Annual Seminar ECMWF 2020 14-18 September 2020

Kinetic energy backscatter (KEB) parameterizations for ocean circulation models with intermediate resolution and their testing in NEMO ocean model

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Introduction

Modern numerical climate models use as their part ocean models at eddy-permitting resolution. At this resolution, ocean mesoscale turbulence is resolved partly, which leads to underestimation of eddy kinetic energy (EKE). Mesoscale dynamics can be amplified using kinetic energy backscatter (KEB) parameterizations returning energy from unresolved scales. We consider two types of KEB: stochastic and negative viscosity. Tuning of their amplitude is based on the local budget of kinetic energy, thus, they are "energetically-consistent" KEBs. In this work, KEB parameterizations are applied to NEMO ocean model [G Madec et. al., 2015] in Double Gyre configuration at eddy-permitting resolution (1/4 degree). To evaluate results, we compare this model to eddy-resolving one (1/9 degree). We show that with the use of KEB, meridional overturning circulation (MOC), meridional eddy heat flux and sea surface temperature (SST) can be significantly improved. In addition, better match is found in time power spectra of eddy-permitting and eddy-resolving model solutions.

Double Gyre configuration [M. Levy et. al., 2010]

NEMO model is based on primitive equations:

$$\frac{dT}{dt} = F_T, \frac{dS}{dt} = F_S \ (1)$$

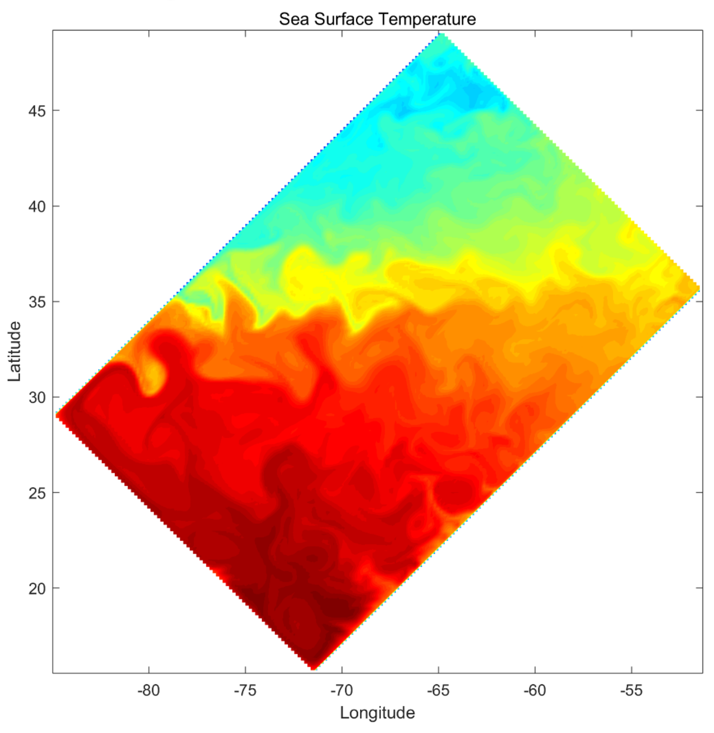
$$\frac{\partial \boldsymbol{U}_h}{\partial t} + \boldsymbol{adv}_h + \boldsymbol{cor}_h = -\frac{1}{\rho_0}\nabla_h p + \boldsymbol{F}_{\boldsymbol{U}_h} \ (2)$$

$$\frac{\partial p}{\partial z} = -\rho g \ (3)$$

$$\nabla \cdot \boldsymbol{U} = 0 \ (4)$$

$$\frac{\partial \eta}{\partial t} = -H\nabla_h \overline{\boldsymbol{U}}_h \ (5)$$

$$\rho = \rho_0\big(1 - a(T - T_0) + b(S - S_0)\big) \ (6)$$



where $T, S, \boldsymbol{U}, \eta, \rho, p$ – potential temperature, salinity, velocity, free surface height, density, pressure; $\boldsymbol{U}_h$ – is the horizontal part of velocity and $\overline{\boldsymbol{U}}_h$ is its vertical average. $F_T, F_S, \boldsymbol{F}_{\boldsymbol{U}_h}$ – external forcings and physical parameterizations.

