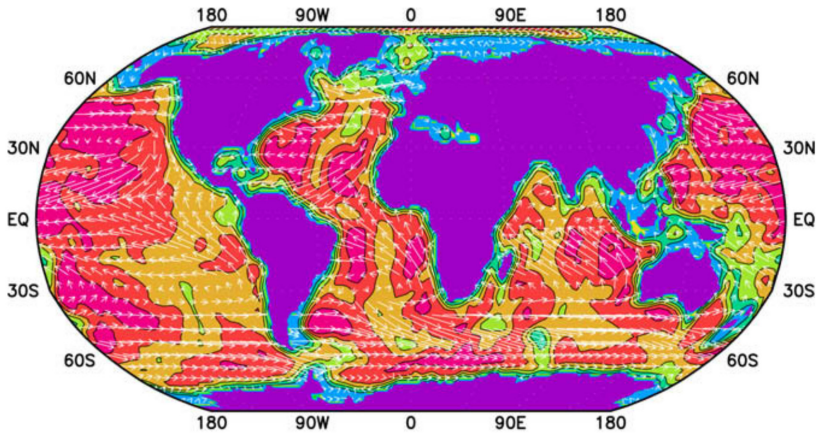


Figure: Winds used by Frisius et al. (2009).

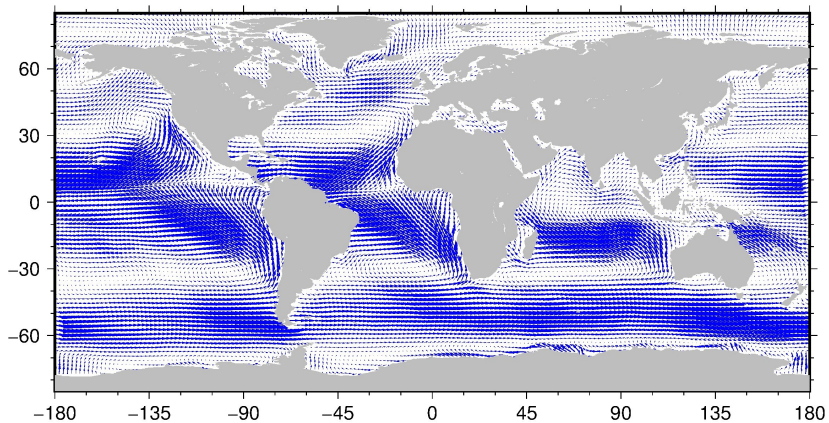


Figure: Winds in the LSOMG.

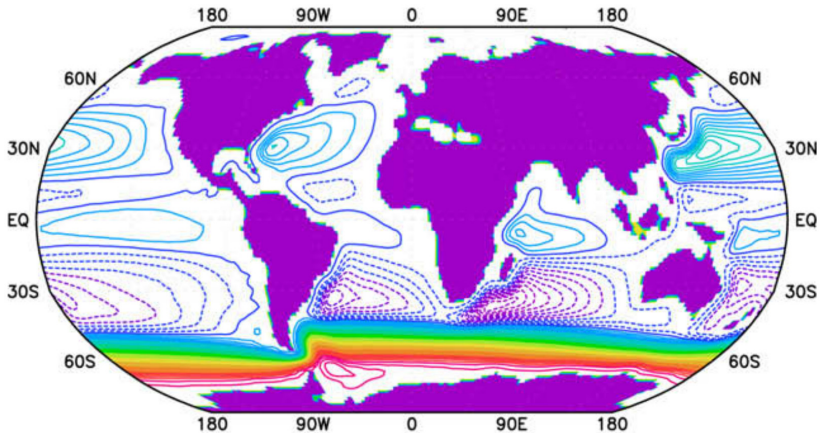


Figure: BT stream function [Sv] in BT wind-driven run of Frisius et al. (2009), contour interval 5 Sv.

