

Ocean model utility and horizontal resolution: A Southern Ocean case study

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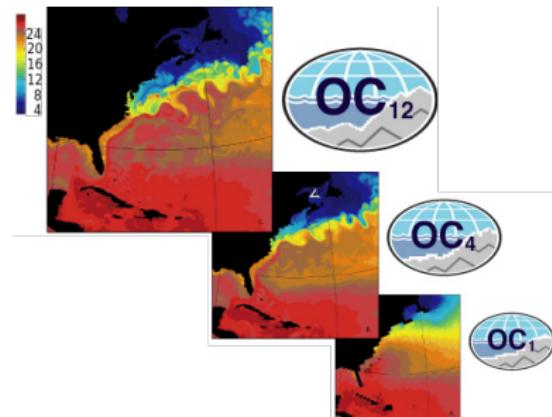
**National
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NATIONAL ENVIRONMENT RESEARCH COUNCIL



1st July 2016

Outline

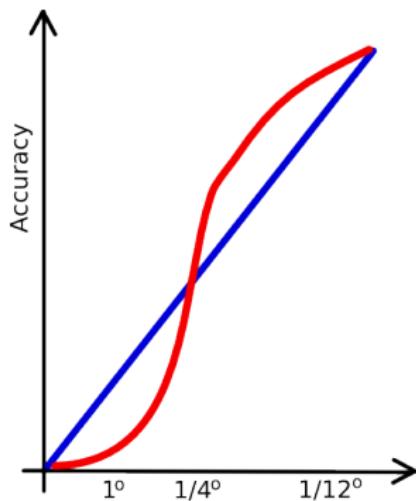
- 1 The model: NEMO
- 2 Surface: Mixed Layer Depth
- 3 Interior: Steric variability
- 4 Bottom: Bottom Pressure Torque
- 5 Utility



Systematic assessment of changes with ocean model resolution

Take home: Different resolutions suitable for different applications!

Motivation

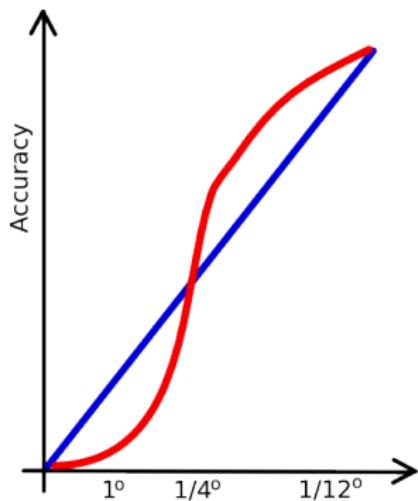


- Really big, hard, question!
- What resolution is “good enough”?
- IPCC -> Drive towards higher resolution. Is it worth it?
- Low resolution is faster, easier, cheaper...

Boundary layers key

Southern Ocean case studies: Mixed Layer Depth and bathymetry interactions

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Southern Ocean case studies: Mixed Layer Depth and bathymetry interactions

Nucleus of European Modelling of the Ocean: **NEMO** (Madec, 2008)



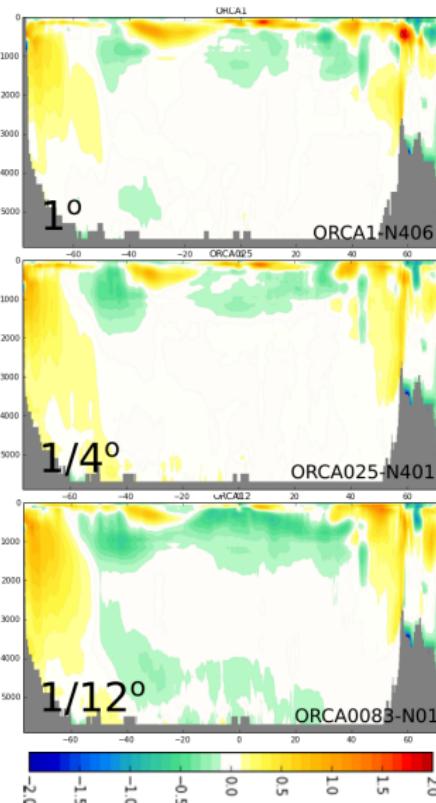
Suite of realistic GCM runs from 1978-2007
forced with DFS4.1 (Brodeau *et al.*, 2010)

What parameters change with resolution?

Name Resolution	ORCA1-N406 1°	ORCA025-N401 1/4°	ORCA0083-N01 1/12°
z, x, y	75,292,362	75,1021,1442	75,3059,4322
GM active	Yes	No	No
Horiz. laplacian eddy viscosity ($m^2 s^{-1}$)	10^4	500	500
Horiz. bilaplacian eddy viscosity ($m^4 s^{-1}$)	-1.25×10^{10}	-2.2×10^{11}	-2.2×10^{11}
Isopycnal eddy tracer diffusivity ($m^2 s^{-1}$)	10^3	300	125
Timestep (s)	3600	1440	200

Runs were designed by Andrew Coward and Beverly de Cuevas to be as comparable as feasible

Tools for comparing the model runs



- Changes compared to observations
- $\psi(z, y)$: Depth-latitude streamfunction
- EN3 bias ($^{\circ}\text{C}$) (Hyder *et al.*, In Prep.)
 - Do these changes “matter”?
 - When/where? Is cost **merited**?
- We use area averaged PDF

Introduction: Bathymetry interactions

- **Southern Ocean** zonal pressure/buoyancy gradients **not** balanced by topography
- Non-linear eddy terms become important
- Southern Ocean is key climatically

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Question:

How do balance of forces expressed through $J(p_b, H)$ change with resolution?

Introduction: Bathymetry interactions

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Question:

How do balance of forces expressed through $J(p_b, H)$ change with resolution?