Computational domain is a flat-bottom rectangular box $3180\,km \times 2120\,km \times 4km$ with free-slip and no-flux lateral boundary conditions and quadratic bottom drag in β-plane approximation. Box is rotated 45^o relative to zonal direction. Initial flow is absent. Average vertical distribution of temperature and salinity in Atlantic ocean is used as initial conditions. Model is forced by the zonal wind stress being maximum at 35 Latitude and by the following buoyancy fluxes on the surface: thermal conductivity with prescribed Atmosphere temperature, Fresh Water flux and Solar Radiation. Rossby radius of deformation varies from 5km at the north to 40km at the south.

	R1	R4	R9
$n_x \times n_y \times n_z$	$30\times 20 \times 30$	$120\times 80 \times 30$	$270\times 180 \times 30$
mesh step	$1^0, 106\,km$	$1/4^0, 26.5\,km$	$1/9^0, 11.7\,km$

We accomplish spin-up of R4 and R9 models, firstly running R1 model for 1000 years and then continuing computations with R4 or R9 models for 120 years. Last 20 years are stored for analysis.

Negative viscosity KEB

This parameterization supplements horizontal biharmonic momentum damping in momentum equation (2) with additional term returning energy in the form of Laplace operator as proposed in [Jansen, Held 2014]:

$\frac{\partial \boldsymbol{U}_h}{\partial t} = \cdots \nu_4 \Delta_h^2 \boldsymbol{U}_h + \nabla_h(\nu_2 \nabla_h \boldsymbol{U}_h)$ $\nu_2 = -c_{back}\Delta x\sqrt{\max(e,0)}$ $\frac{de}{dt} = c_{diss}\dot{E}_{diss} + \dot{E}_{back} + \nu_e \nabla_h^2 e$	$\nu_2, \nu_4 \le 0$ $\dot{E}_{diss} = \nu_4 \nabla_h \boldsymbol{U}_h \cdot \nabla_h(\Delta_h \boldsymbol{U}_h)$ $\dot{E}_{back} = \nu_2 \nabla_h \boldsymbol{U}_h \cdot \nabla_h \boldsymbol{U}_h$

Here $e \equiv e(x,y,z,t)$ – amount of subgrid energy which is produced by biharmonic damping ($\dot{E}_{diss}$) and backscattered to resolved scales ($\dot{E}_{back}$) according to [Jansen et. al., 2015]. $\nu_e = 1000 m^2 s^{-1}, c_{diss} = 0.8, c_{back} = 0.4\sqrt{2}$.

Stochastic KEB

Additional term in momentum equation (2) has a form of white in time noise:

$\frac{\partial \boldsymbol{U}_h}{\partial t} = \cdots \nu_4 \Delta_h^2 \boldsymbol{U}_h + \alpha \nabla_h^{\perp} S^n(\psi)$ $\psi(x,y,z,t^n) = \phi(x,y,t^n) \cdot \sqrt{\max(\dot{E}_{diss}, 0)}$	$S(\psi) = \psi + \frac{(\Delta x)^2}{8}\nabla_h^2 \psi$ $\frac{\alpha^2 \Delta t}{2}\int \left|\nabla_h^{\perp} S^n(\psi)\right|^2 dxdydz = \int \dot{E}_{diss} dxdydz$

$\phi(x,y,t^n)$ – generated discrete space-time white noise, $\nabla_h^{\perp} = (-\partial_y, \partial_x)$. Spatial correlation of noise is controlled by the amount of filter $S(\psi)$ applications as proposed in [Grooms, Lee, Majda, 2015], $n = 6$. We use quasi-2d streamfunction $\psi(x,y,z,t^n)$ scaled by local dissipation as proposed in [Berner et. al., 2009].

