Vertical heat and salinity fluxes due to resolved and parameterized meso-scale eddies

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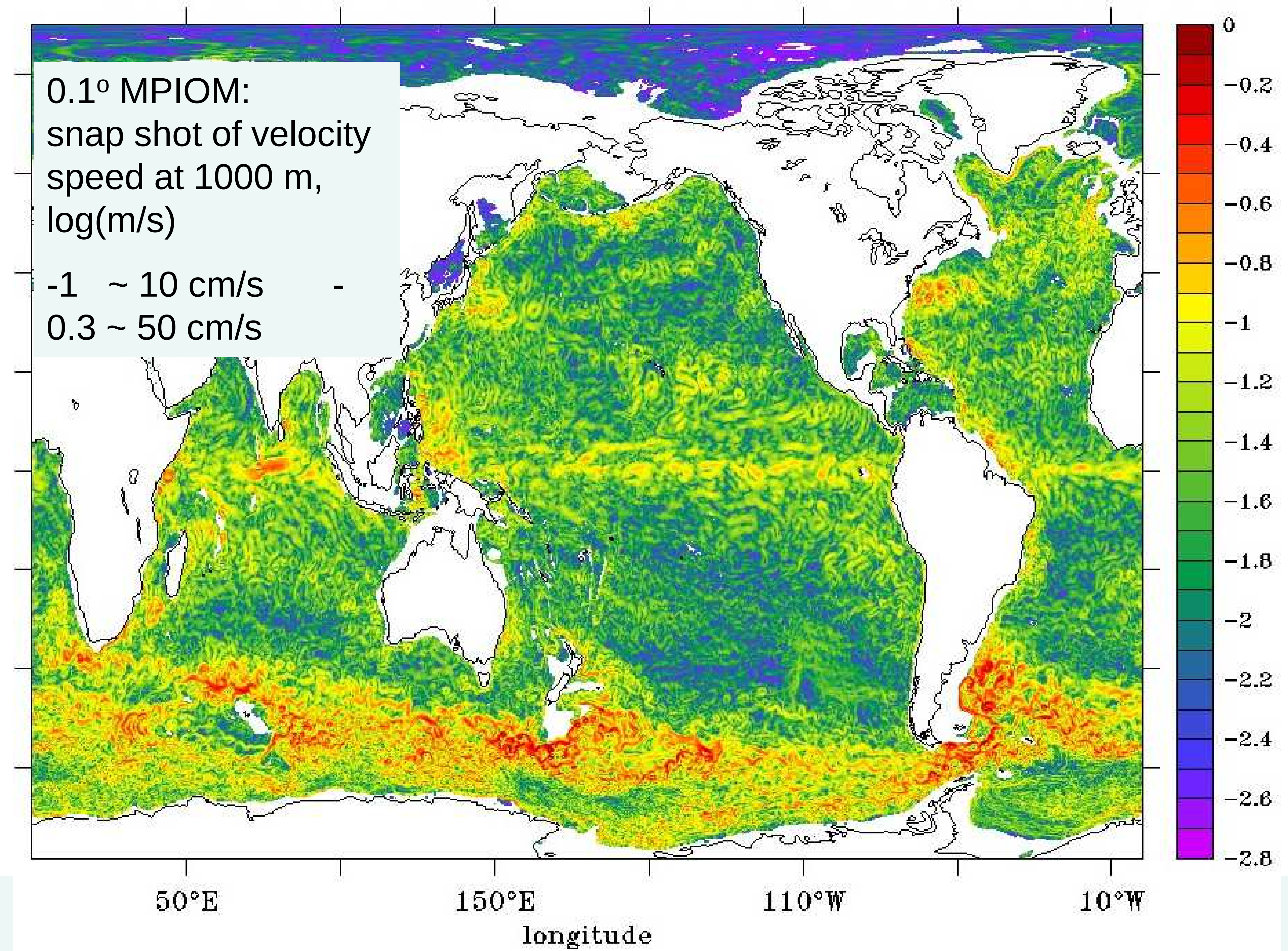
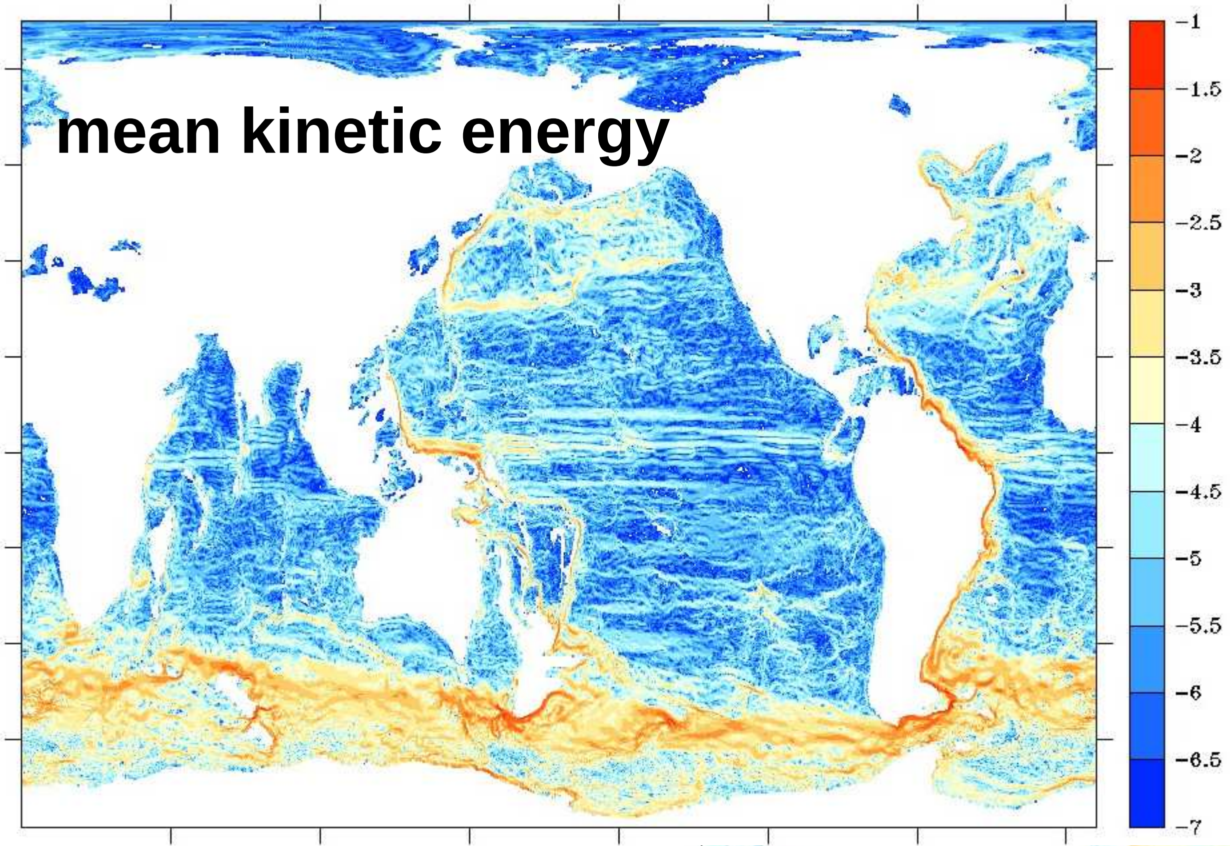
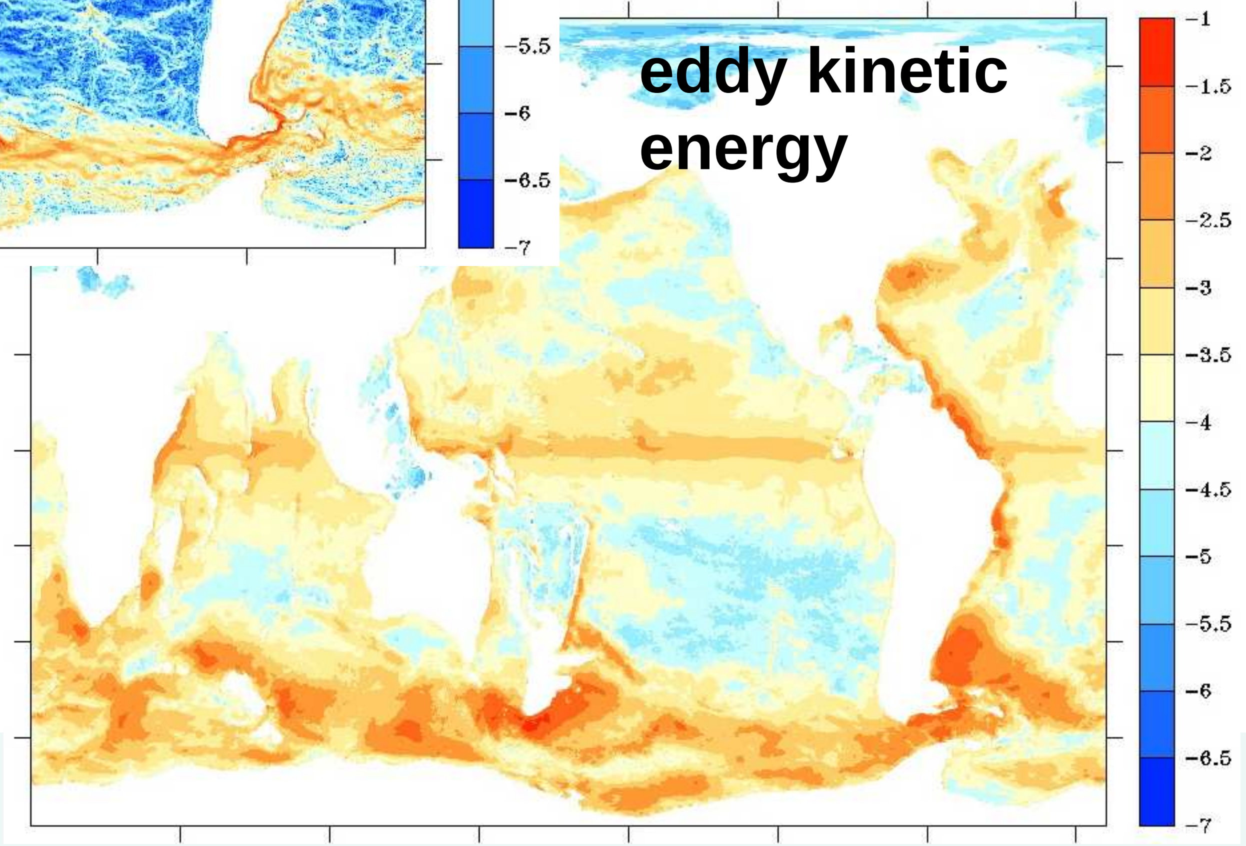
- Background and motivation
- Approach
- Result
  - large-scale circulations simulated by MPIOM at different resolutions
  - biases at different resolutions
  - resolved and parameterized vertical eddy heat and salinity fluxes and the related eddy forcing (divergence of eddy fluxes)
- Conclusions


