Backscatter parameterizations in NEMO ocean model

P. A. Perezhogin. INM RAS

CITES 2019

Motivation

- Mesoscale eddies are badly resolved in climate ocean models
- Consequently, eddy activity is damped
- It leads to wrong eddy fluxes and mean state
- Eddy activity can be amplified using backscatter parameterizations

Kinetic energy backscatter (KEB)

- KEB is a process of energy flux from unresolved to resolved turbulence motions
- KEB is opposite to turbulent viscosity
- KEB can be estimated using high resolution model
- Contrary to 3D turbulence, in 2D backscatter is much stronger due to the inverse direction of energy cascade
- Energetically consistent backscatter is calibrated together with turbulent viscosity based on the fact: in 2D turbulence total energy exchange of unresolved and resolved scales is zero

Double Gyre configuration of NEMO primitive equation model

$$\frac{dT}{dt} = 0, \frac{dS}{dt} = 0$$

$$\frac{\partial \boldsymbol{U}_h}{\partial t} + \mathbf{adv}_h + \mathbf{cor}_h = -\frac{1}{\rho_0}\nabla_h p$$

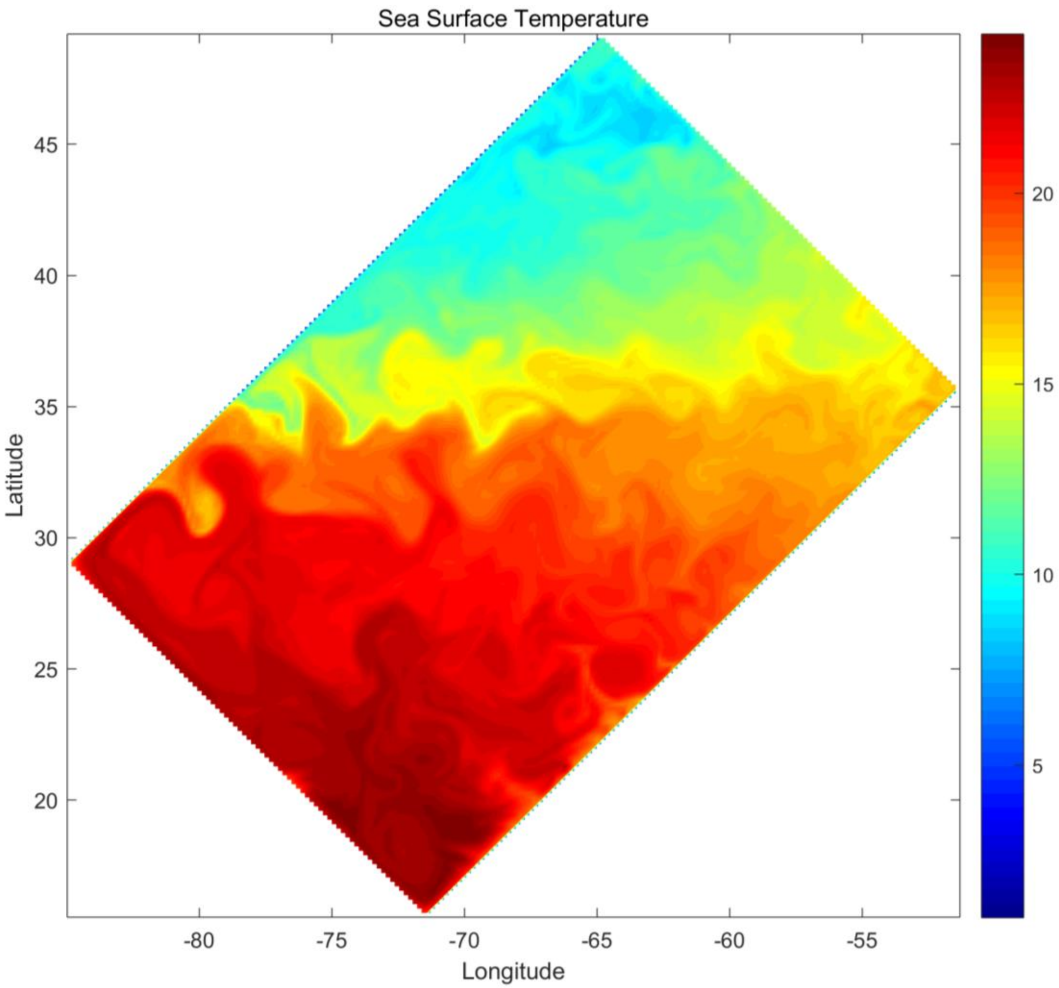
$$\frac{\partial p}{\partial z} = -\rho g$$

$$\nabla \cdot \boldsymbol{U} = 0$$

$$\frac{\partial \eta}{\partial t} = -\nabla_h \cdot \left((H + \eta)\overline{\boldsymbol{U}_h}\right)$$

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

$T, S, \boldsymbol{U}, \boldsymbol{U}_h, \overline{\boldsymbol{U}_h}, p, \eta, \rho, H$ – potential temperature; salinity; velocity; horizontal velocity; vertically-averaged horizontal velocity; pressure; surface elevation; density; depth.