Introduction: Bathymetry interactions

- Ocean heat fluxes important for **climate**
- Gyre circulation, geostrophic f/H contours:

vertical bottom vel.

$$\beta \psi_x = \underbrace{-fw_B}_{\text{wind stress}} + \underbrace{\nabla \times \tau}_{\text{wind stress}} + \underbrace{R'}_{\text{Non-lin terms}}$$

- Interactions with **bathymetry**:
- $$w_B = u_B \cdot \nabla(-H) = \frac{1}{\rho_0 f} J(p_B, -H)$$
- Bathymetry can profoundly influence model behaviour; **Horizontal resolution**

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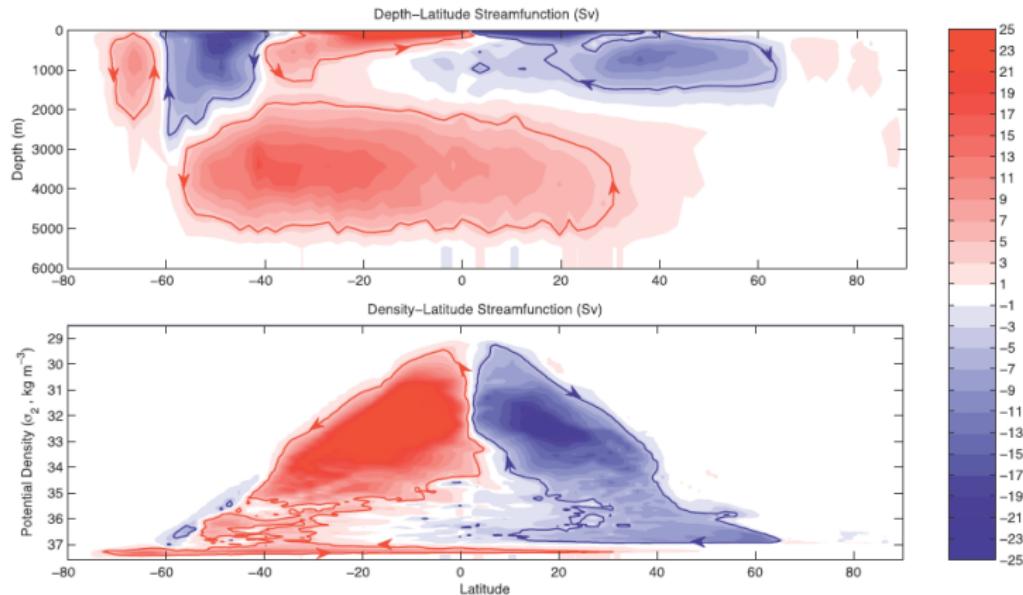
Marshall and Speer (2012)

Density-latitude streamfunction ($\psi(\sigma, y)$): Definition

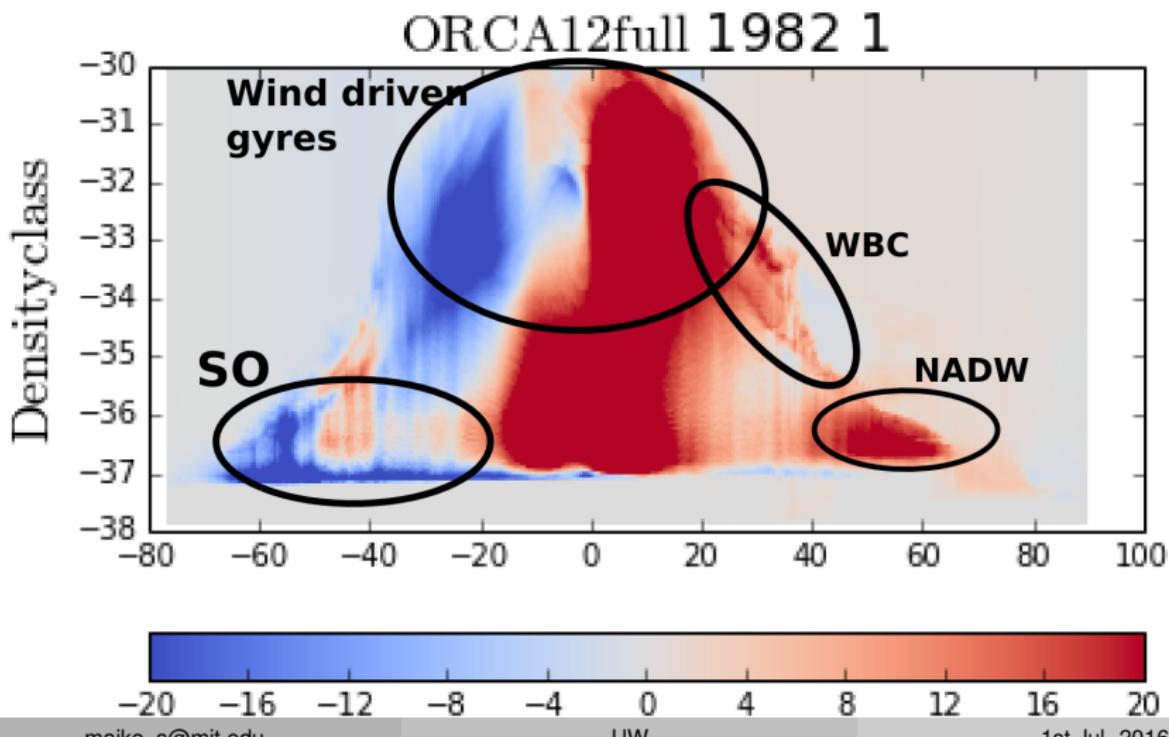
Illustrating the heat transport in the system:

Zika et al. (2012), Nurser and Lee (2004)