0.1º MPIOM:
snap shot of velocity speed at 1000 m, log(m/s)
-1 ~ 10 cm/s -0.3 ~ 50 cm/s
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
-2.2
-2.4
-2.6
-2.8
50°E
150°E
110°W
10°W
longitude



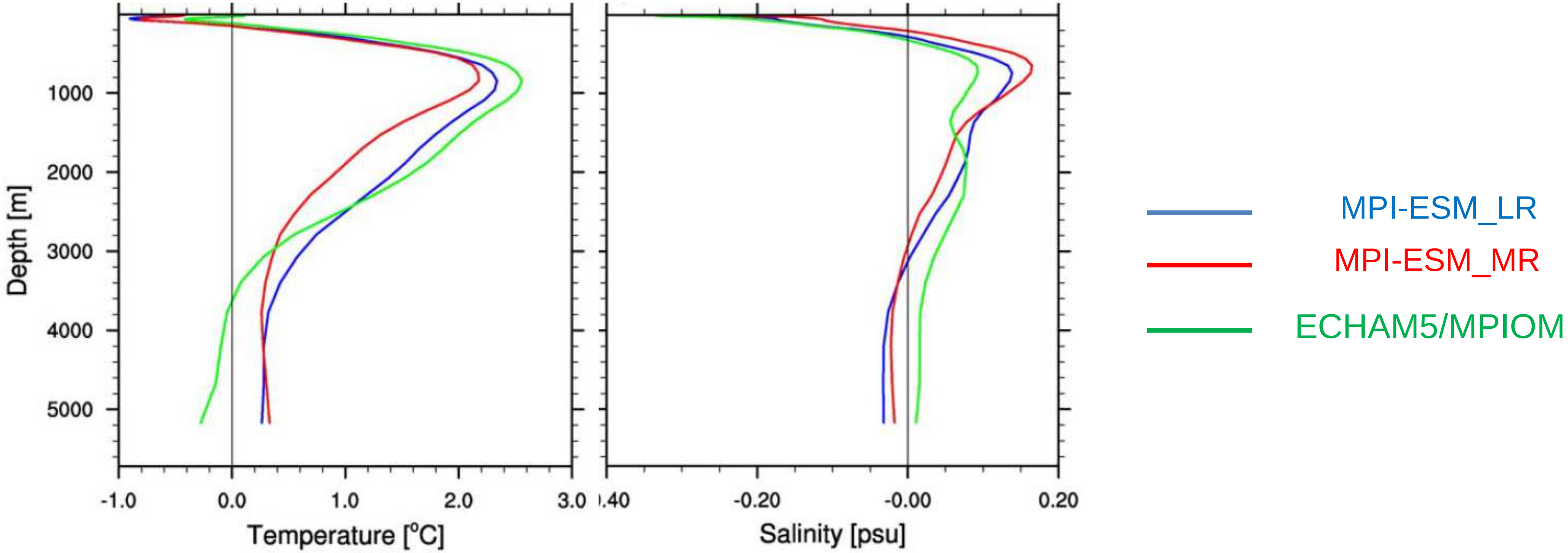
kinetic energy of the time-mean and time-varying circulation at **2038 m**. Unit: logarithm of m^2/s^2



-2 corresponds velocity speed of 10 cm/s

The global 0.1° simulation allows us to study the effects of the resolved mesoscale eddies on the overall performance

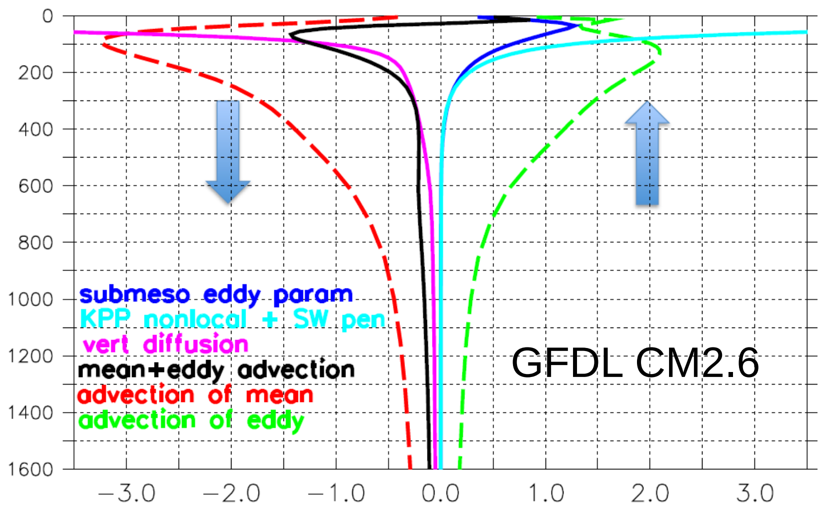
Global time-mean T-/S- biases relative to PHC3 in
CMIP3 (green)/CMIP5(red, blue) PICTRL coupled runs



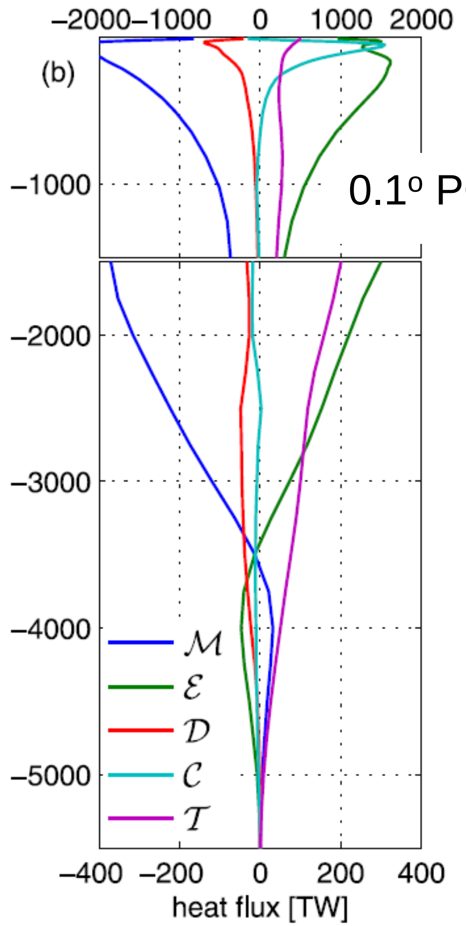
Jungcluas et al. 2013

Motivation

Recent studies point to the significance of the vertical eddy heat flux



Griffies et al. 2015



The global ocean vertical heat transport larger than 1 PW is found in two 0.1-degree simulations

Wolfe et al. 2008

Motivation

Less-well known aspects of vertical eddy fluxes:

- their impact on the global vertical T-, S-distribution and on the global T- and S-biases of non-eddy-resolving models that rely on inadequate parameterization of mesoscale eddies

Motivation

Special role of vertical eddy fluxes:

Since the influence of horizontal eddy fluxes vanishes for globally averaged T/S-budgets, the total effect of mesoscale eddies (in form of the 3-dimensional eddy fluxes) is encapsulated in the globally averaged vertical eddy flux.

We are now able

- to quantify the total effect of resolved eddies
- to assess whether and to what extent this effect is captured by the parameterization of mesoscale edddies

Approach: using MPIOM at different resolutions

In low-resolution MPIOM, the effect of mesoscale eddies is parameterized by the isoneutral diffusion of Redi (1982) and the eddy-induced transports following Gent et al. (1995)

Isoneutral diffusion of Redi:
- small slope approximation
- a scale-dependent diffusion coefficient A_{Redi}=1000 $m^2 s^{-1}$ for a grid size of 400 km
- having a small globally averaged effect

Eddy-induced transport of GM:

$$\mathbf{u}^* = (\mathbf{u}_h^*, w^*), \quad \text{with } \mathbf{u}_h^* = -\kappa_{GM} L_z \text{ and } \nabla \mathbf{u}^* = 0$$

κ_{GM} : thickness diffusivity, $L = -\nabla\rho / \rho_z$: isoneutral slope vector

Approach: using MPIOM at different resolutions

Two suites of ocean-only simulations with MPIOM/L80, all driven by the 6 hourly NCEP/NCAR reanalysis from 1948-2014, are used to analyze the vertical eddy fluxes (analysis period 1981-2010)

1. suite	TP6M	TP04	GR15
Horizontal resolution	0.1°	0.4°	1.5°
κ_{GM} [m^2s^{-1}] for Δx =400km	0	250	250
A_{redi} [m^2s^{-1}]	25	100	375