Experiments with eddy-permitting model

We perform simulations with (R4 negative viscosity, R4 stochastic) and without negative viscosity parameterization at R4 resolution and compare them with respect to high-resolution model R9.

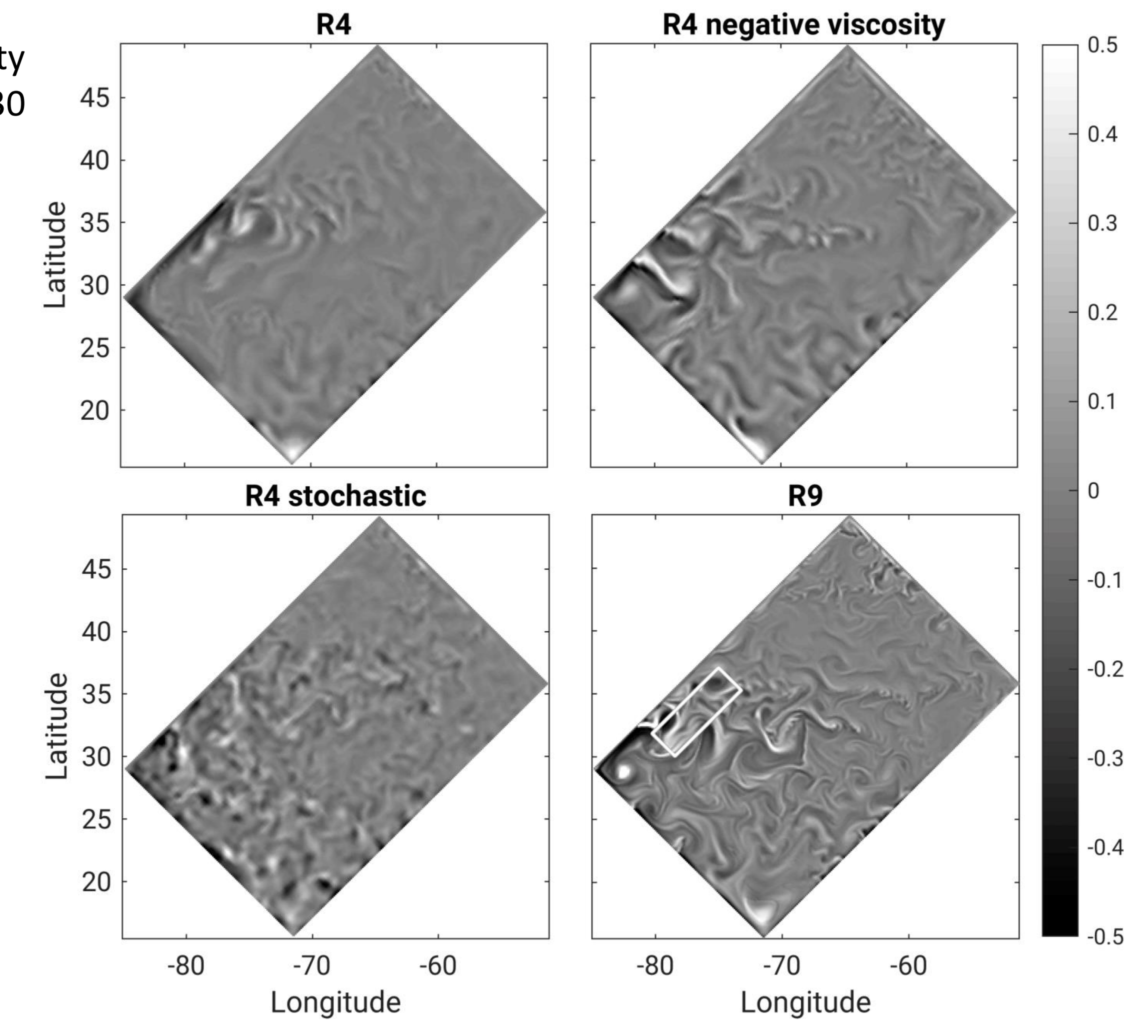


Figure 1. Snapshot of relative vorticity in Coriolis parameter (f) units. 30 march after spin-up.