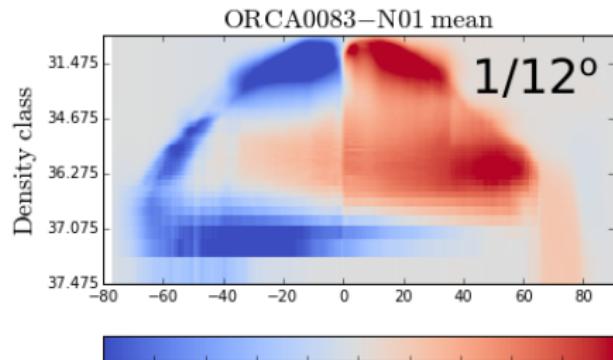
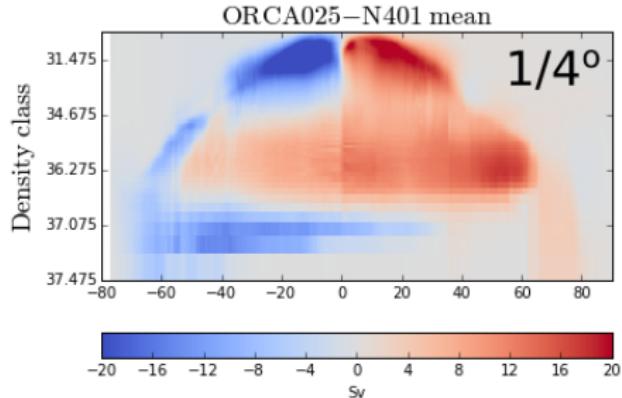
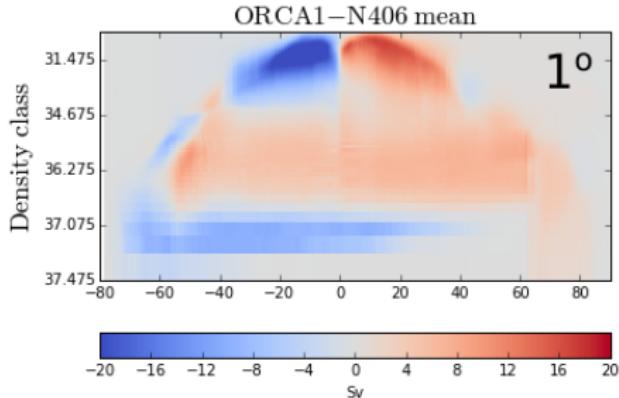
$$\psi(\sigma, y) = \int \int_{\sigma^* < \sigma} v(x, y, z) dz dx$$



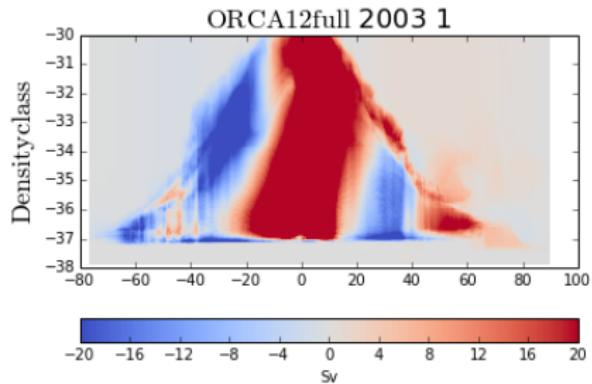
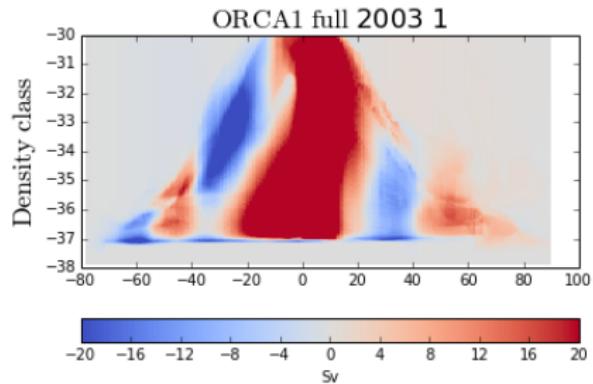
Density-latitude streamfunction ($\psi(\sigma, y)$): Interpretation