2. suite	GR15	GR15_4x	GR15_16x
Horizontal resolution	1.5°	1.5°	1.5°
κ_{GM} [m^2s^{-1}] for Δx =400km	250	1000	4000

NOTE: All simulations use the same PP-scheme, the same background diffusivity, the same parameterization for convection

Approach: using MPIOM at different resolutions

The analysis focuses on

- divergence of the resolved eddy fluxes, e^x

$$e^x = -\nabla \cdot \left(\overline{b'\mathbf{u}'}\right),$$

$$E^x = -\frac{1}{V}\int_A \int_{k^+}^{k^-} e\, dzdA = -\frac{1}{V}\int_A \int_{k^+}^{k^-} \frac{\partial \overline{b'w'}}{\partial z}\, dzdA = \frac{1}{V}\int_A \left(\left(\overline{b'w'}\right)_{k^+} - \left(\overline{b'w'}\right)_{k^-}\right) dA$$

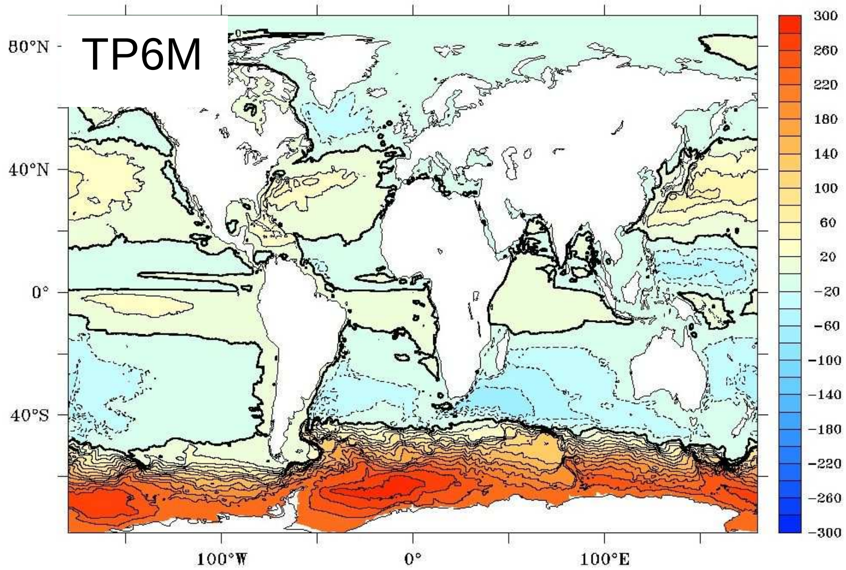
- divergence of the parameterized eddy-induced transports, e_{GM}, diagnosed as the tendency forcing in the T- and S-equation

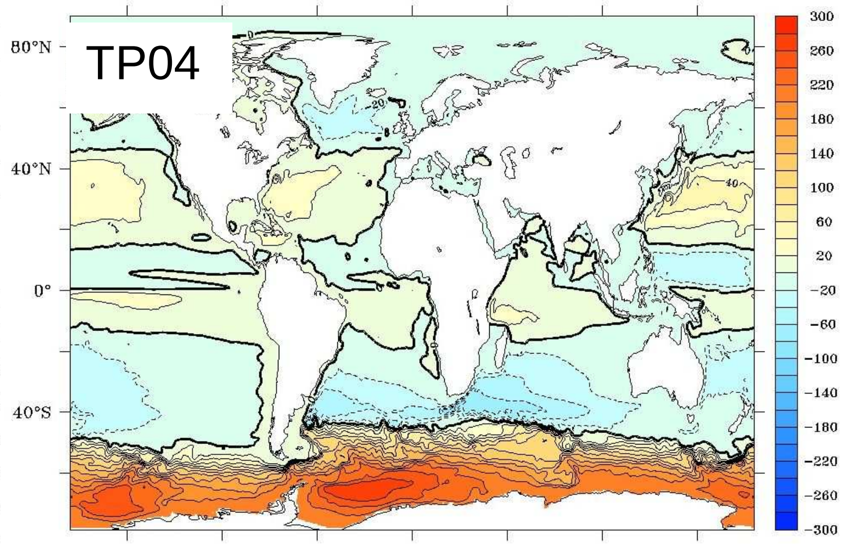
$$e_{GM} = -\nabla \cdot \left(\mathbf{u}^* b\right), \qquad E_{GM} = -\frac{1}{V}\int_A \int_{k^+}^{k^-} e_{GM}\, dzdA$$

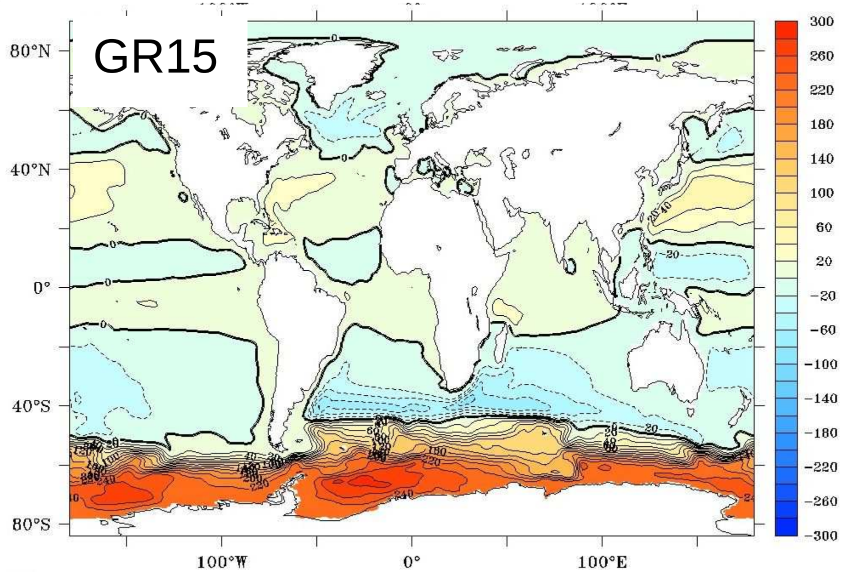
- divergence of the isoneutral flux, e_{Redi}, diagnosed as the tendency forcing in the T- and S-equation

$$e_{\mathrm{Redi}} = \nabla \cdot \left(K \nabla b\right), \qquad E_{\mathrm{Redi}} = -\frac{1}{V}\int_A \int_{k^+}^{k^-} e_{\mathrm{Redi}}\, dzdA$$

Result: Circulations simulated by MPIOM at different resolutions



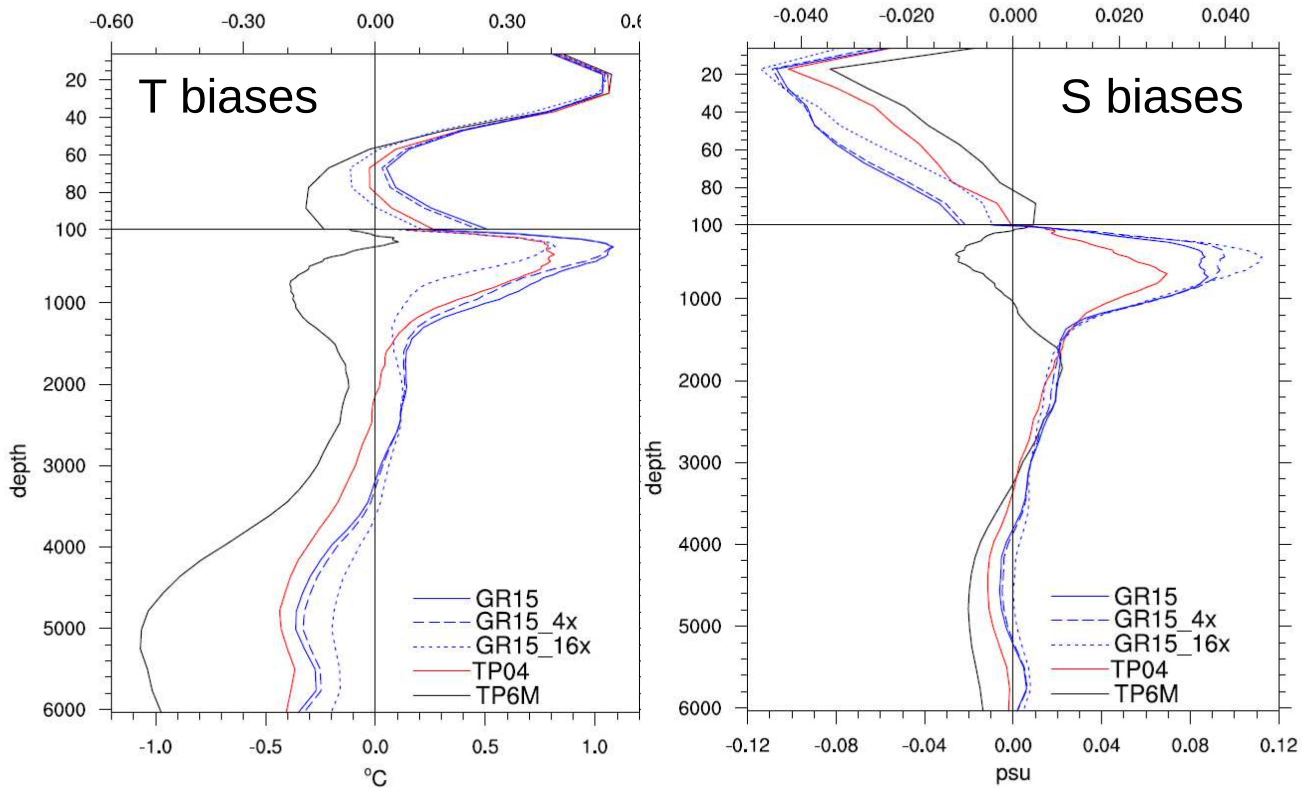




- the overall structure comparable, but the gyres are about 10-20 Sv stronger in TP6M
- the retroflection of the Agulhas current is much too weak in low-resolution simulations, leading to a strong ‘super gyre’ in GR15
- ACC are too strong in all three runs (234 Sv in TP6M, 214 Sv in TP04 and 231 Sv in GR15, relative to 130-140Sv in obs)