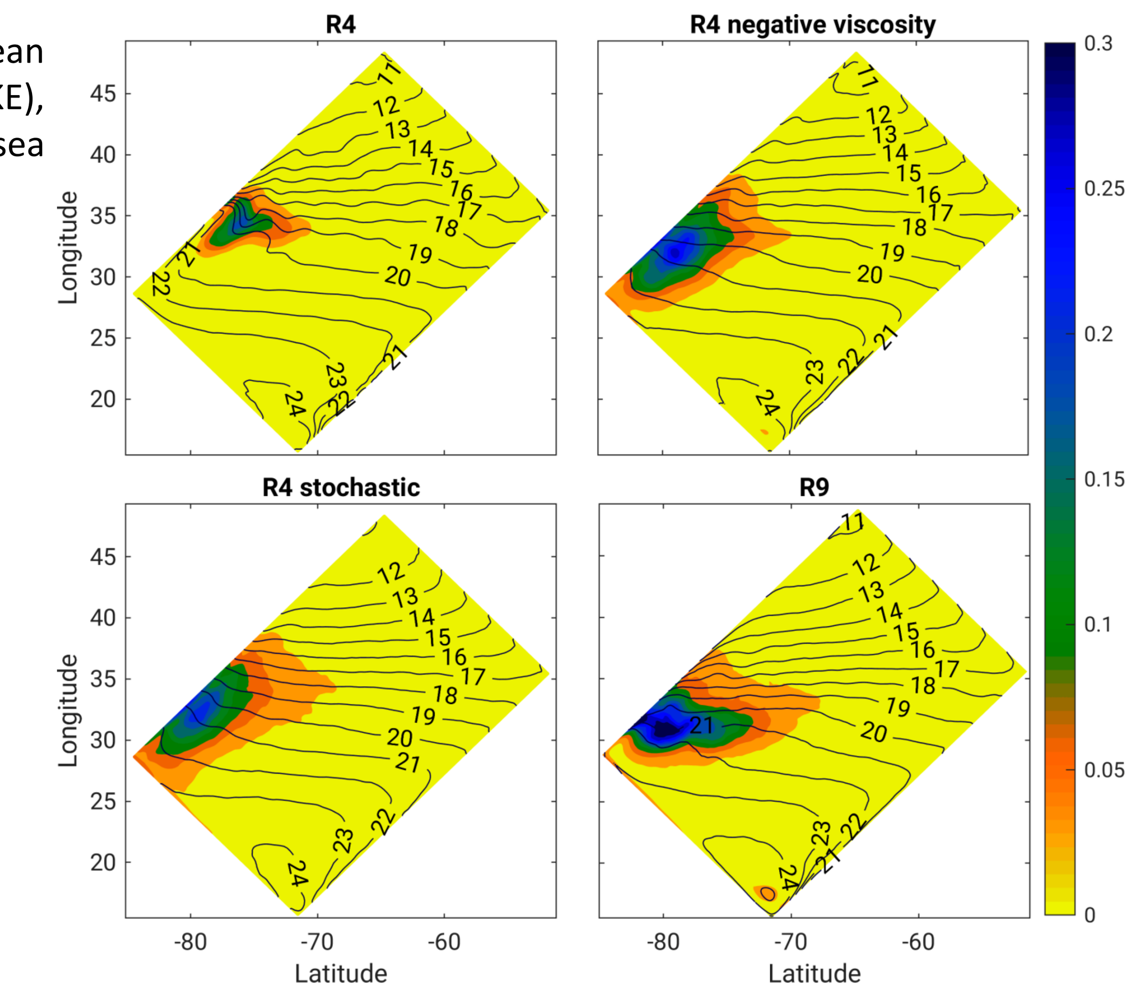


Figure 2. In colour: 20-years mean surface eddy kinetic energy (EKE), m^2/s^2. In contours: 20-years mean sea surface temperature (SST), C^o.