Double Gyre parameters

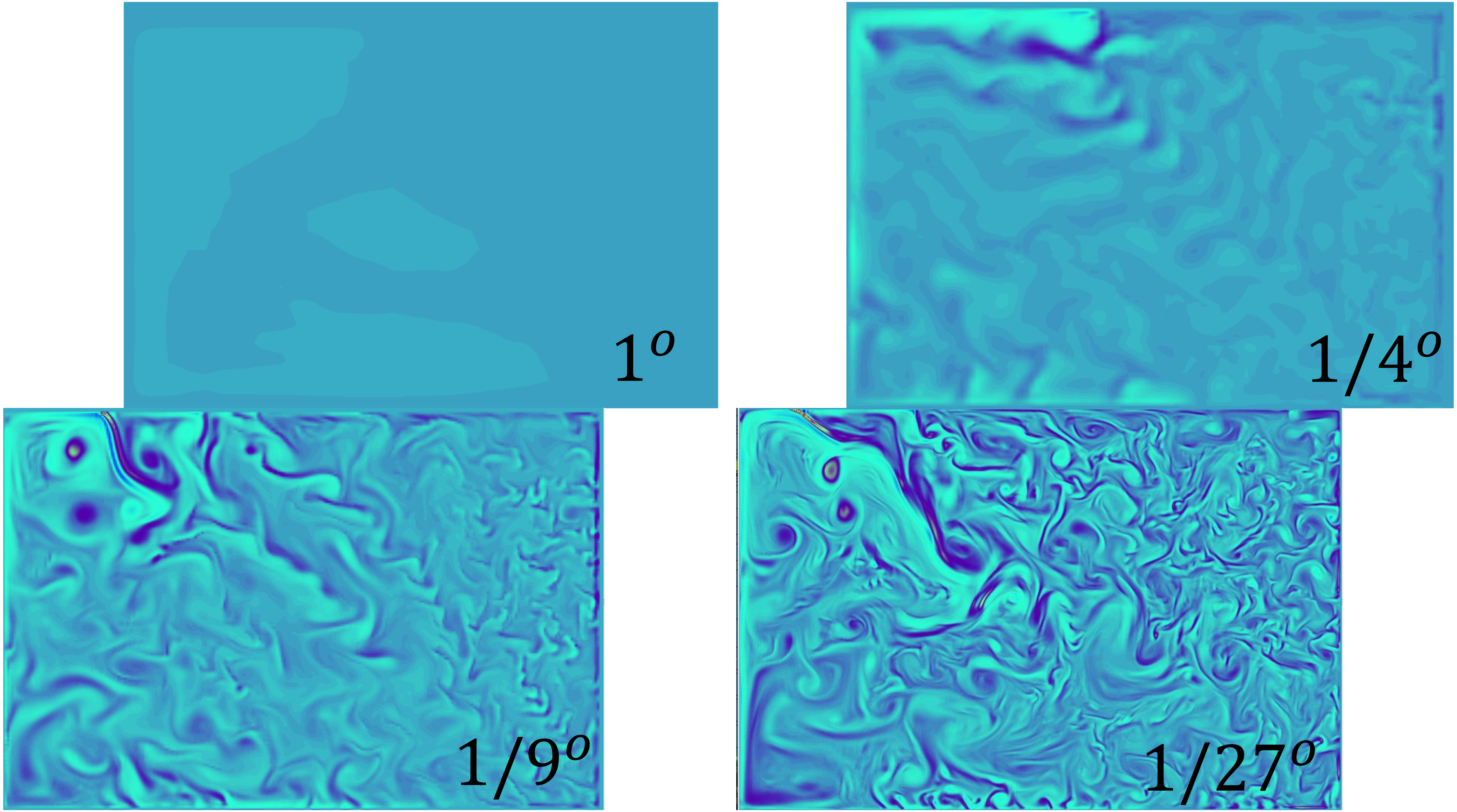
- $3180\ km \times 2120\ km \times 4km$
- Box is rotated 45^o to zonal direction
- Beta-plane approximation
- Free-slip boundaries, quadratic bottom drag
- Surface forcings:
  - Zonal wind
  - Atmospheric heat flux
  - Fresh water flux
  - Solar radiation

Model spin-up

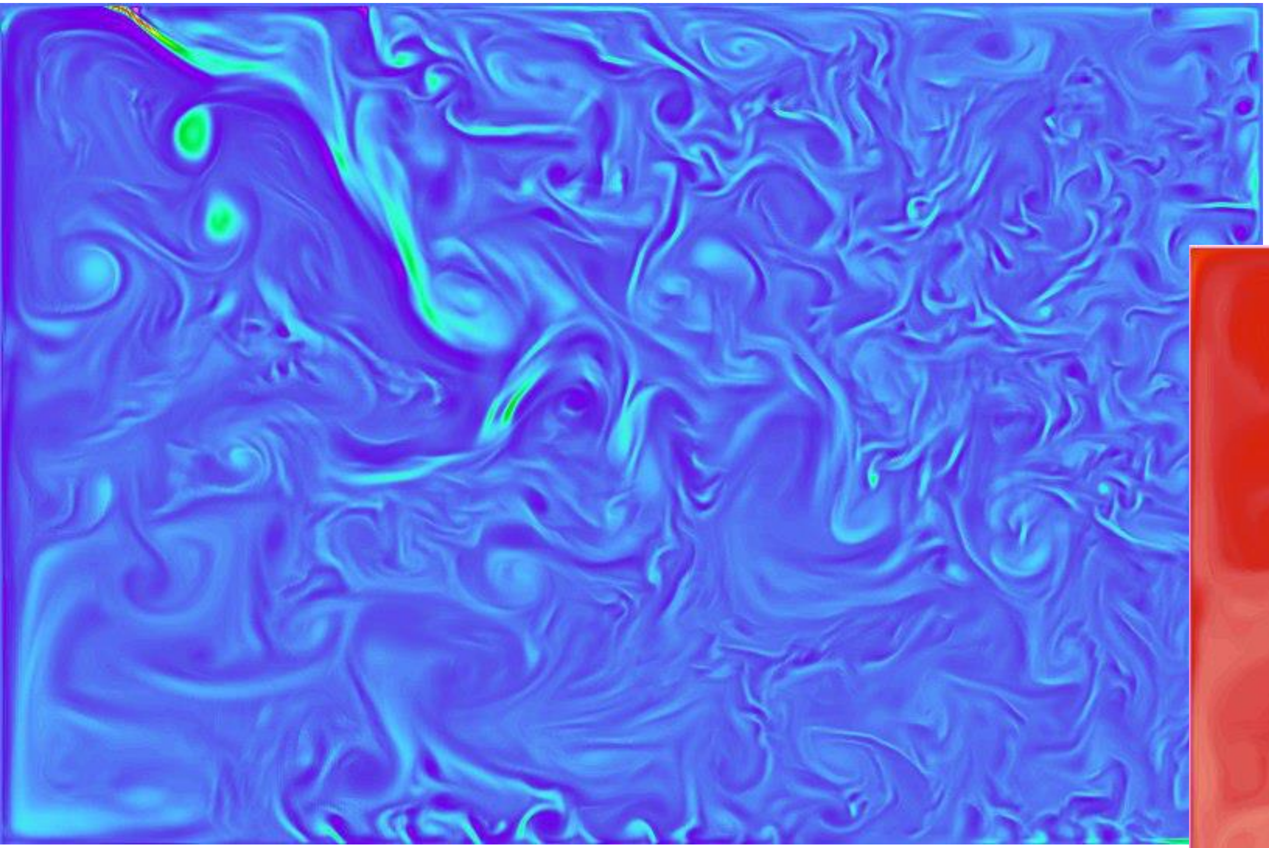
	R1	R4	R9
$n_x \times n_y \times n_z$	$30 \times 20 \times 30$	$120 \times 80 \times 30$	$270 \times 180 \times 30$
mesh step	$1^0, 106\ km$	$1/4^0, 26.5\ km$	$1/9^0, 11.7\ km$
	Non-eddy-resolving	Eddy-permitting	Eddy-resolving