Result: Biases at different resolutions

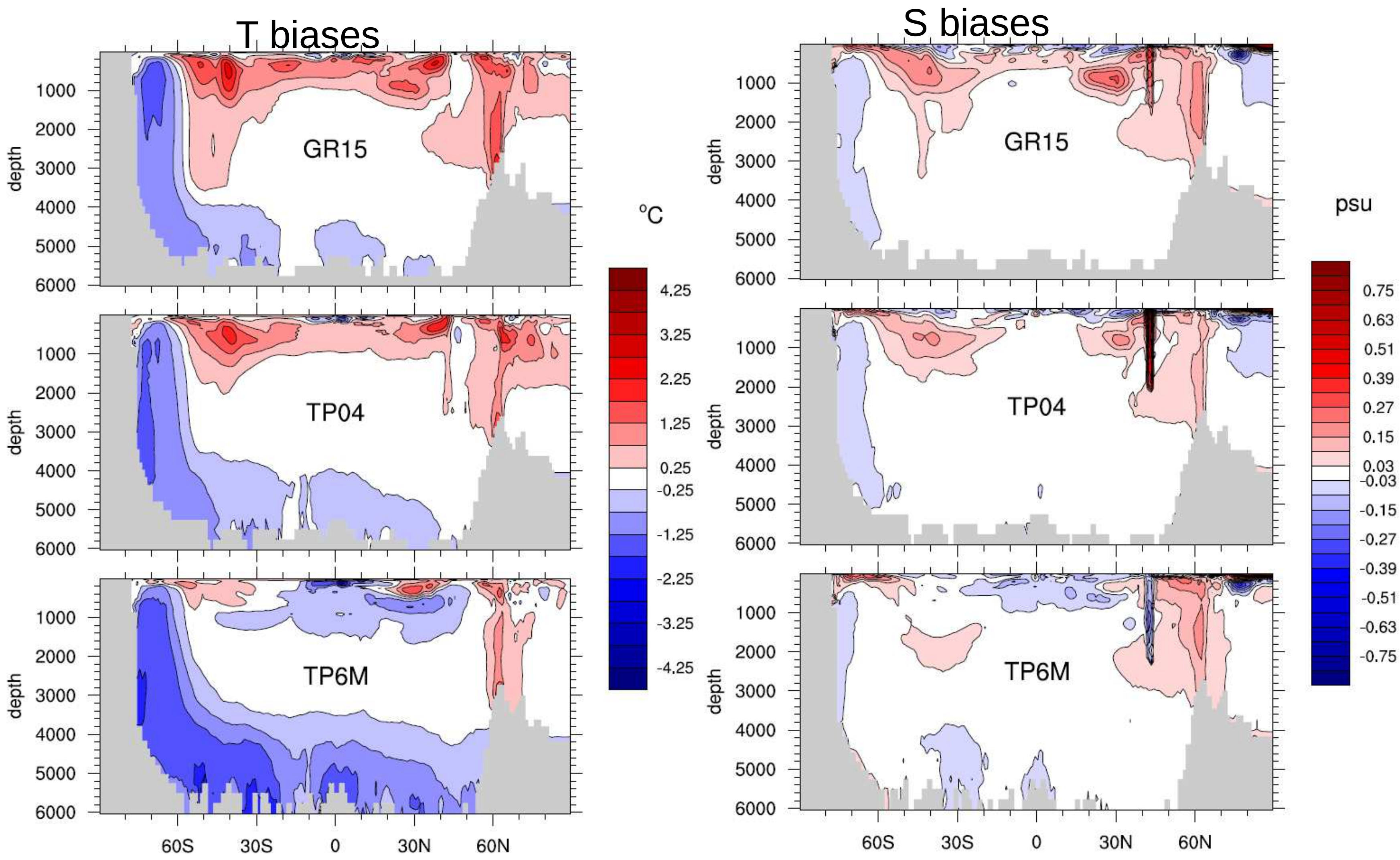
Area-averaged biases (relative to PHC3)



- The long-standing warm and saline biases in TP04 and GR15 at the intermediate depths from 100-1500 m are reduced in TP6M

Result: Biases at different resolutions

Zonally averaged biases (relative to PHC3)

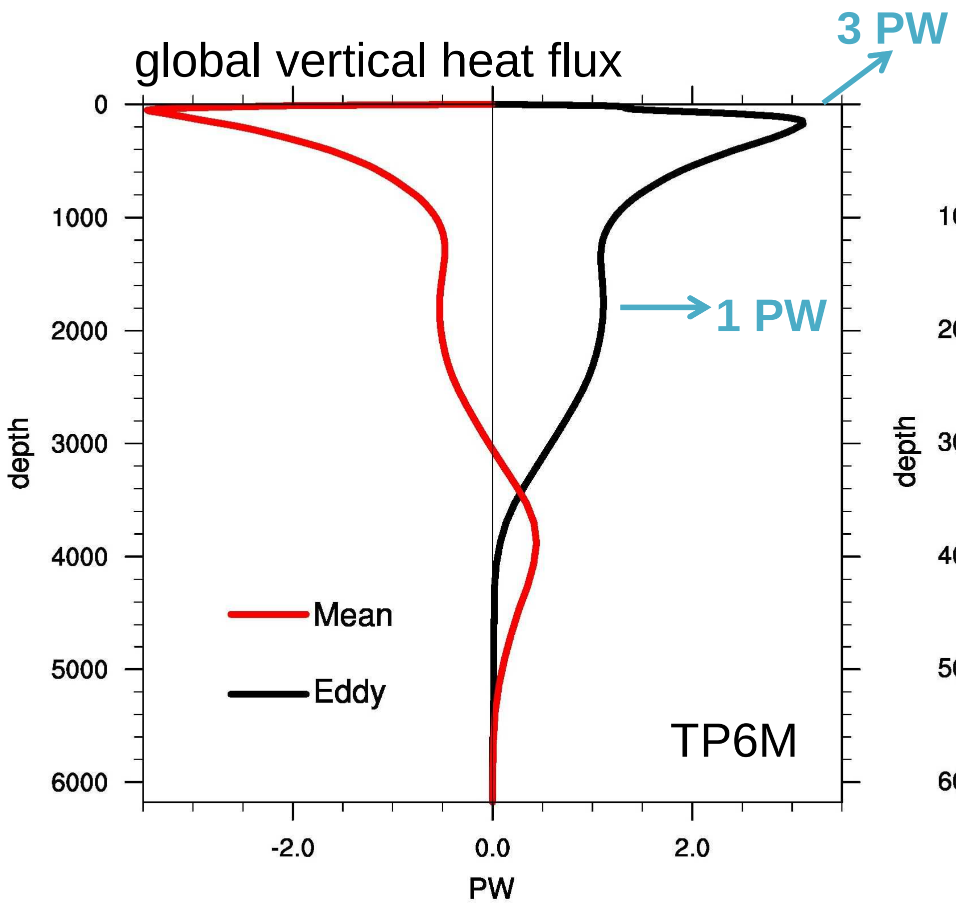


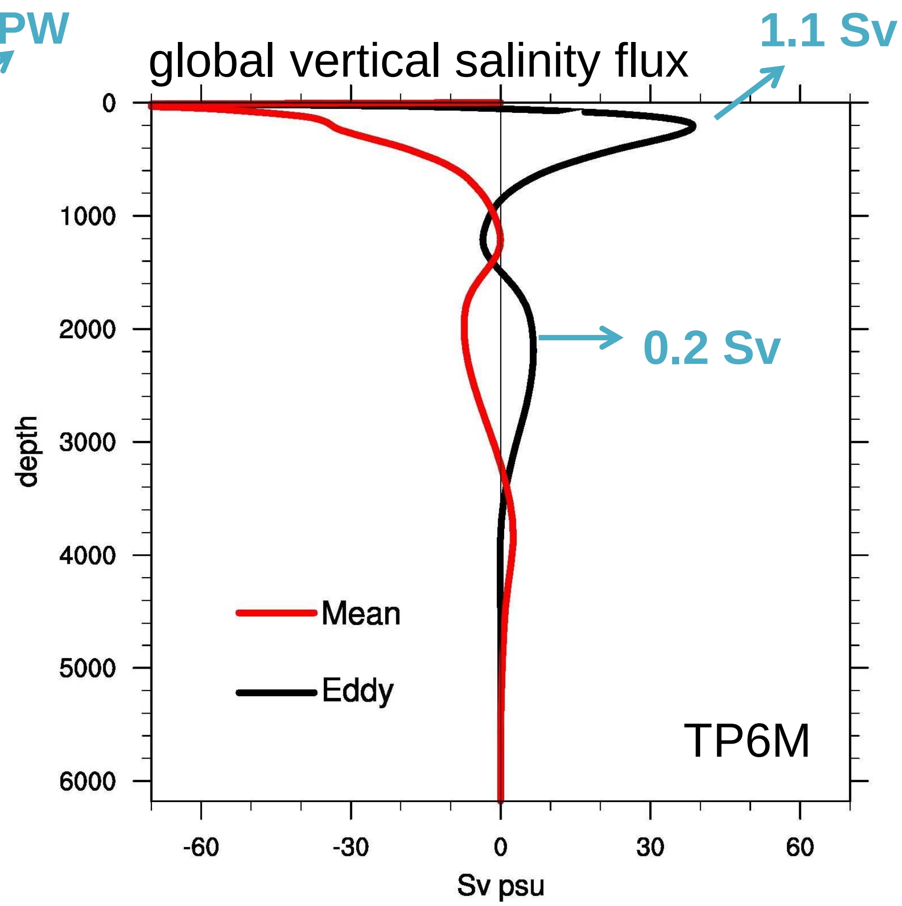
Result: Biases at different resolutions

- The strength of the ACC depends on the meridional density gradient and hence the water-mass properties in the high-latitude SO with weak stratification
  which can be improved by coupling MPIOM to ECHAM/T255, reducing the strength to 140 Sv (Stössel et al. 2014)