Density-latitude streamfunction ($\psi(\sigma, y)$): Mean 1978-2007

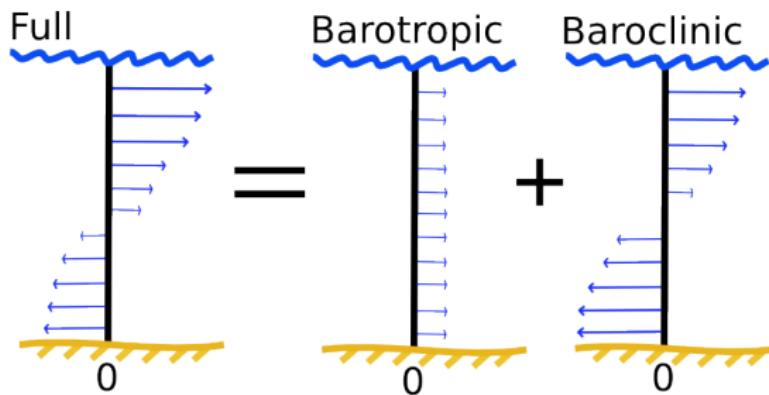


Density-latitude streamfunction ($\psi(\sigma, y)$): Transient

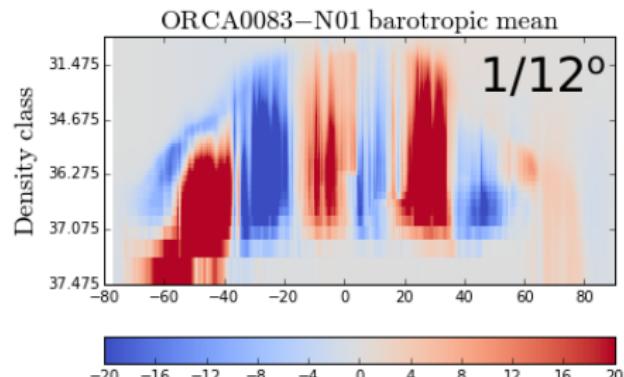
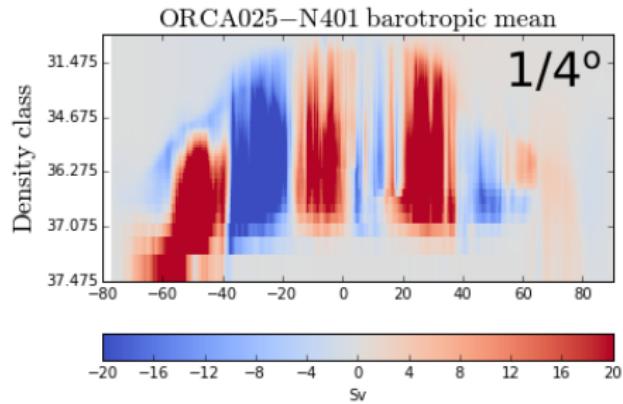
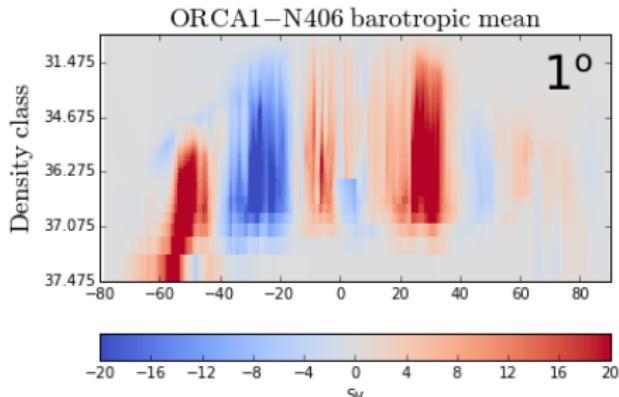


The barotropic ($\bar{\psi}$) and baroclinic (ψ') decomposition

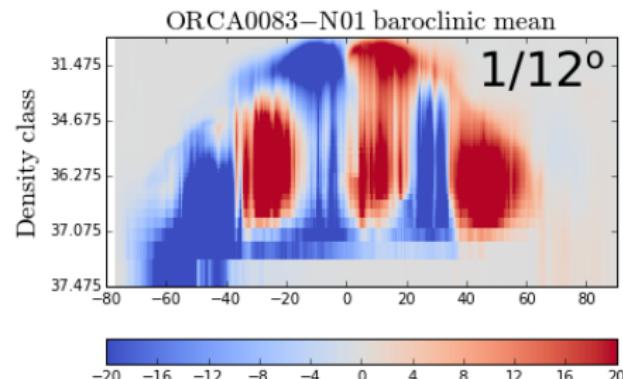
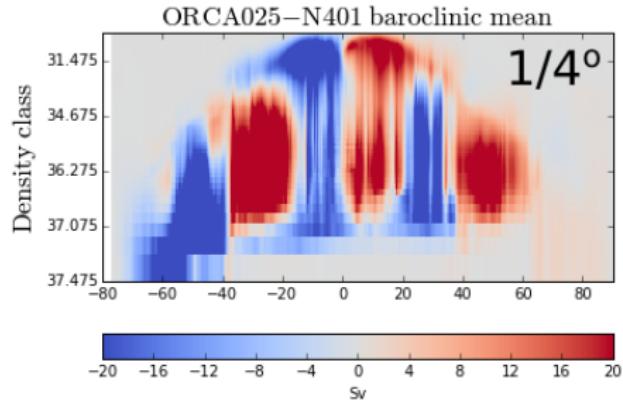
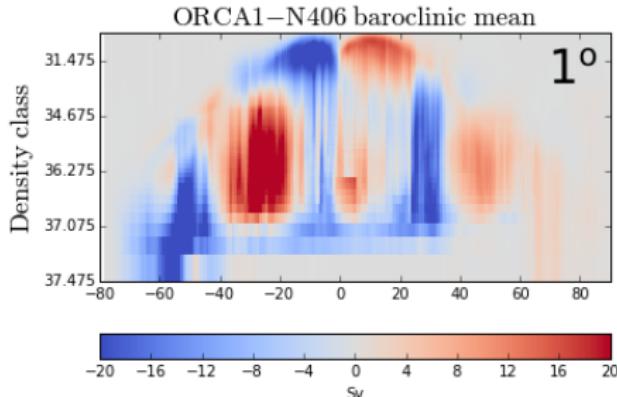
$$\psi_{\sigma y} = \bar{\psi}_{\sigma y} + \psi'_{\sigma y}$$