- 1000 years R1 model
- Then 100 years R4 and R9

Relative vorticity snapshots at different resolutions

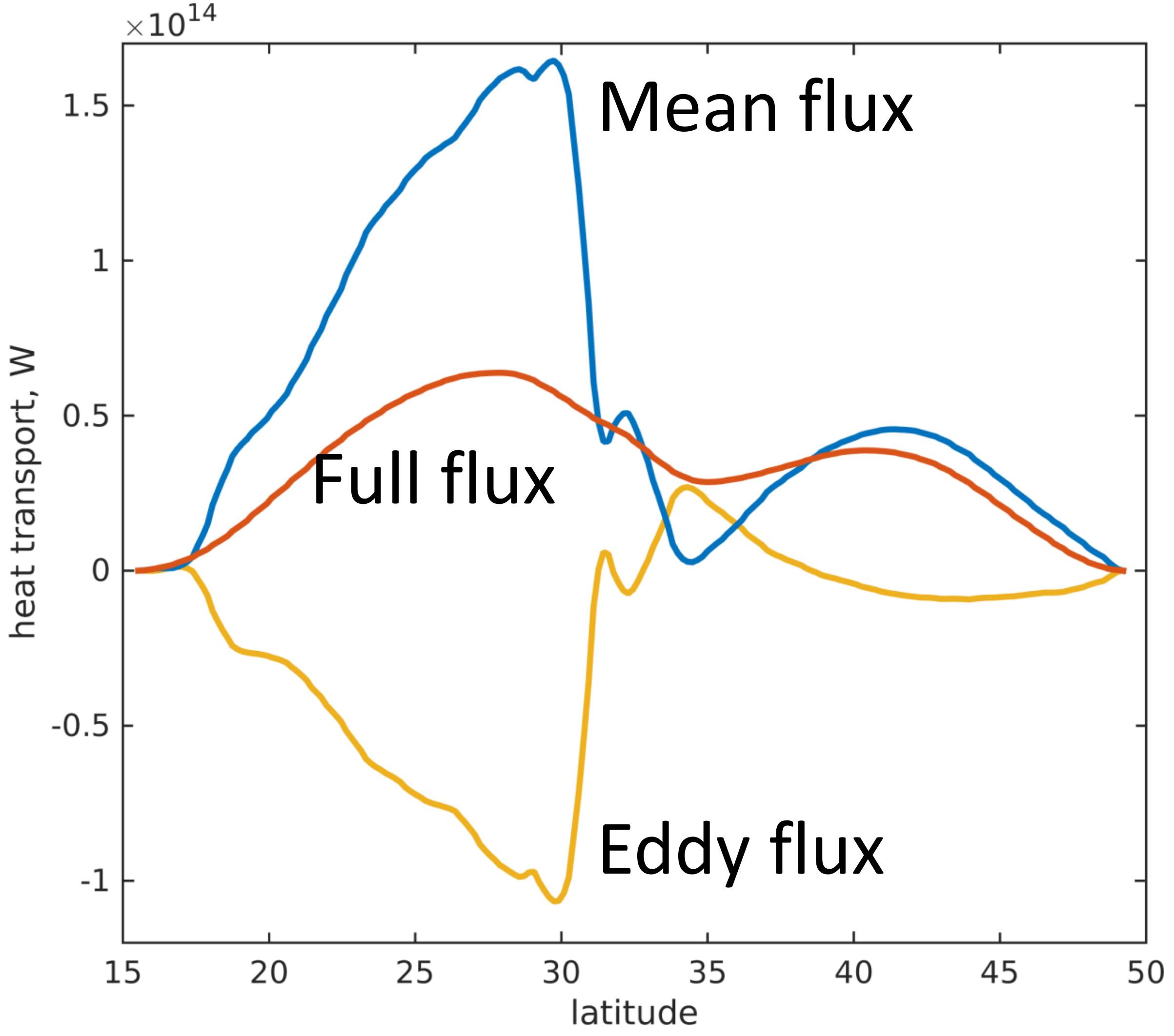


Vorticity

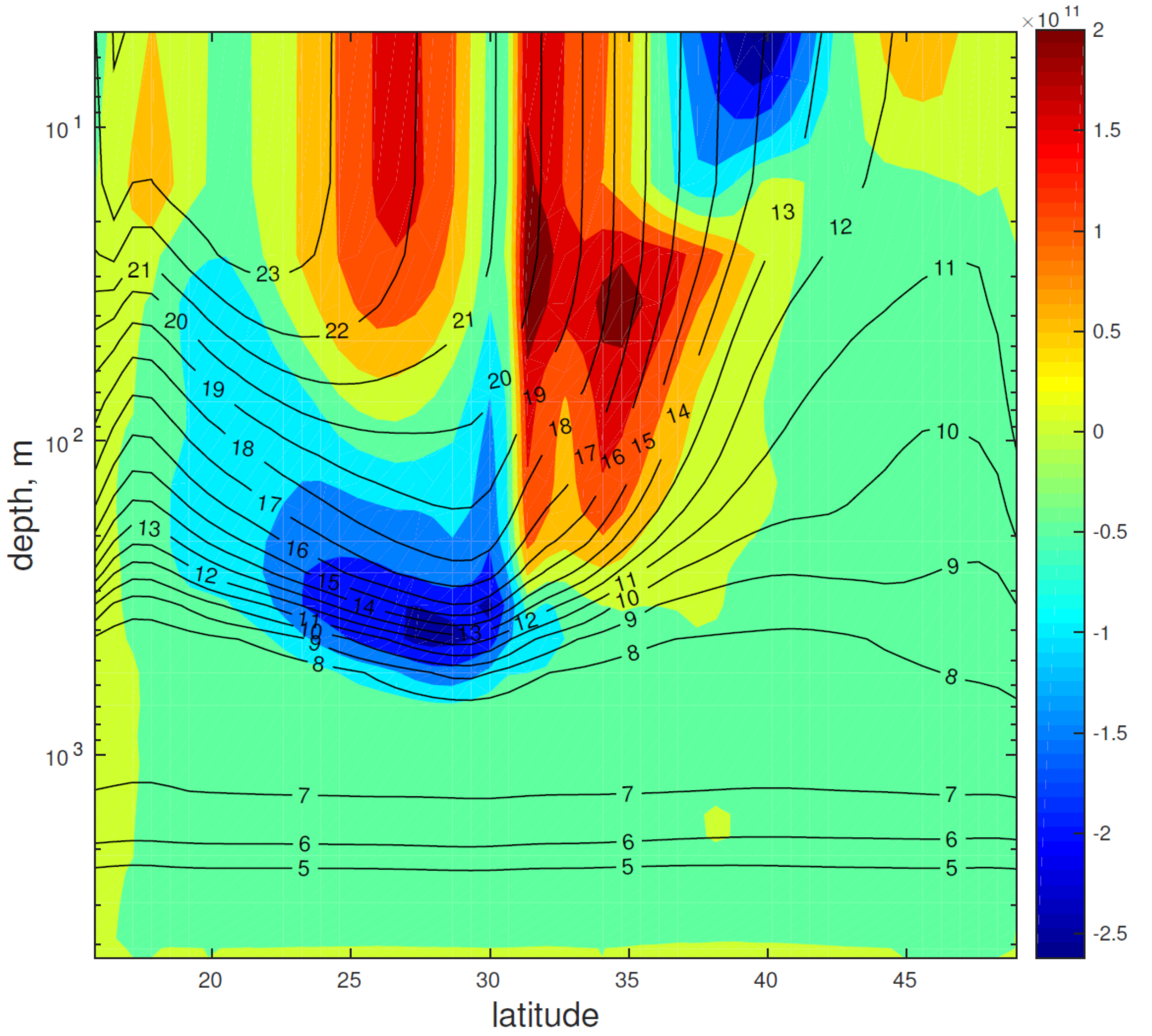


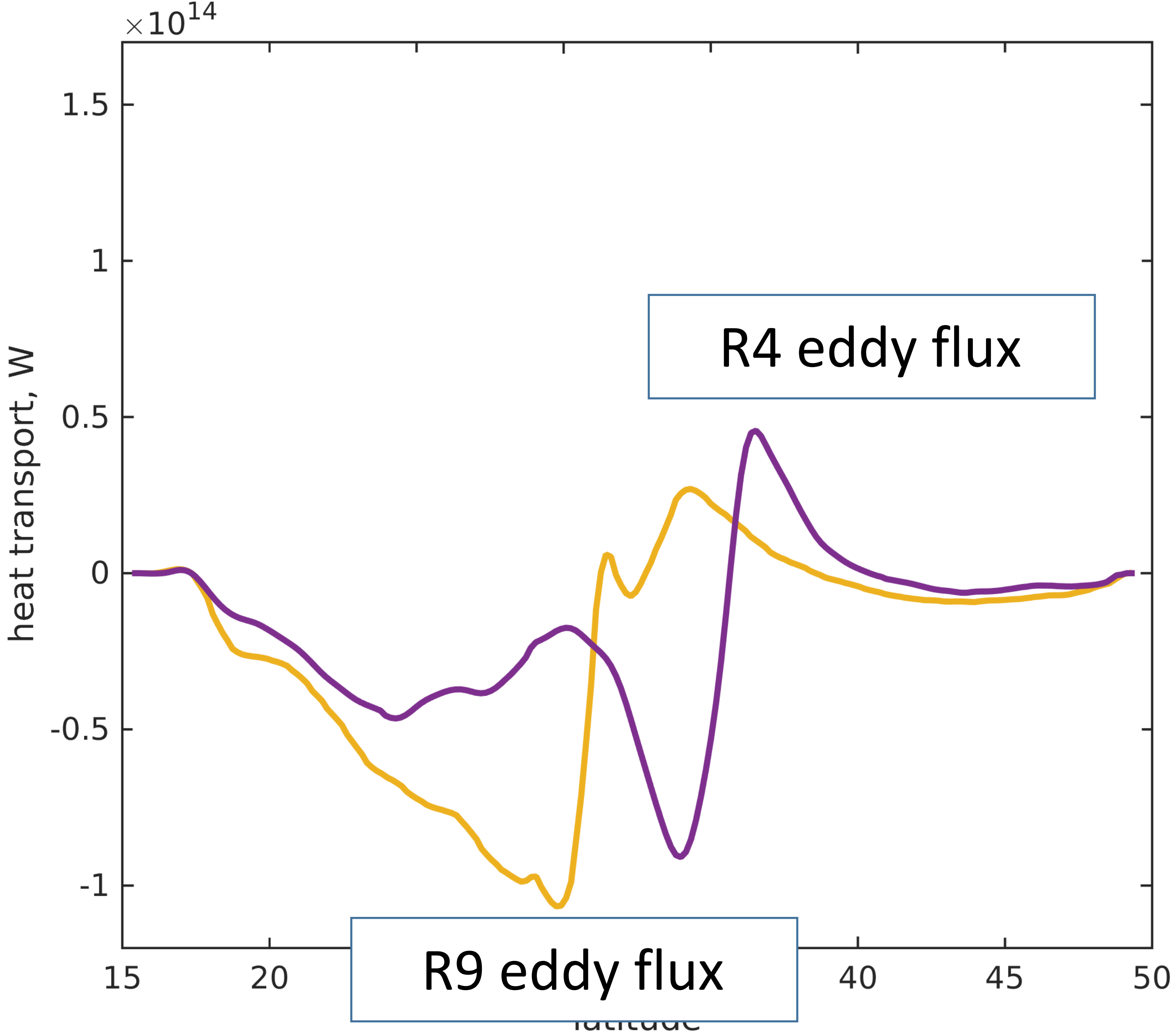
Temperature

Meridional heat flux, R9