- Since the near-surface T and S are closely linked to the imposed surface forcing and the eddy activity is weak in the deep ocean (below 3000 m), and since the biases in the deep ocean are directly related to the ACC-problem, we will concentrate on the biases at the intermediate depths from 100m-1500m

Result: vertical heat / salinity fluxes in TP6M

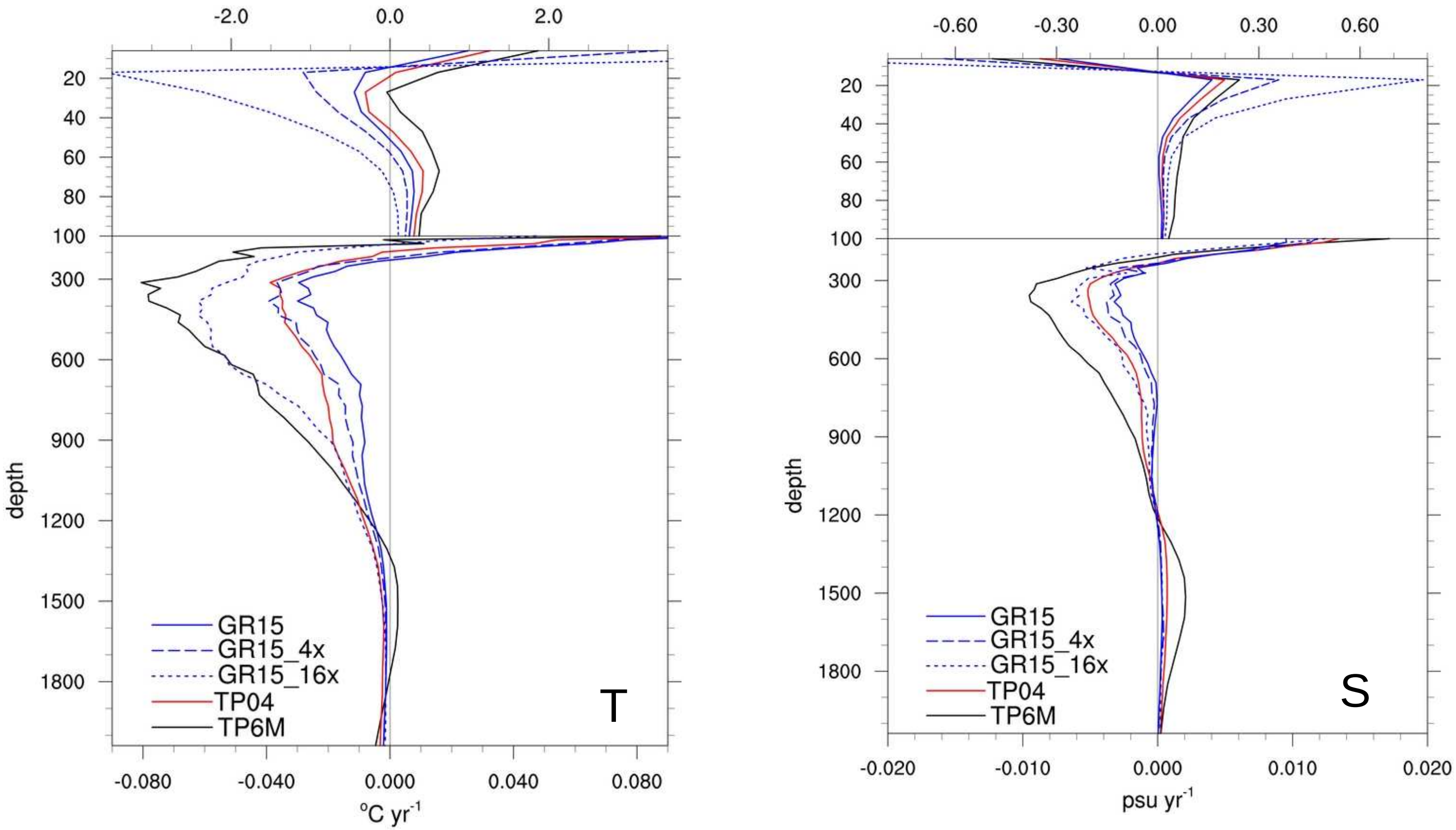




In TP6M:

- vertical fluxes due to mean flows transport heat and salt downward
- vertical fluxes due to eddies transport heat and salinity upward

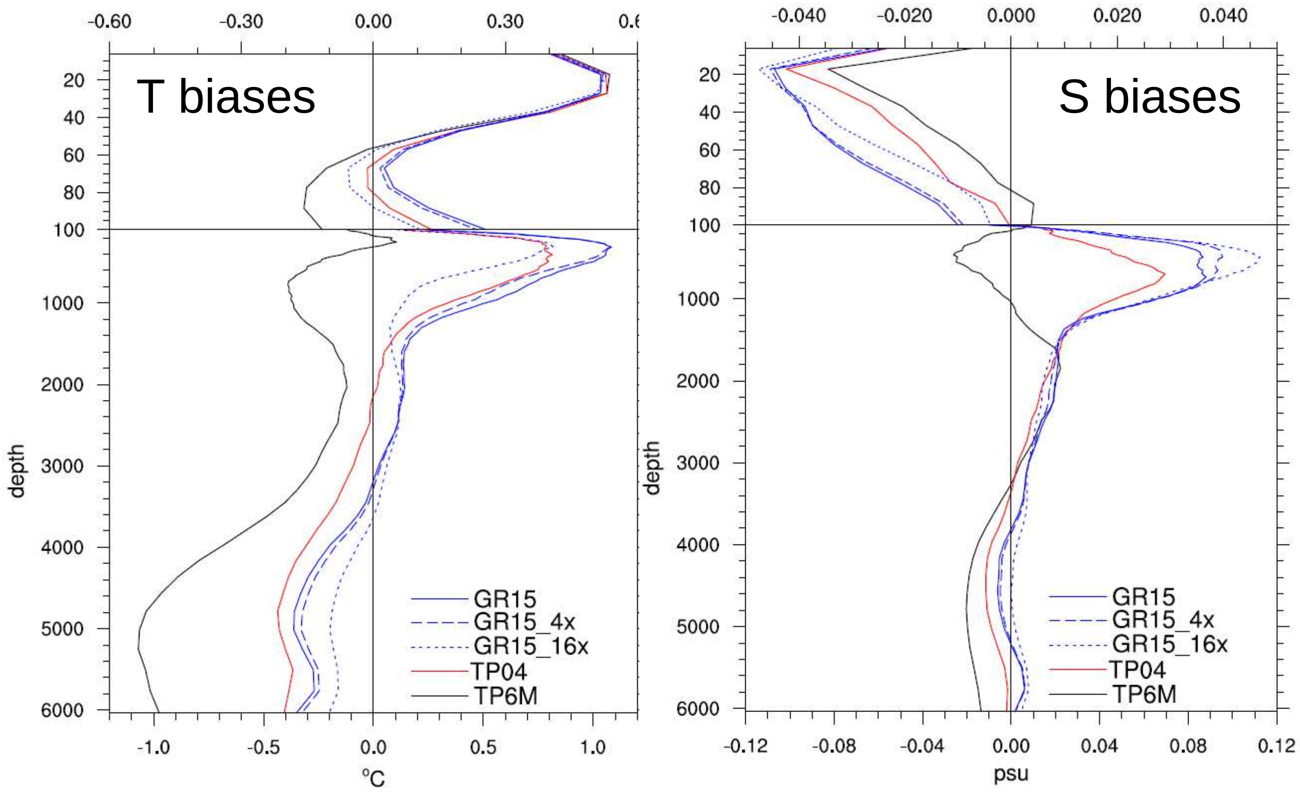
Result: resolved and parameterized eddy forcing



- At the intermediate depths: both resolved and parameterized eddy forcing cools and freshens the water masses, with $E=E^{x}+E_{GM}$ in GR15/TP04 weaker than E^{x} in TP6M.
- Increasing thickness diffusivity increases $|E|$ at the intermediate depths. However, the magnitude is unrealistically large directly below the surface (due to vanishing vertical density gradient there, which needs to be tapered following Danabasoglu et al. 2008)

Result: resolved and parameterized eddy forcing

Area-averaged biases (relative to PHC3)



- Increasing thickness diffusivity reduces the warm biases, but increases the saline biases

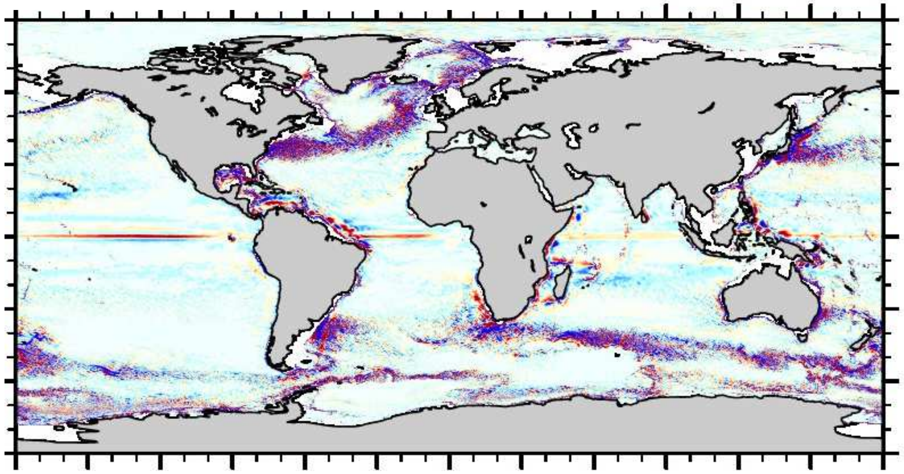
Result: resolved and parameterized eddy forcing