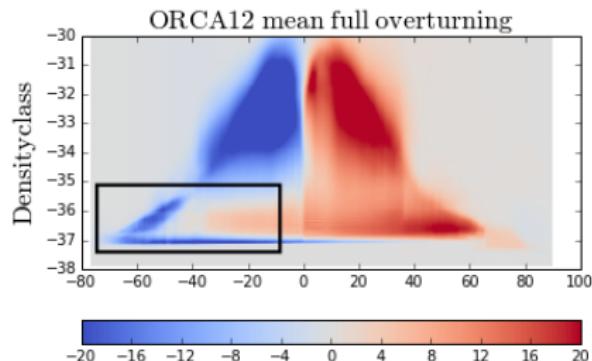
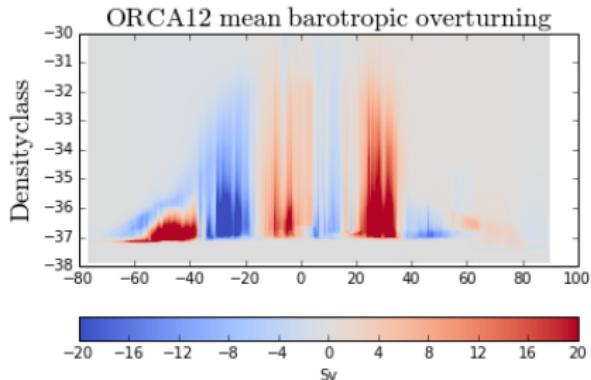
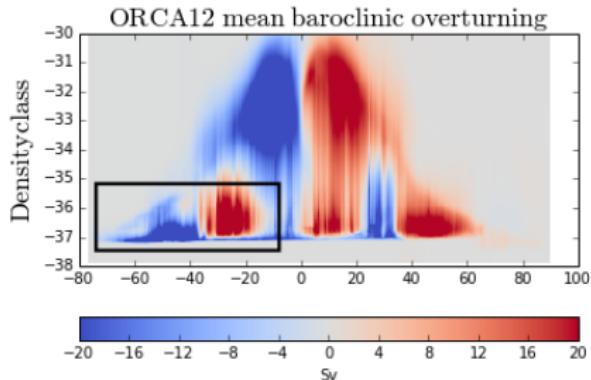
$\bar{\psi}(\sigma, y)$: Barotropic streamfunction



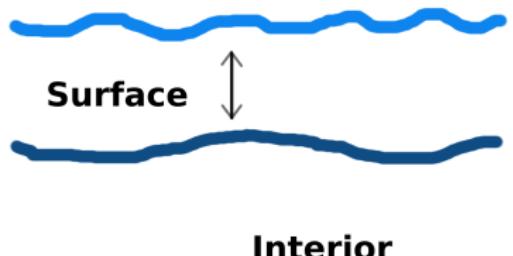
$\psi'(\sigma, y)$:Baroclinic streamfunction



1/12°: Eddy compensation? Farneti et al. (2010), Hallberg and Gnanadesikan (2006)



Where should we look for changes?



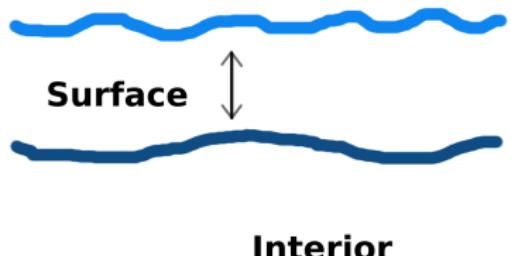
- ① Mixed Layer Depth
- ② Steric height
- ③ Bottom interactions



Depth-integrated momentum equation:

$$f\mathbf{k} \times \mathbf{U} + \nabla P = p_b \nabla H + \tau_w - \tau_b - \mathbf{R},$$

Where should we look for changes?



- ① Mixed Layer Depth
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Depth-integrated momentum equation:

$$f\mathbf{k} \times \mathbf{U} + \nabla P = p_b \nabla H + \tau_w - \tau_b - \mathbf{R},$$

The mixed layer: Schematic

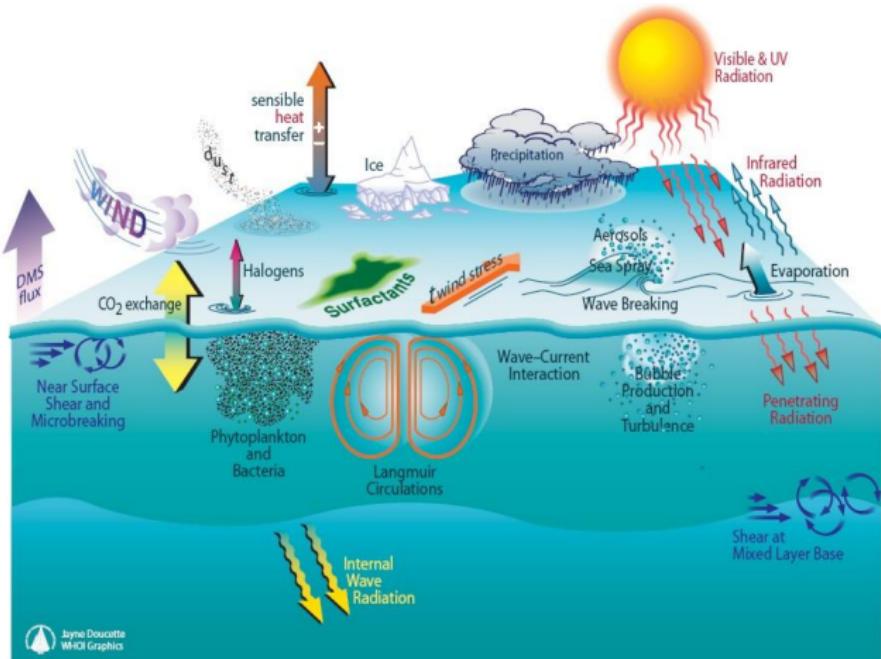
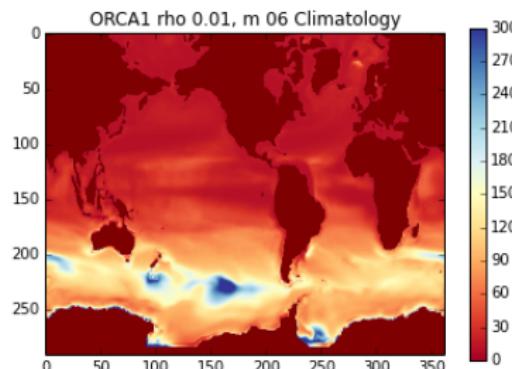
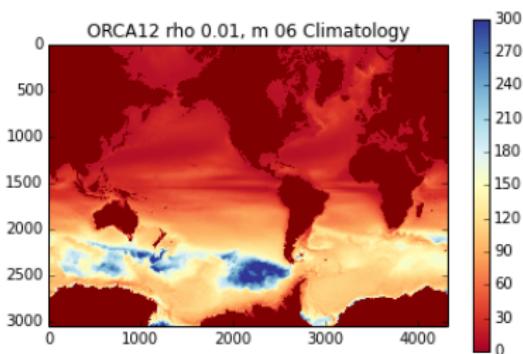