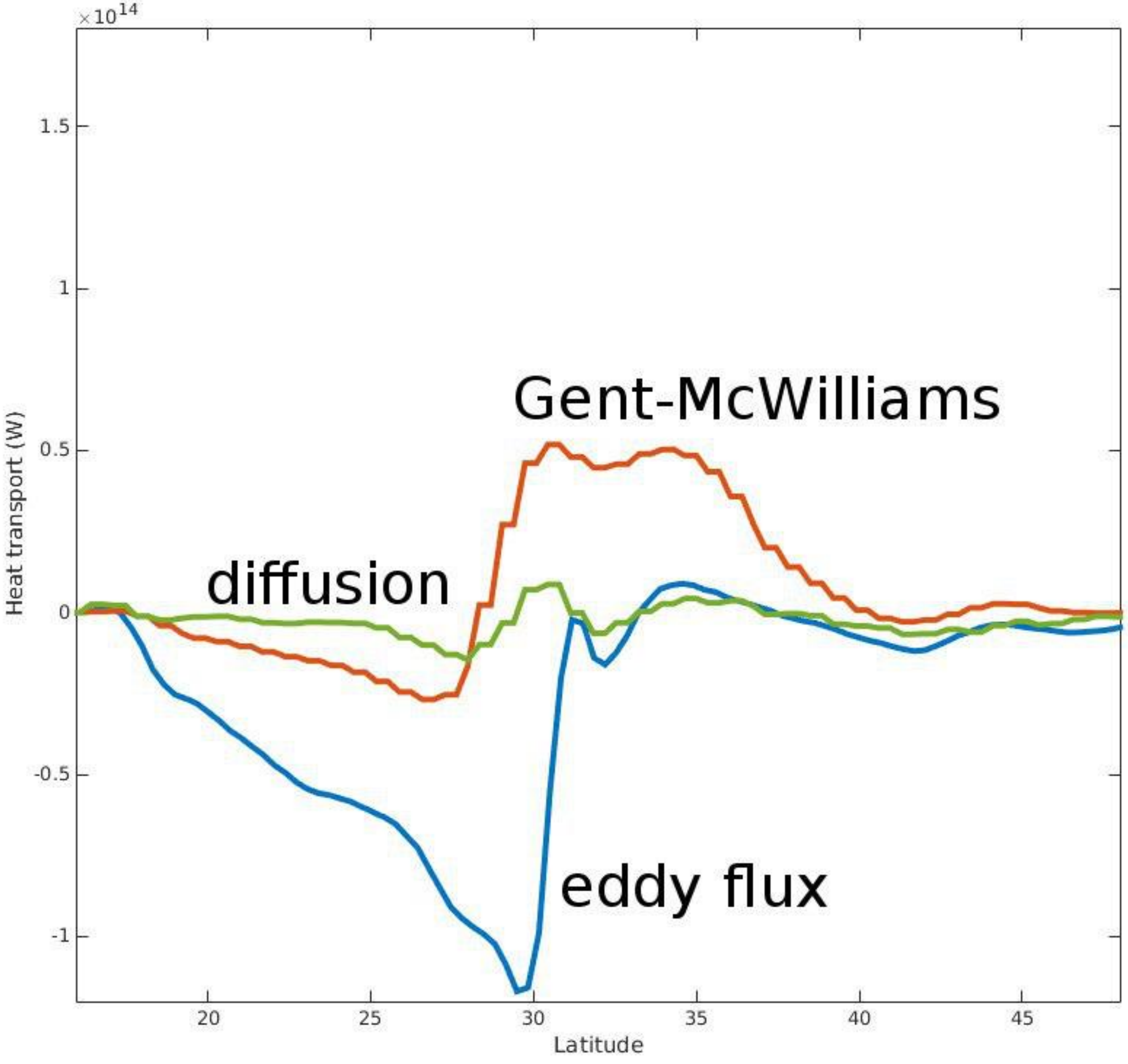
Eddy flux in depth



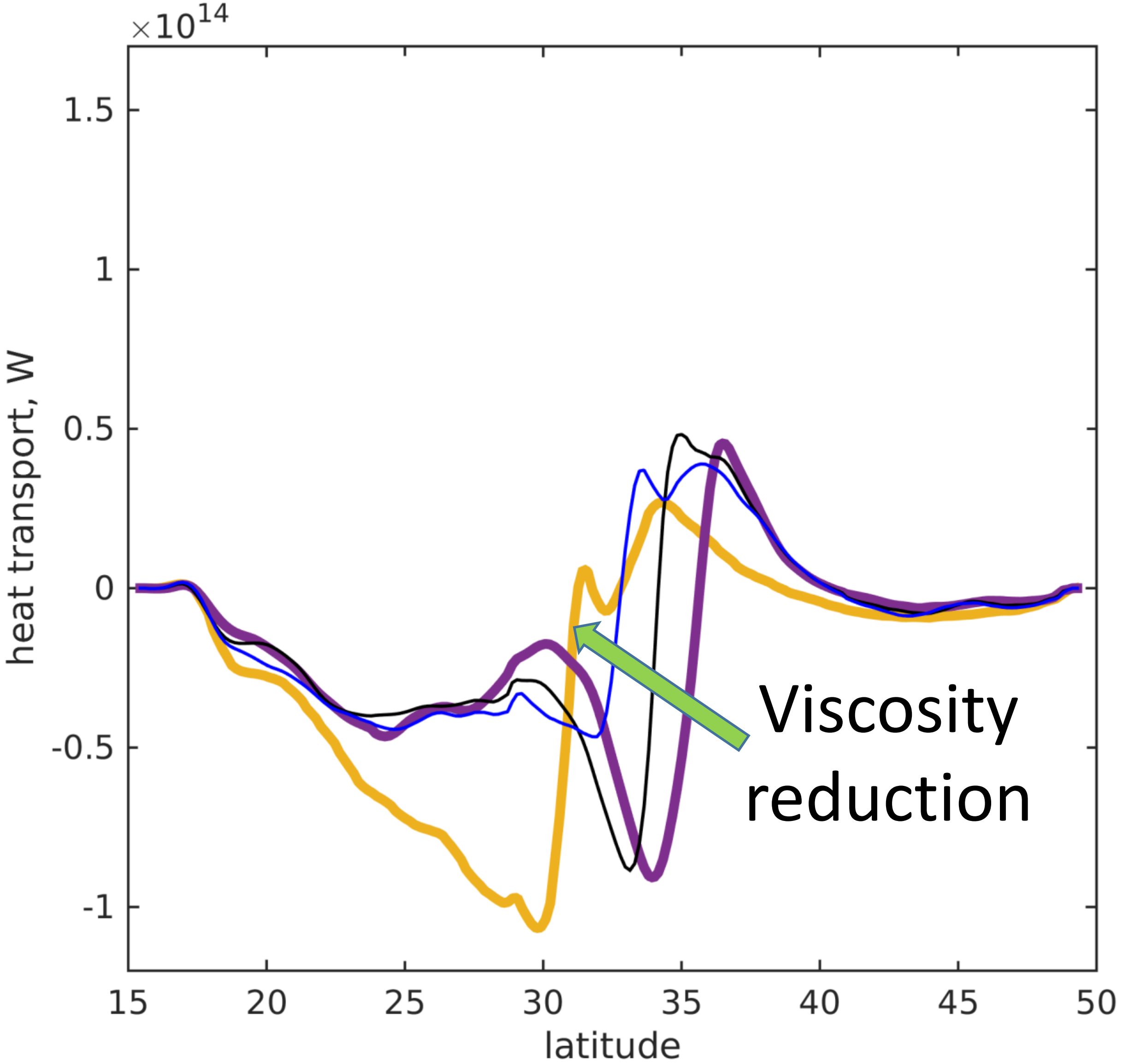


×10^14
1.5
1
0.5
0
-0.5
-1
heat transport, W
15
20
40
45
50
R4 eddy flux
R9 eddy flux

Eddy heat flux models



Viscosity reduction in R4



Negative viscosity backscatter (Jansen 2015)