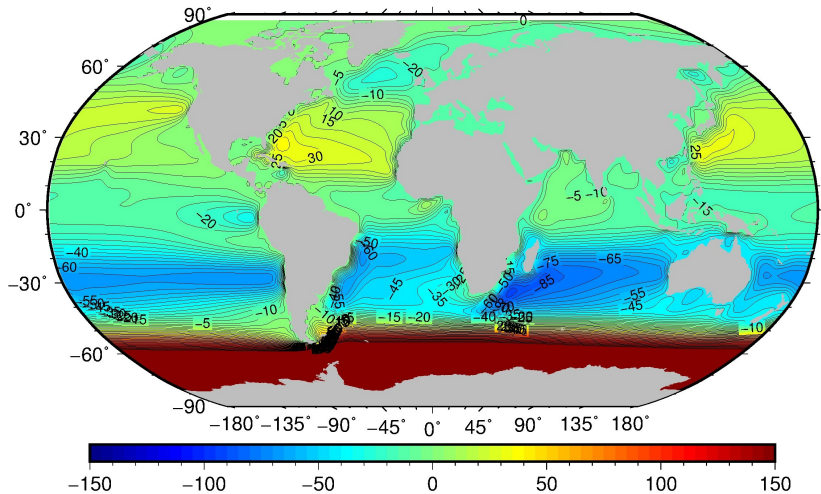


Figure: BT stream function [Sv] in BT LSOMG wind-driven 1° run.

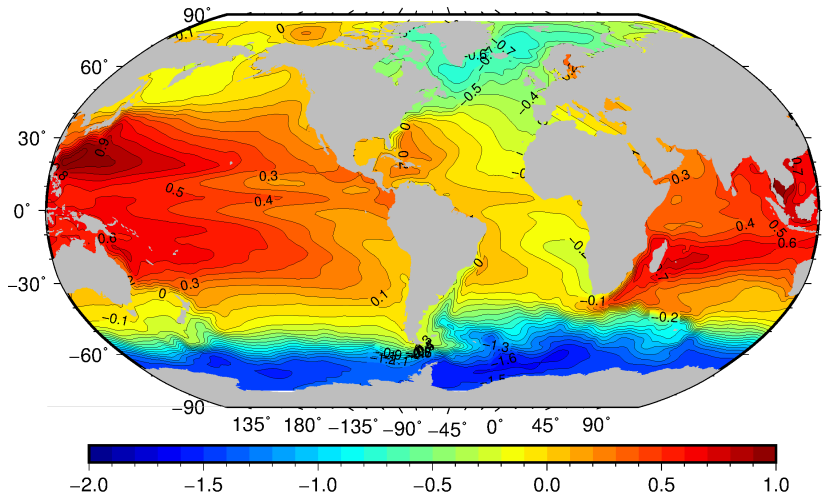


Figure: Surface elevations [m] in LSOMG wind-driven 1° run.

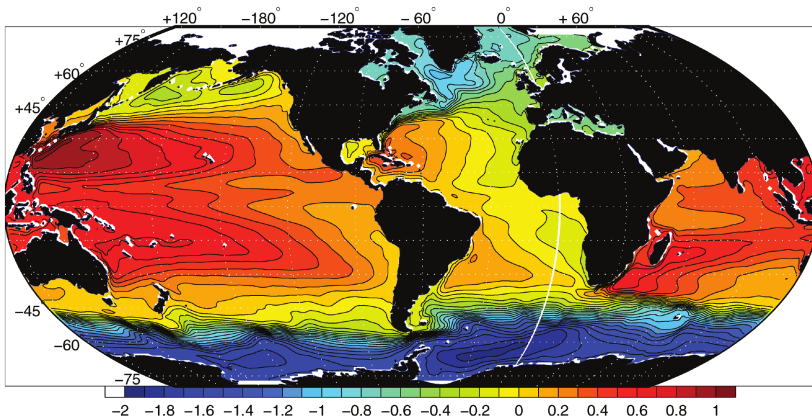


Figure: Surface elevations [m] in ECCO wind-driven 1° run (Wunsch, 2011).