Image from: <http://www.ifremer.fr/cerweb/deboyer/mld/SurfaceMixedLayerDepth.php>

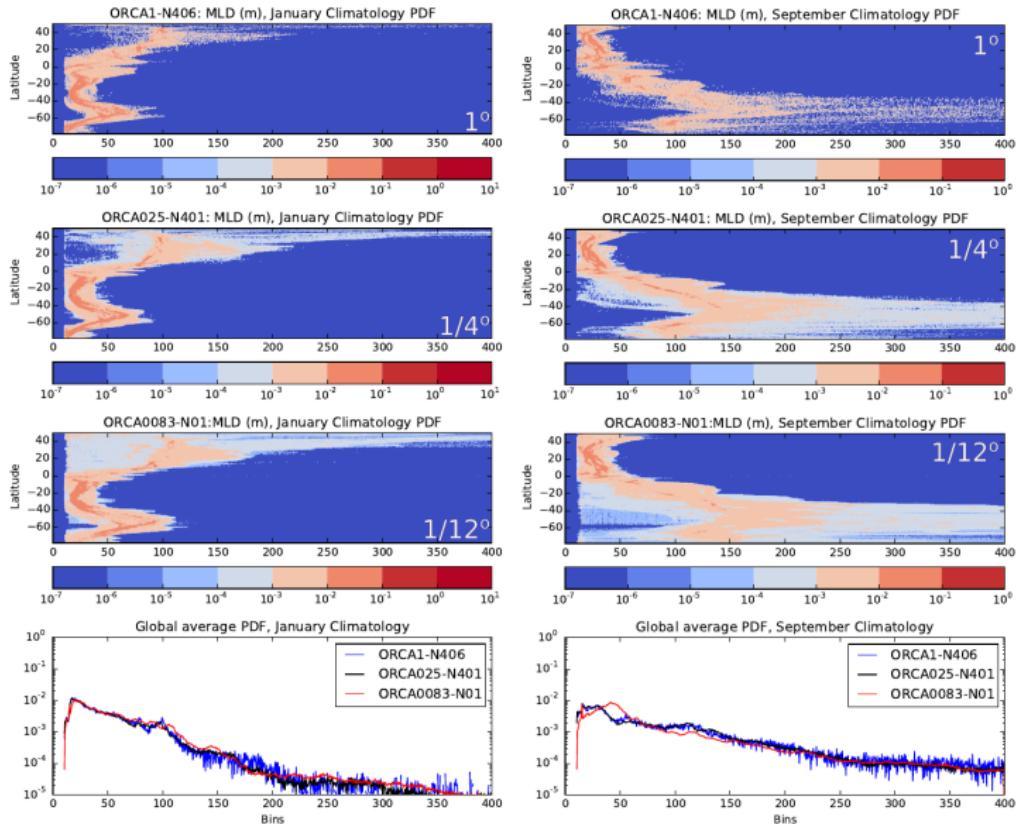
MLD (m) climatology movie, 1978-2007



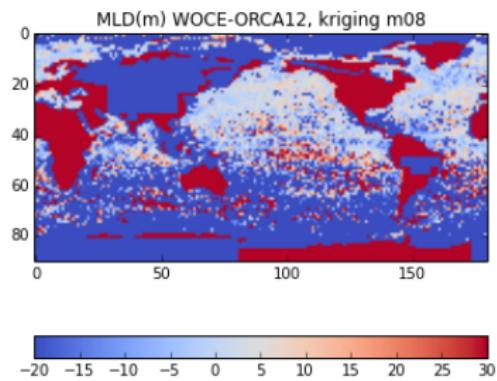
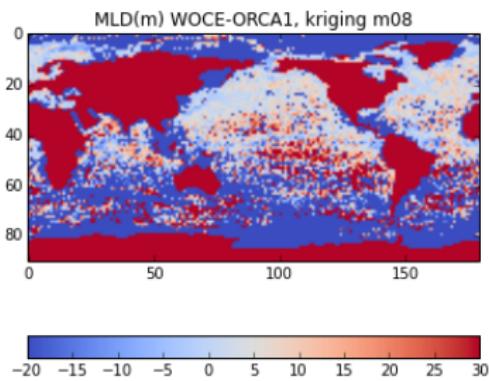
MLD criterion

$$\Delta\rho = 0.03\text{kgm}^{-3}, \Delta\rho = |\rho_s - \rho_d|$$

January and September MLD PDFs



Bias: de Boyer Montégut *et al.*, 2004 - NEMO



Surface: Summary

- No significant change in MLD observed
- Compares well with observed MLD

Likely not a place the runs differ greatly in terms of energy pathways

- This and case study of Southern Ocean zonal asymmetry:
Sonnewald, M., Ferrari, R. and Nurser, A.G., In prep.
- Now on to the interior...