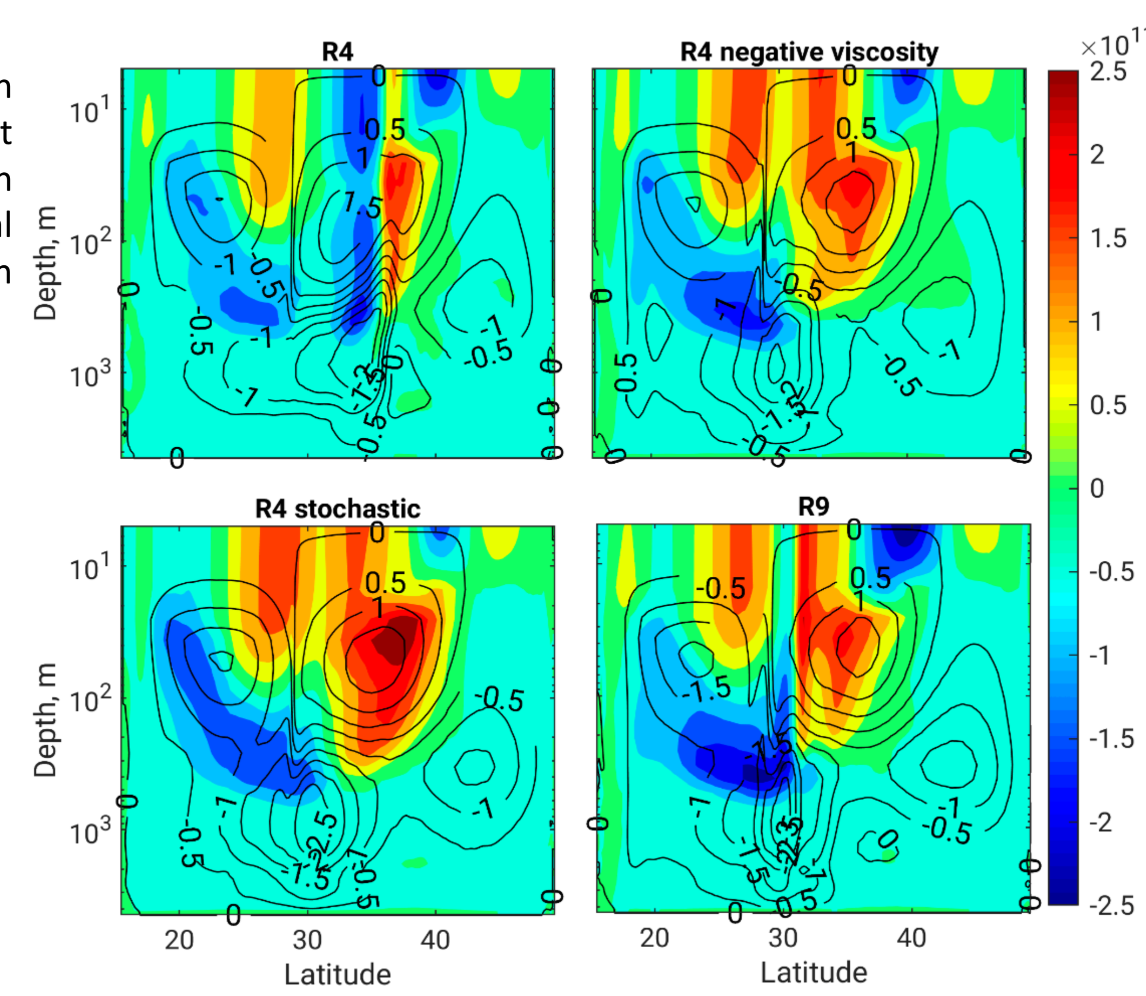


Figure 3. In colour: 20-years mean eddy meridional heat transport integrated zonally, W/m. In contours: 20-years mean meridional overturning streamfunction Ψ_{MOC} in Sverdrups.