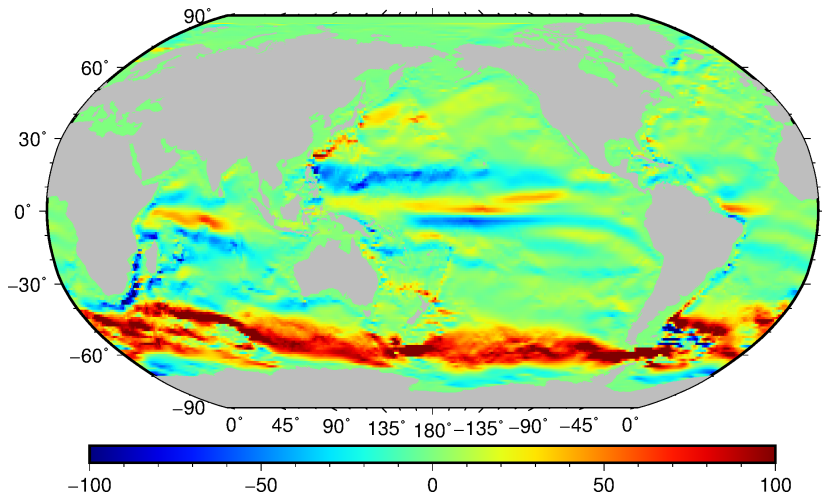


Figure: Zonal BT transports [m^2/s] in LSOMG wind-driven 1° run

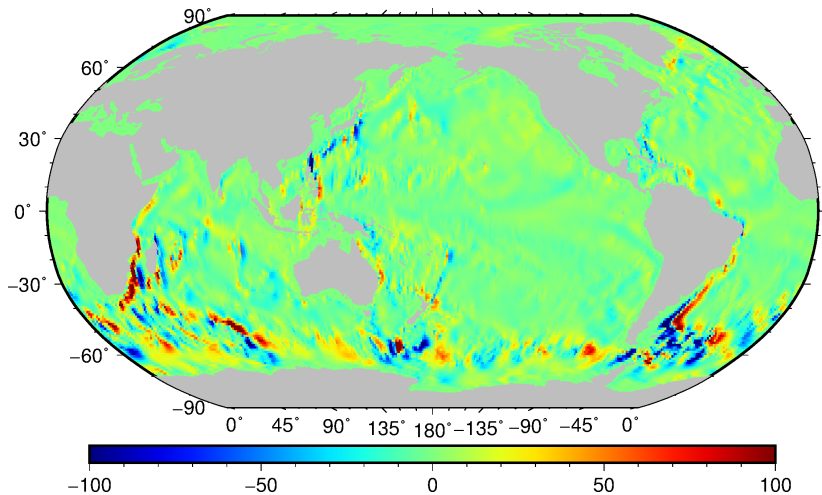


Figure: Meridional BT transports [m^2/s] in LSOMG wind-driven 1° run

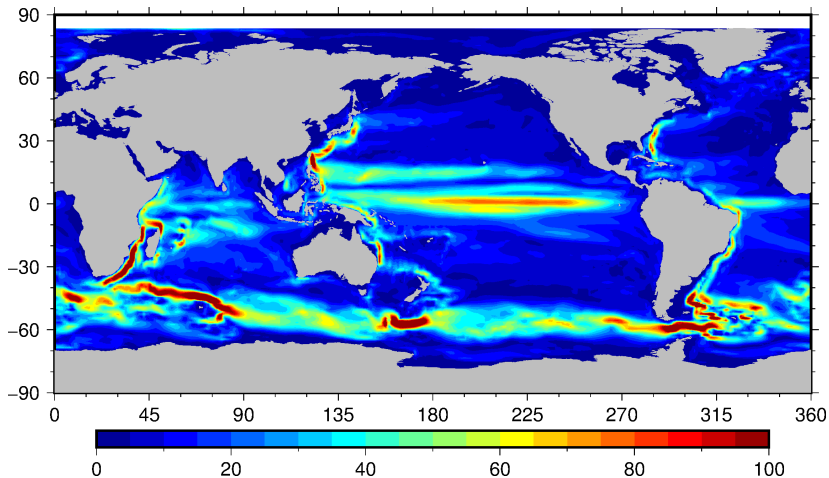


Figure: Barotropic transports [m^2/s] in LSOMG wind-driven 1° run