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Steric changes

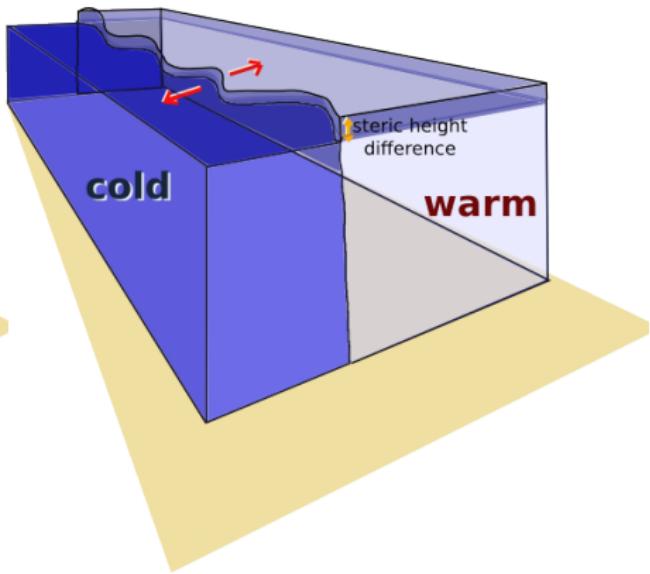
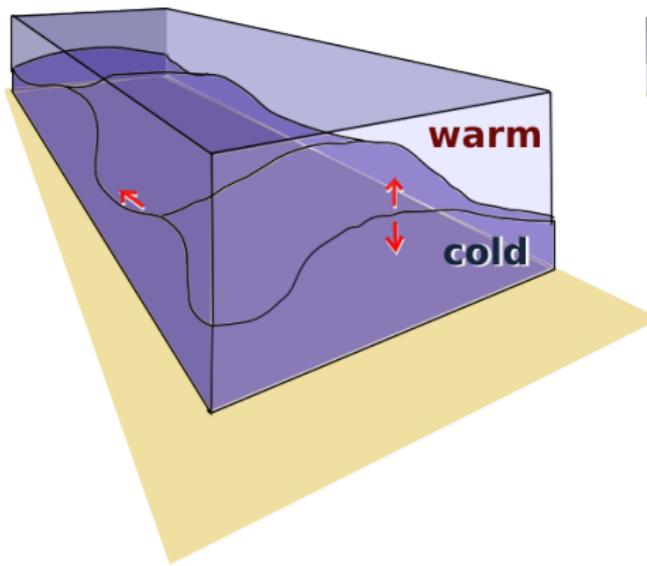
$$\eta = \frac{1}{\rho_0 g} (p_b - p_a) + SH$$

$$p_B = \int_{-H}^0 \rho g dz$$

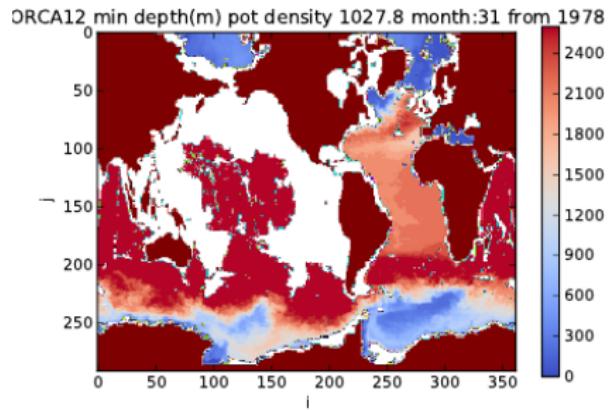
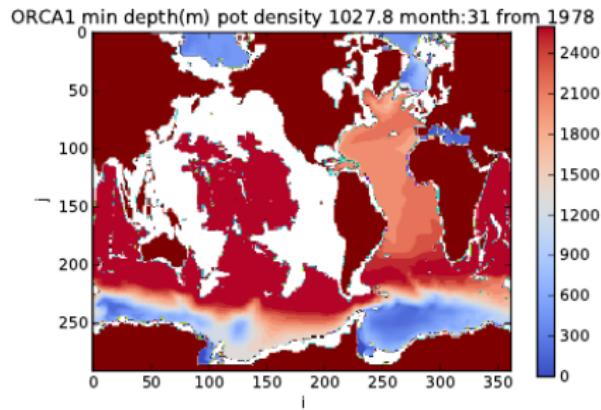
$$SH = -\frac{1}{\rho_0} \int_{-H}^0 \rho z$$

Steric variability

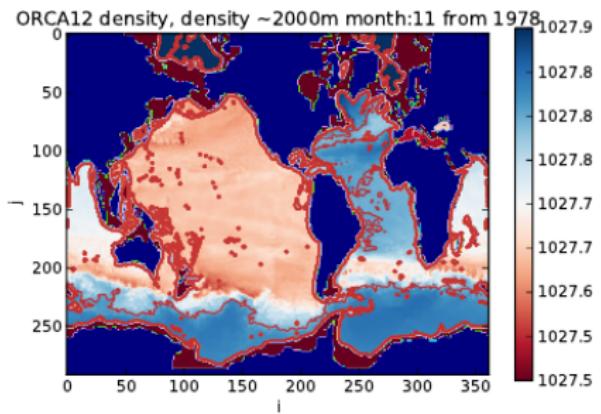
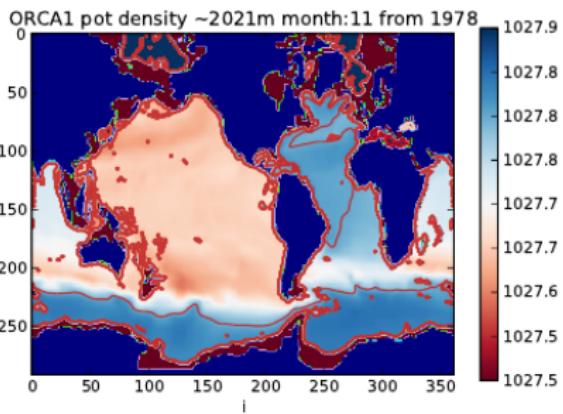
$$SH = \int_{-H}^0 \frac{\rho_0 - \rho}{\rho_0} dz$$