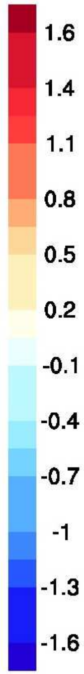
Hypothesis: horizontal distribution of e^x in TP6M differs from that of $e^x + e_{GM} + e_{Redi}$ in TP04/GR15

→ different density distribution

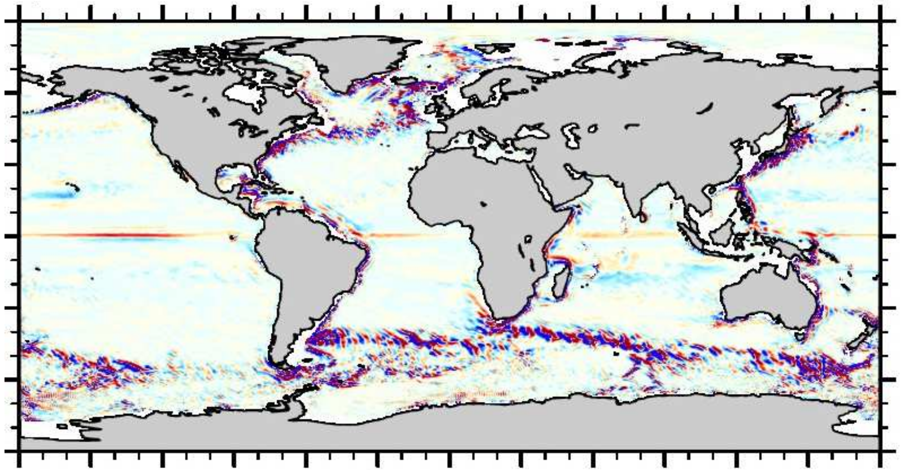
→ different area-averaged T-/S-biases

e^x for T in TP6M at 312m

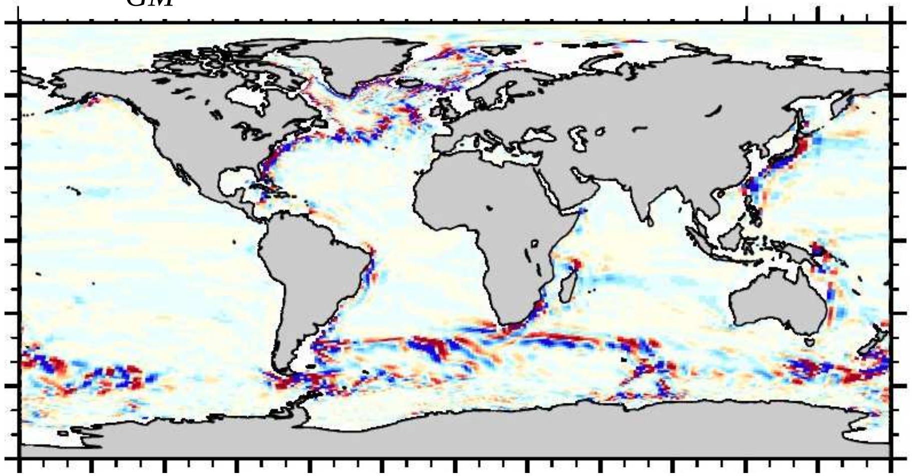




$e^x + e_{GM}$ for T in TP04 at 312m

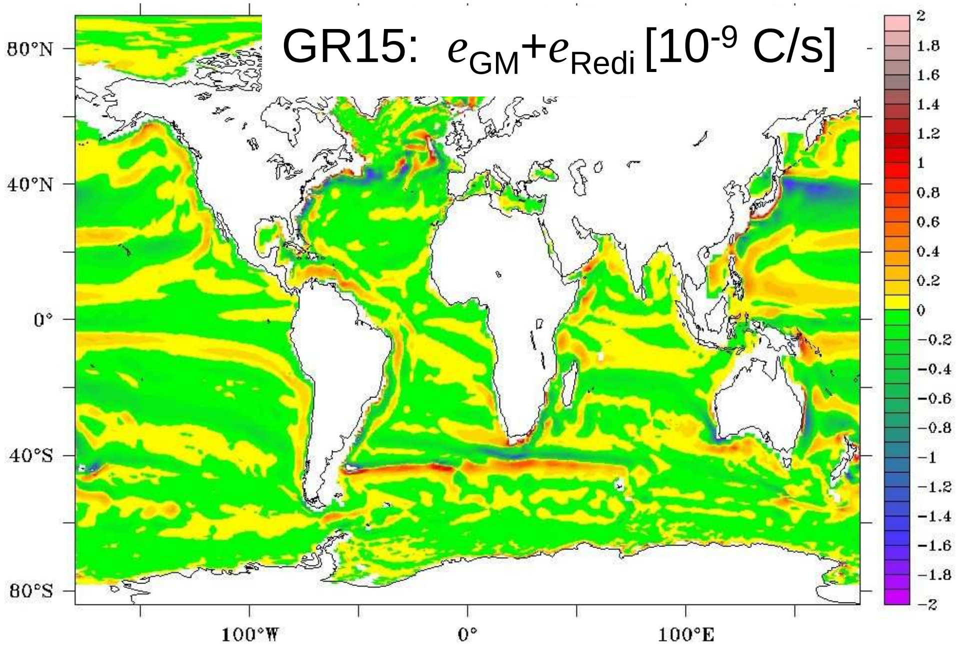


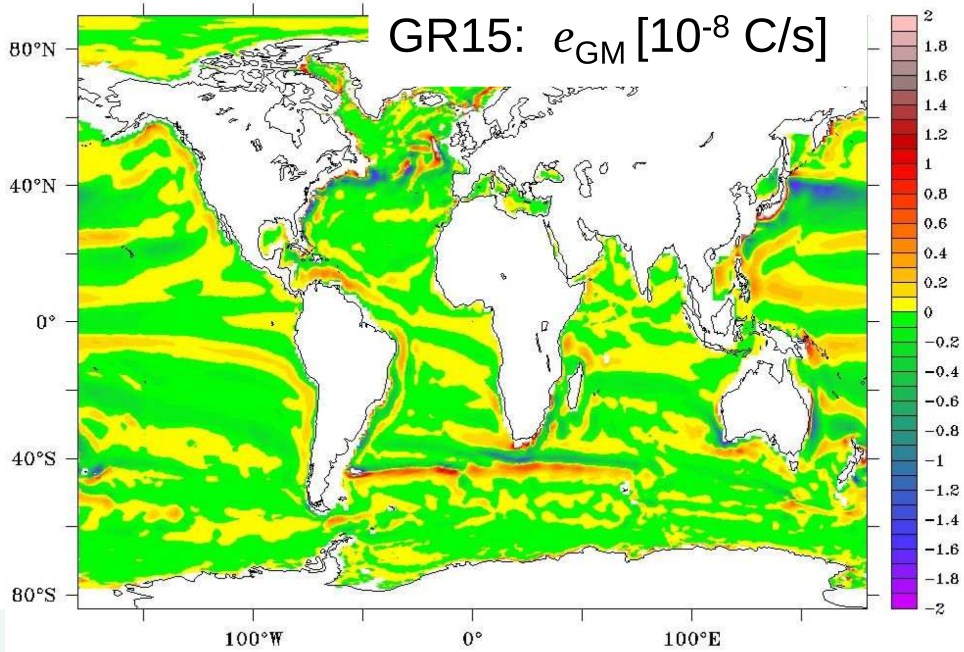
$e^x + e_{GM}$ for T in GR15 at 312m

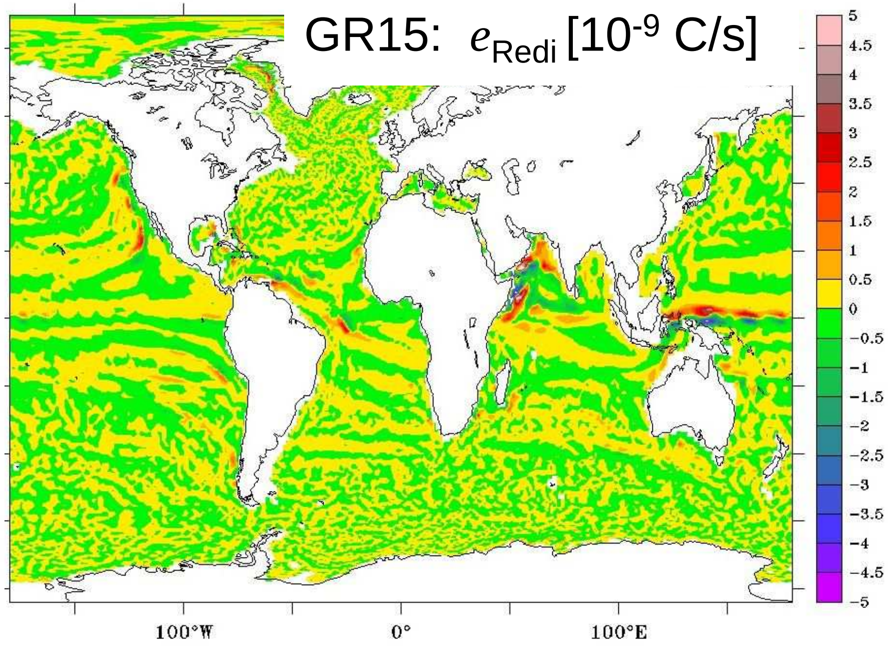


10^{-7} °Cs^{-1}

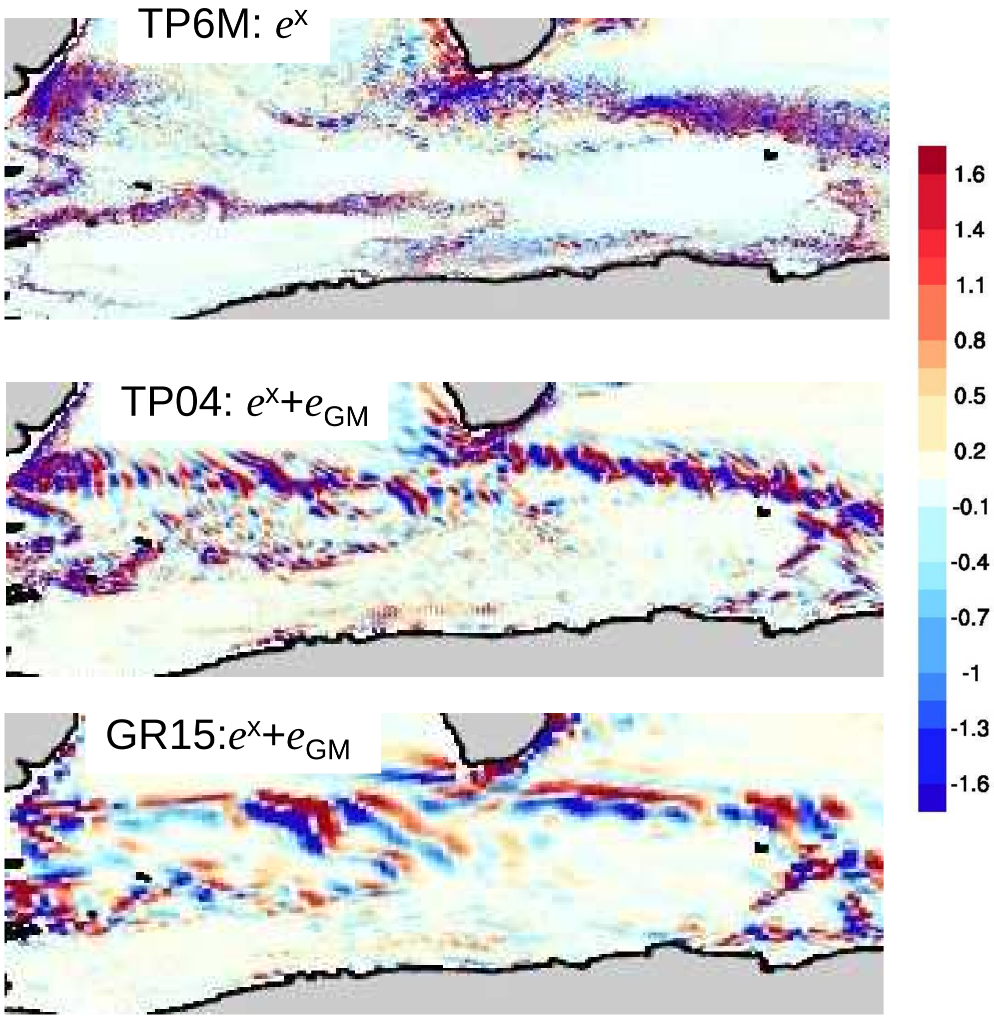