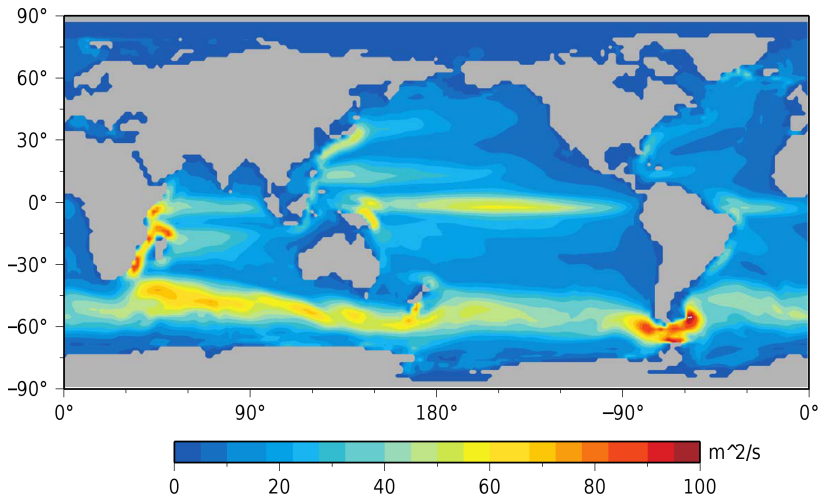


Figure: Barotropic transports [m^2/s] in OMCT wind-driven 1.875° run (Irrgang et al., 2015)

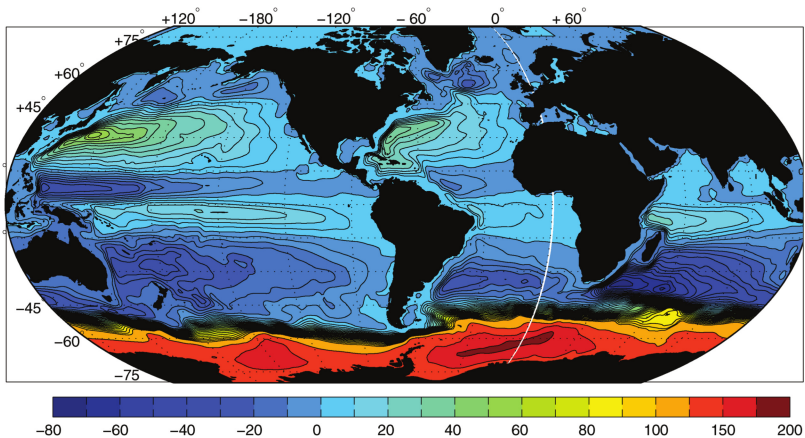


Figure: BT stream function [Sv] in ECCO wind-driven 1° run (Wunsch, 2011).

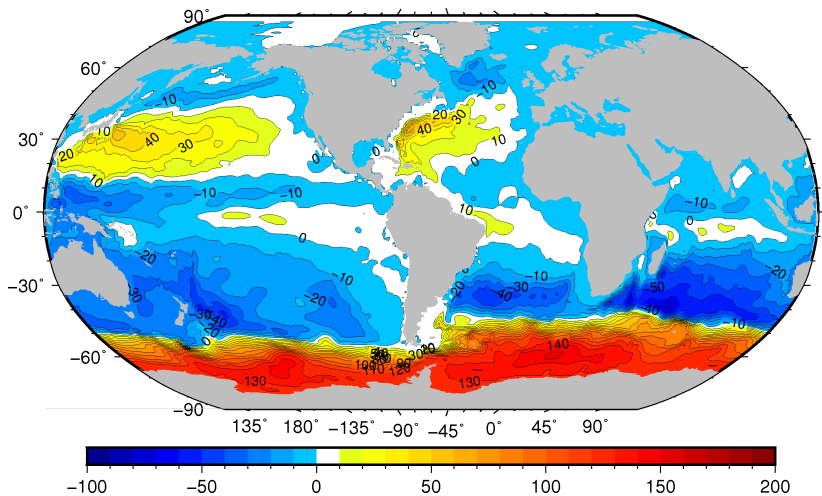


Figure: BT stream function [Sv] in LSOMG wind-driven 1° run after 1 month.