- “Energetically consistent” – zero energy exchange with unresolved scales
- Energy returning using Laplace operator with negative viscosity
- Viscosity varies in space and time $\nu_2(x, y, z, t)$
- Additional equation for subgrid energy $e(x, y, z, t)$

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

Stochastic backscatter (Grooms, Majda2017; Berner2009)

- $\psi(x, y, z) = \phi(x, y) \cdot \sqrt{\max\left(\dot{E}_{diss}, 0\right)}$
- $\phi(x, y)$ – white noise in space and time, $N(0,1)$

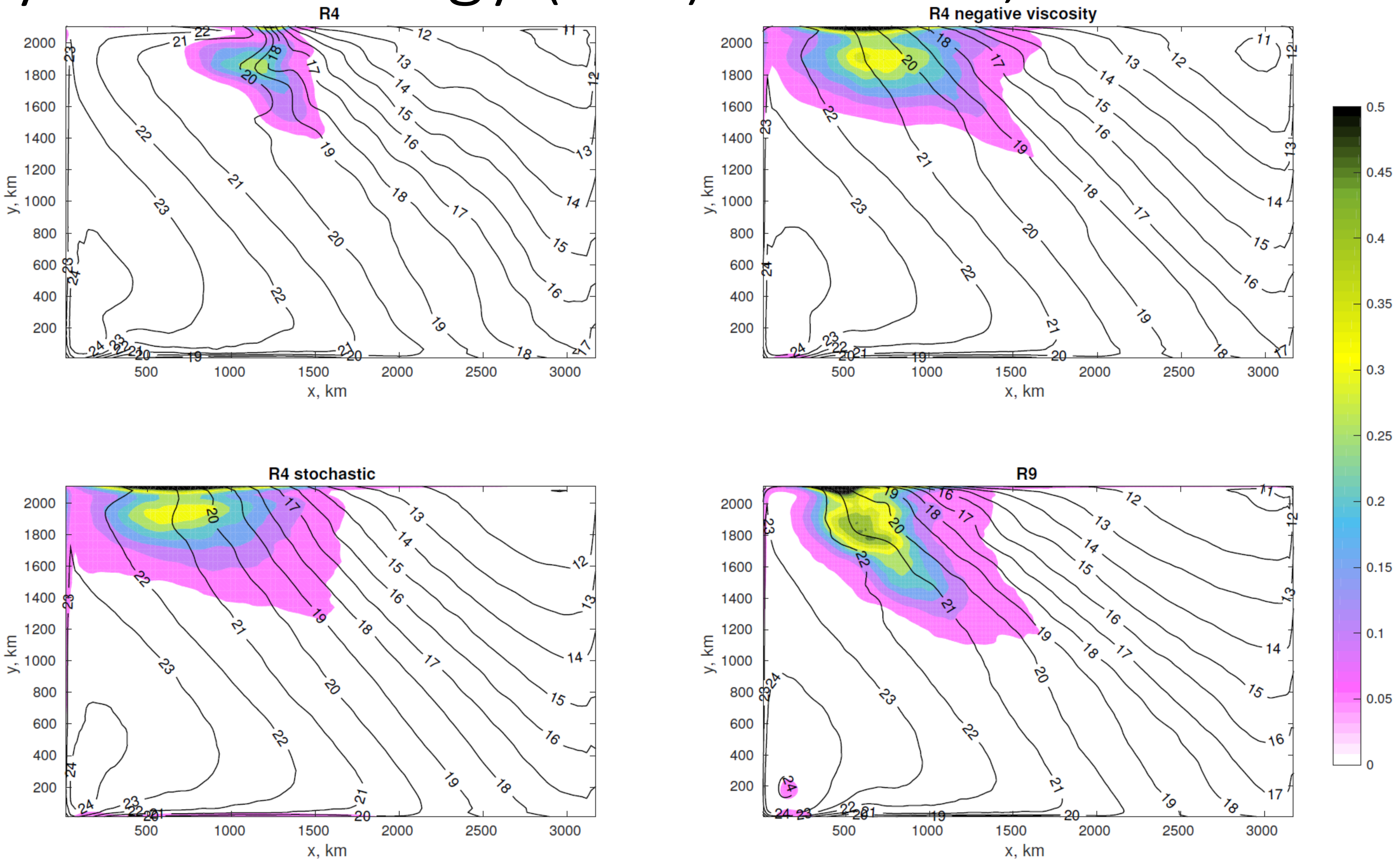
$$\frac{\partial U_h}{\partial t} = \cdots + \alpha \nabla^{\perp} \widehat{\psi},$$