e_{Redi} is negligible relative to e_{GM}







Resolved and parameterized eddy forcing in the southern Atl. and Ind. Ocean sector



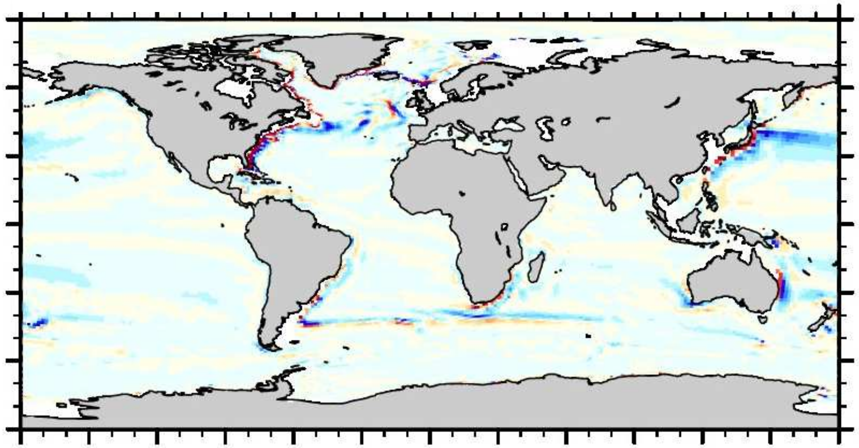
10^{-7} °C s^{-1}

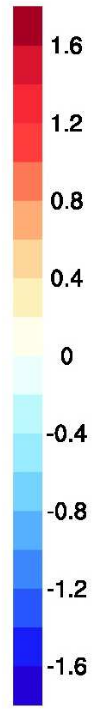
- large values in the Gulf Stream and Kuroshio and their extensions and in the SO, mainly due to resolved and quasi-resolved eddies, but with different spatial scales, resulting in pattern correlation <0.1

Result: resolved and parameterized eddy forcing (divergence of eddy fluxes)

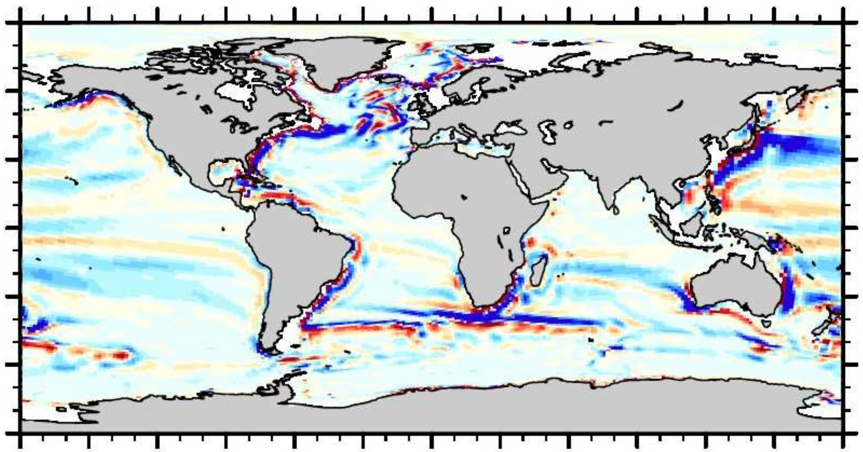
e_{GM} without the effect of quasi-resolved eddies