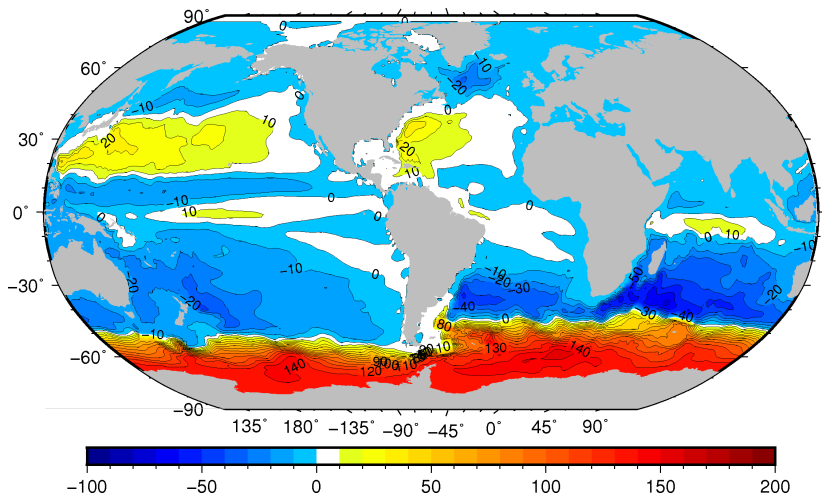


Figure: BT stream function [Sv] in LSOMG wind-driven 1° run after 1 year.

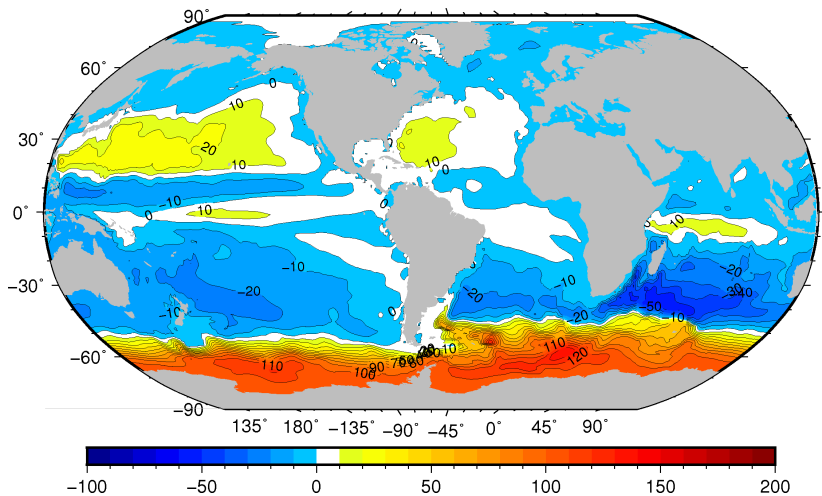


Figure: BT stream function [Sv] in LSOMG wind-driven 1° run after 20 years.

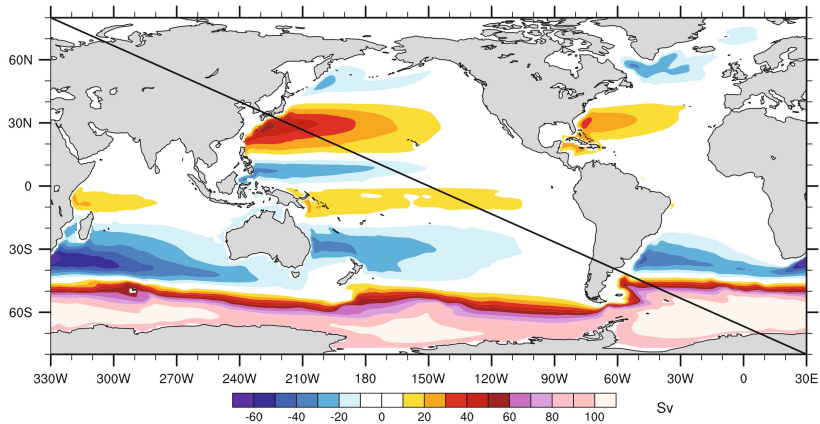


Figure: BT stream function [Sv] in CNRM-CM5.1 model.

Summary

LSOMG model has been

- coded and supplied with input data (initial conditions + forcing)
- tested in several benchmarks
 - tsunami propagation (not shown)
 - tidal benchmarks (not shown)
 - Munk problem
 - Ekman layer
 - advection of tracers
- run in realistic settings
 - BT wind-driven circulation $\Rightarrow$ acceptable BT stream function
 - BC wind-driven circulation
 - SSH comparable with the ECCO model
 - BT transports comparable with the OMCT model
 - BT stream function somewhat weak

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