Where $\widehat{(\cdot)}$ - 6 applications of Laplace filter nullifying chess-noise

- Condition on amplitude α representing global energy balance:

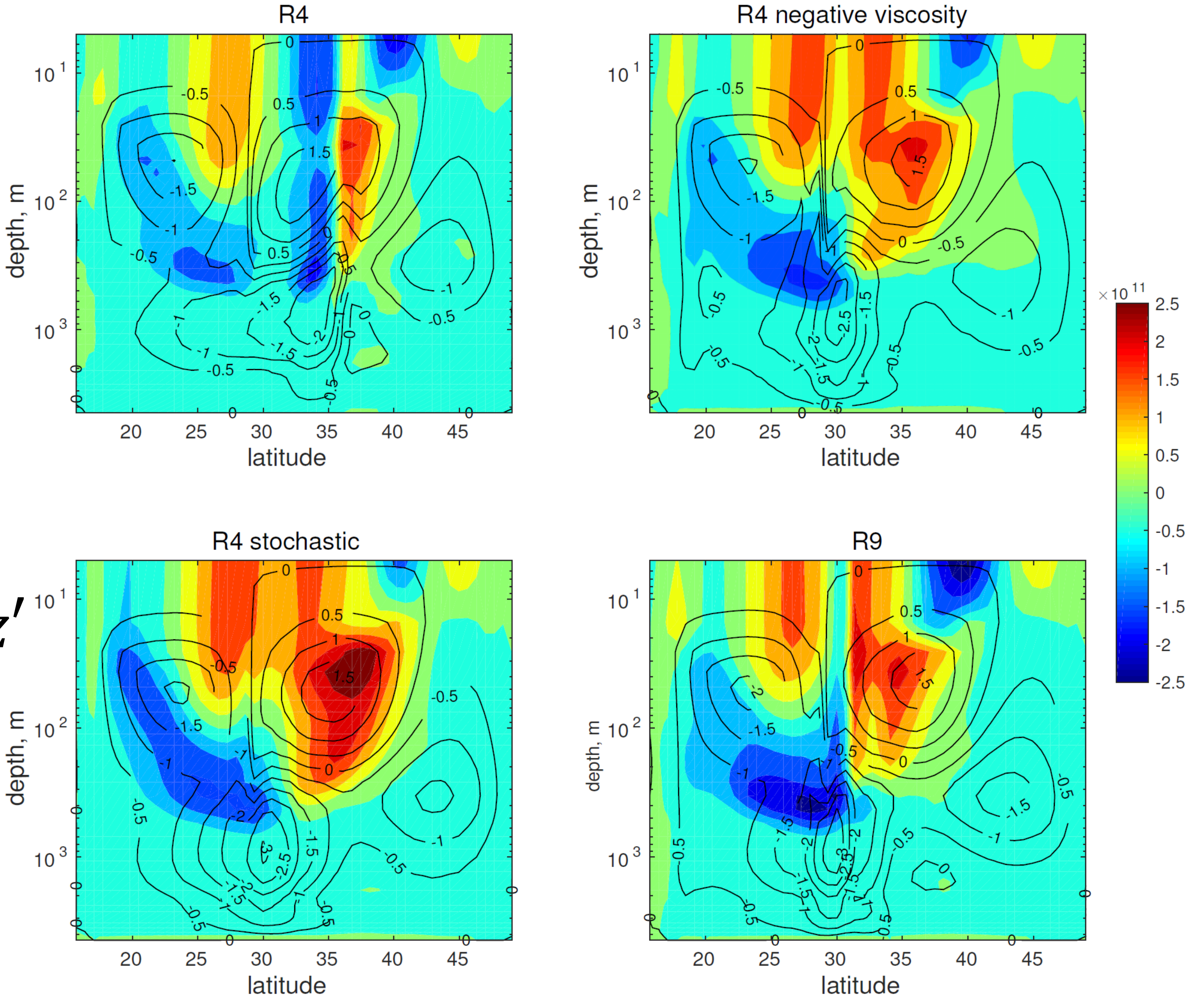
$$\frac{\alpha^2 \Delta t}{2} \int \left| \nabla^{\perp} \widehat{\psi} \right|^2 dV = \int \dot{E}_{diss} \, dV$$

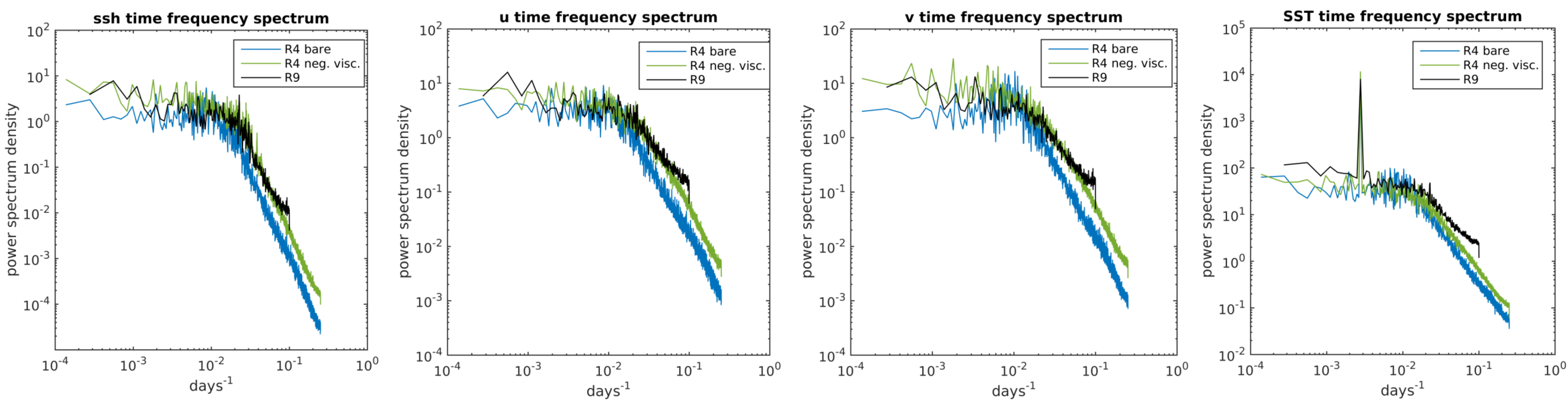
Eddy kinetic energy (EKE) in colour, SST in contours