e_{GM} for T in GR15 at 312m

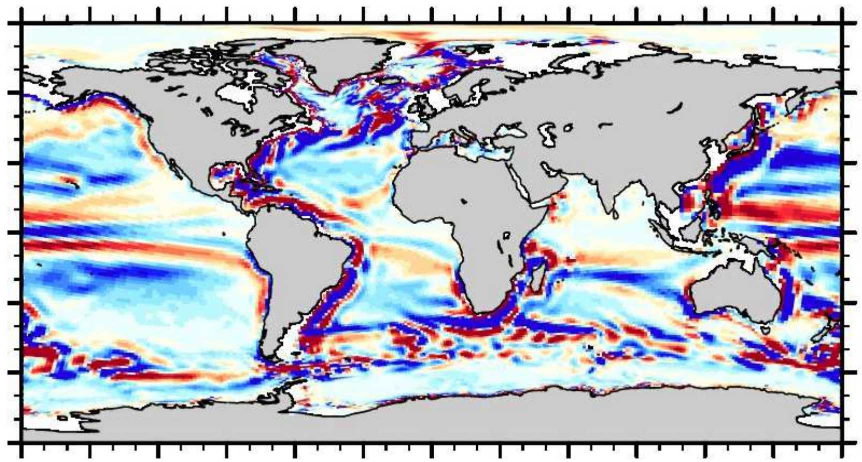




e_{GM} for T in GR15_4x at 312m



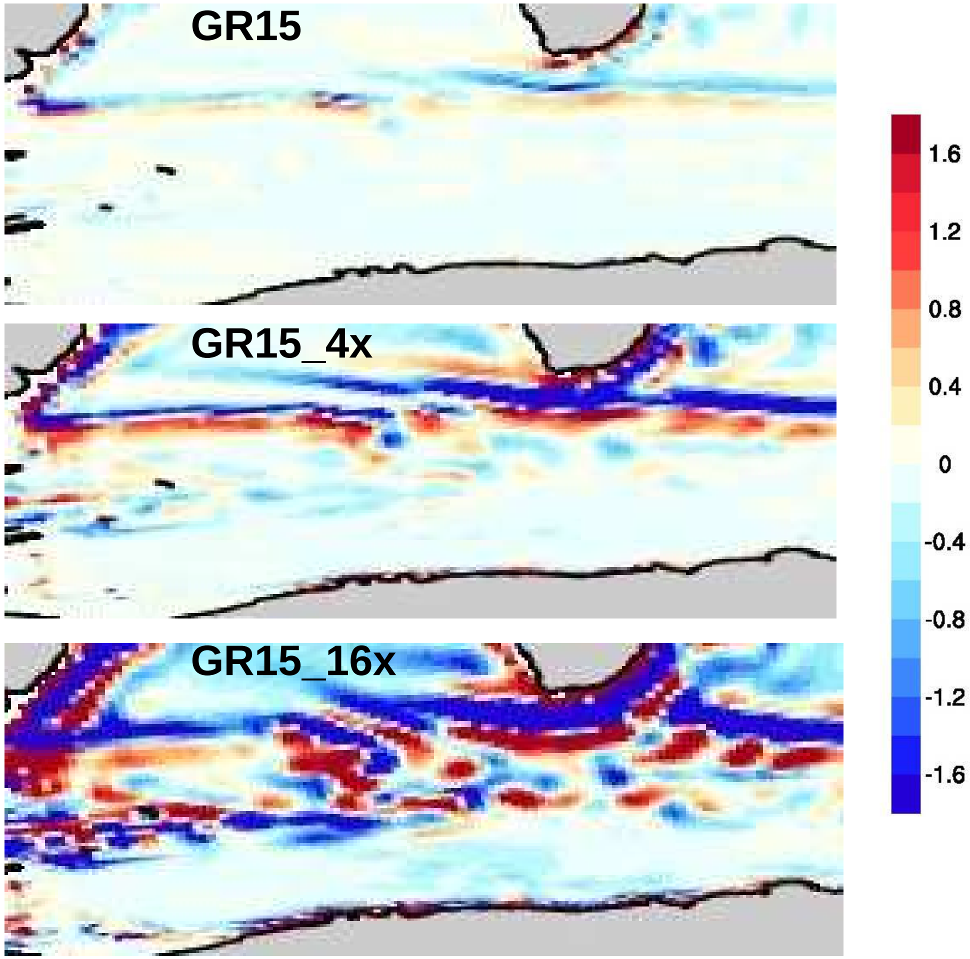
e_{GM} for T in GR15_16x at 312m



10^{-8} °C s^{-1}

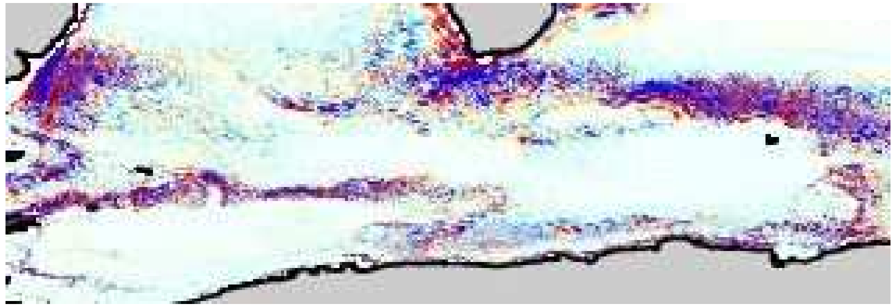
Result: resolved and parameterized eddy forcing

e_{GM}



$10^{-8}\,{}^{o}Cs^{-1}$

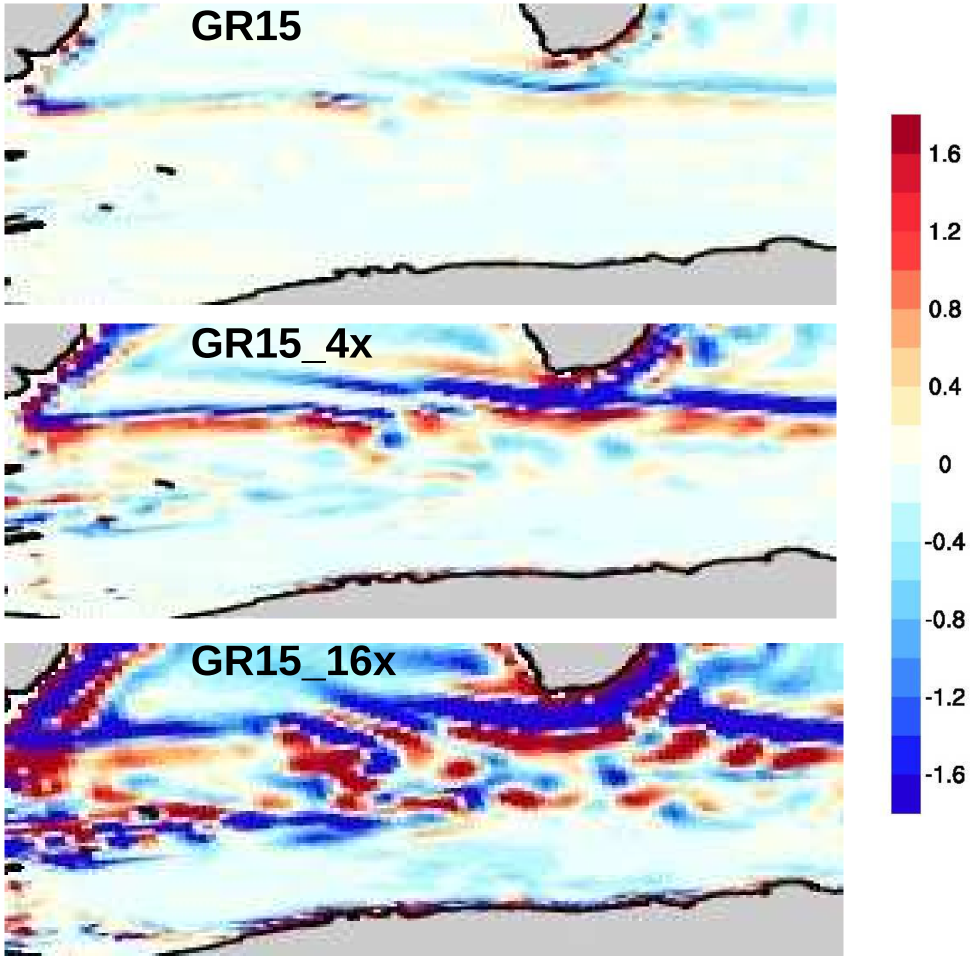
TP6M: e^{x}



- e_{GM} captures some of the desired effect in regions with strong mesoscale eddies, BUT…

Result: resolved and parameterized eddy forcing

e_{GM}



10^{-8} °Cs^{-1}

- e_{GM} reveals also unrealistic structures, resulting from erroneous representation of the density field, e.g. that related to the 'super gyre'
- Increasing κ_{GM} further enhances the erroneous part of e_{GM} related to the ‚super gyre'
- A fundamental weakness of GM: a low-res model with erroneous density distribution generally produces erroneous distribution of L, consequently an erroneous distribution of e_{GM} - a problem cannot be 'cured' using variable κ_{GM}

Conclusions

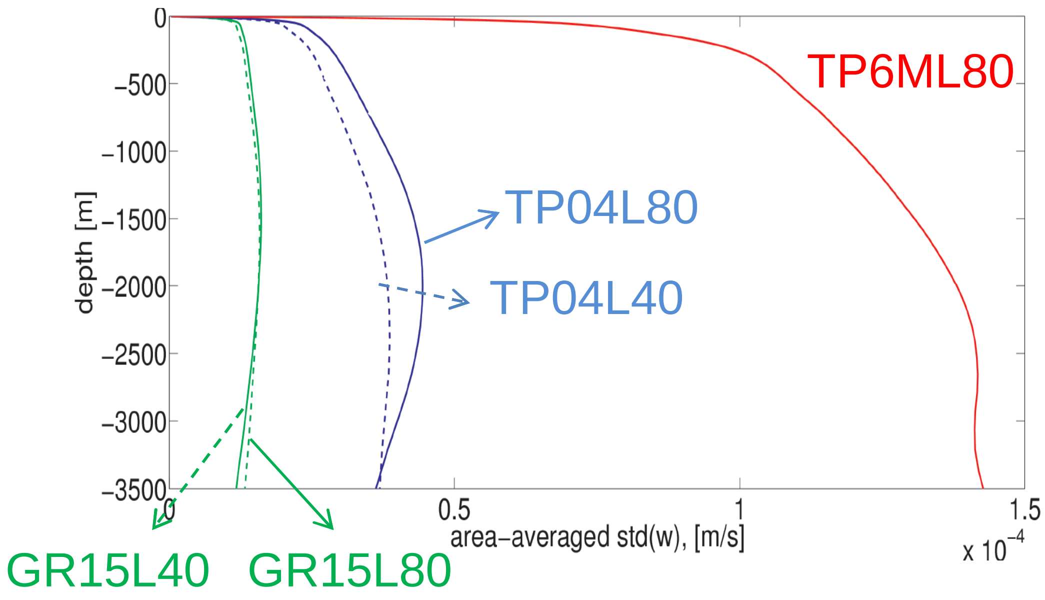
- The global vertical eddy fluxes transport heat and salinity upward with maximum values exceeding 1 PW/0.2 Sv down to 2000 m inTP6M, counteracting the downward transports of heat and salinity due to time-mean circulations. Vertical resolution can play an important role in achieving these large fluxes
- Global-mean divergence of these resolved eddy fluxes cools and freshens the water masses at the intermediate depths, thereby reducing the long-standing global T-/S- biases of the low-resolution MPIOM
- Redi isoneutral diffusion has little effect on the global mean T-/S- biases
- Increasing the thickness diffusivity κ_{GM} does not reduce the warm and saline biases in the same way the resolved eddies, likely due to a fundamental weakness of the GM: because of its direct link to the isopycnal slops, the parameterized eddy-induced transport does not always occur at places where they should

At least in MPIOM/TP6M, vertical eddy fluxes are essential for producing realistic vertical distribution of T and S. The effect of theses fluxes cannot be represented by increasing κ_{GM}

THANKS!

Result: vertical heat / salinity fluxes

- Compared with other 0.1-simualtions:
  - the same direction of eddy fluxes
  - but much larger magnitude:
    - near surface: 3PW in TP6M versus 1.6 PW in the POP run (Wolfe et al. 2008) and 2.1 PW in the GFDL-run (Griffies et al. 2015)
    - at 1000 m: 1 PW in TP6M, well below 0.5 PW in POP and GFDL run
- Likely due to the higher vertical resolution (80 in TP6M versus 40 in POP and 50 in GFDL)



- The area-averaged standard deviation of w suggests that increasing vertical resolution strengthens the w-variability

- MPIOML80 is numerically less stable than MPIOML40