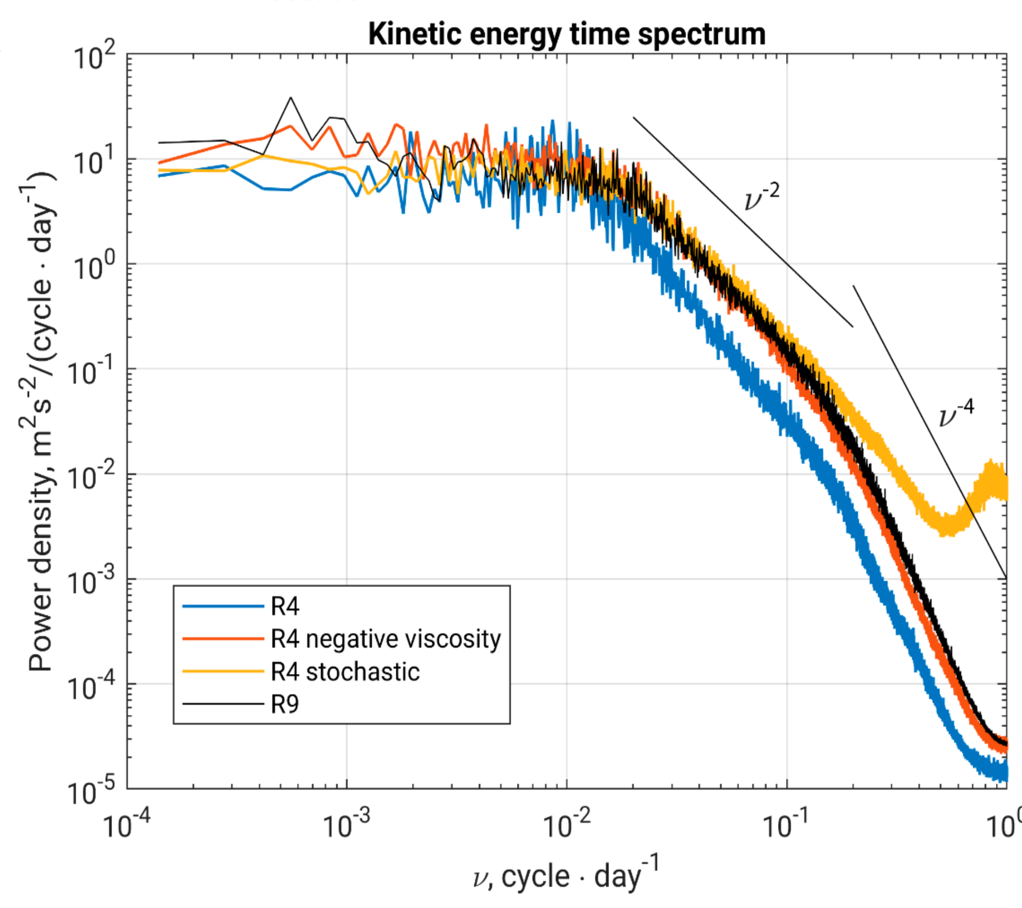


Figure 4. Time power density of surface EKE. Density is averaged over a white rectangle shown in figure 1.

Table. 20-years mean surface-averaged EKE and norm of errors in SST (sea surface temperature) and SSH (sea surface height) fields in R4 models with respect to R9 reference. Two norms for any $\varphi(x,y)$ are the following: $\max(|\varphi_{R4} - \varphi_{R9}|)$; $mean(|\varphi_{R4} - \varphi_{R9}|)$.

	R4	R4 negative visc.	R4 stochastic	R9
surf. EKE, $m^2 s^{-2}$	0.01	0.023	0.027	0.025
error SST, C^o	7.0; 0.40	3.1; 0.30	4.3; 0.27	
error SSH, m	0.68; 0.062	0.38; 0.039	0.40; 0.040	

Funding

The work was supported by the Russian Foundation for Basic Research (projects 19-35-90023, 18-05-60184) and world-class research center "Moscow Center for Fundamental and Applied Mathematics" (agreement with the Ministry of Education and Science of the Russian Federation No. 075-15-2019-1624).