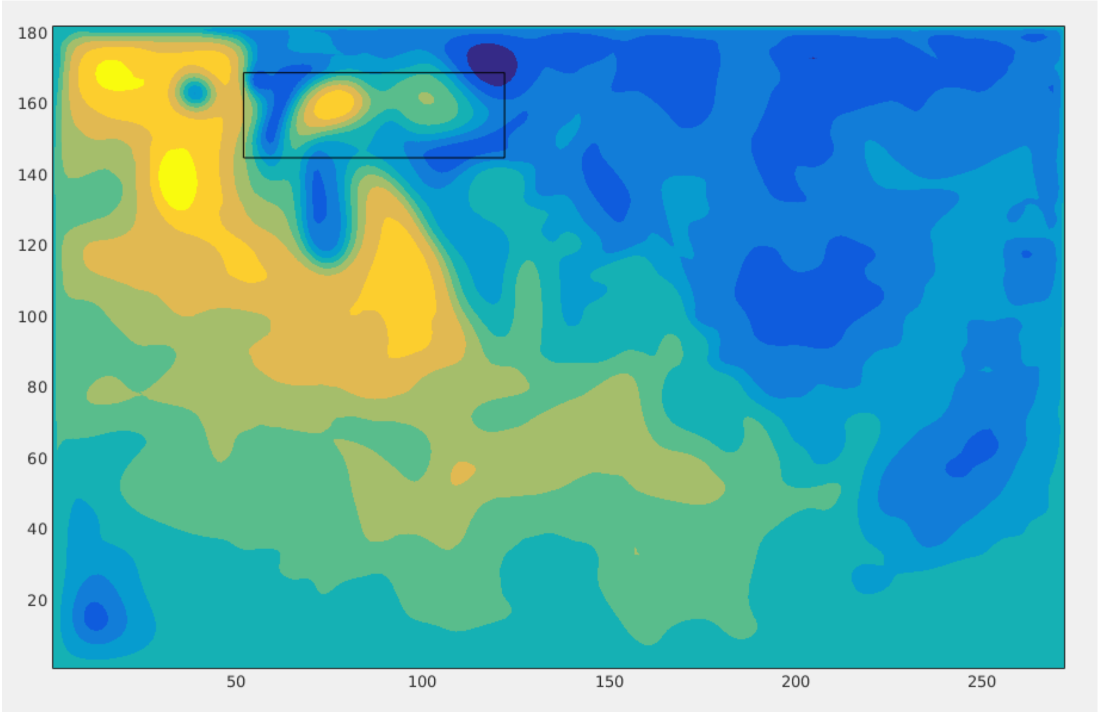
Eddy heat flux in colour, MOC in contours

$$\Psi_{MOC}(y,z) = \int_{-H}^{-z} \int V(x,y,z)\,dx\,dz'$$





Time spectra averaged over the black rectangle

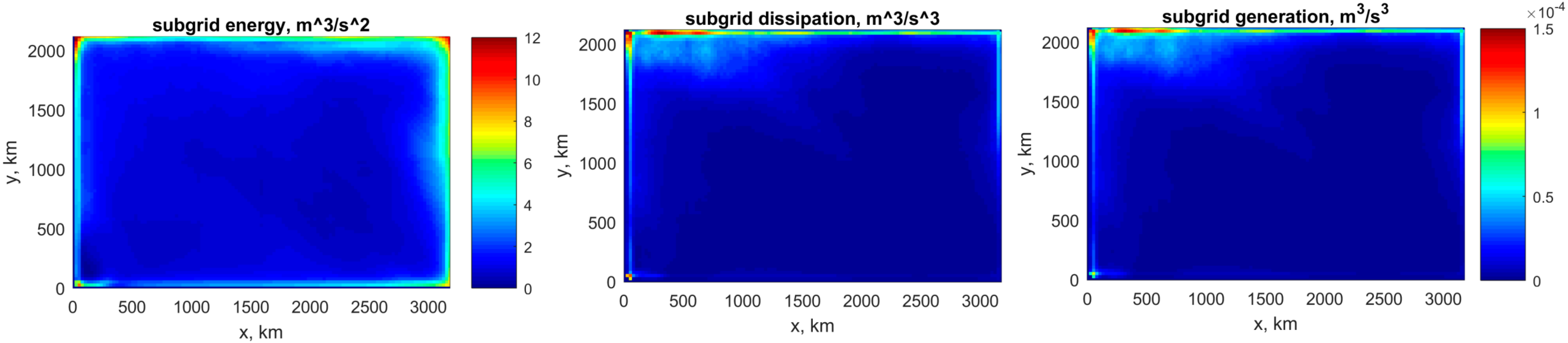


Errors in mean state

$\max(|\phi_{R4} - \phi_{R9}|)$ and $\mathrm{mean}(|\phi_{R4} - \phi_{R9}|)$

	R4		R4 negative viscosity		R4 stochastic	
SST, C^o	7.04	0.37	3.00	0.28	4.33	0.27
SSH, m	0.707	0.063	0.378	0.038	0.419	0.040

The main drawback – maximum energy exchange near the boundary



Conclusions

- Backscatter can amplify mesoscale eddies
- Improvements are seen in mean fields (SST, SSH, MOC), in variability (EKE, time spectra) and in cross-correlation (eddy heat flux)
- Stochastic and negative viscosity KEBs are qualitatively similar

Relative vorticity snapshots at different resolutions