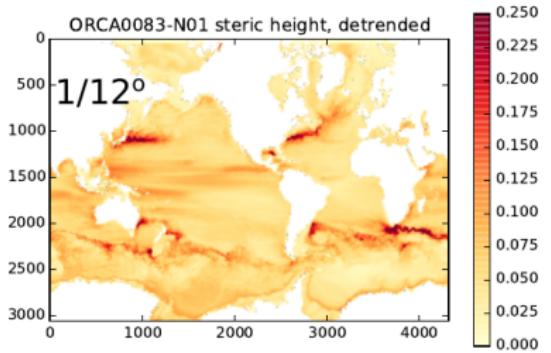
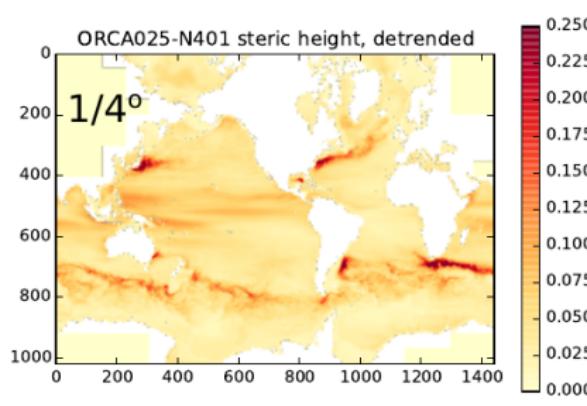
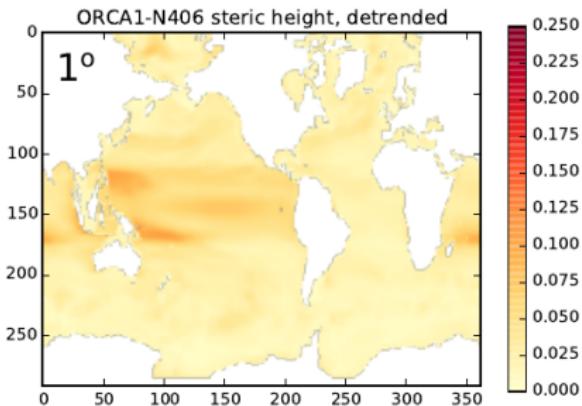
Heaving: What is the deep water water doing?



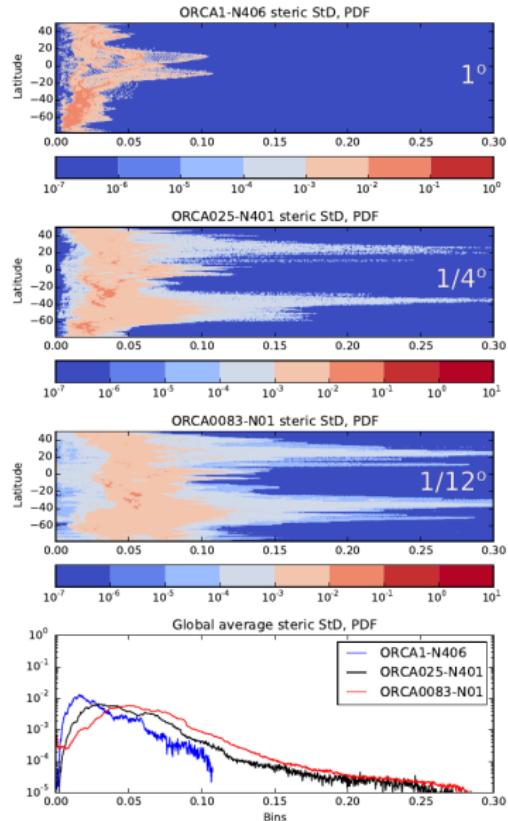
Meandering: What's happening in ρ at 2000m?



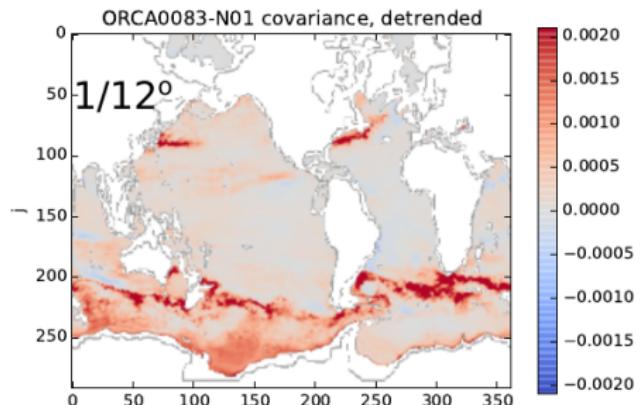
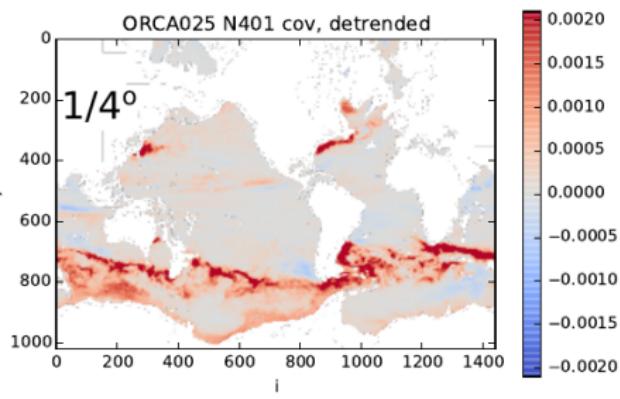
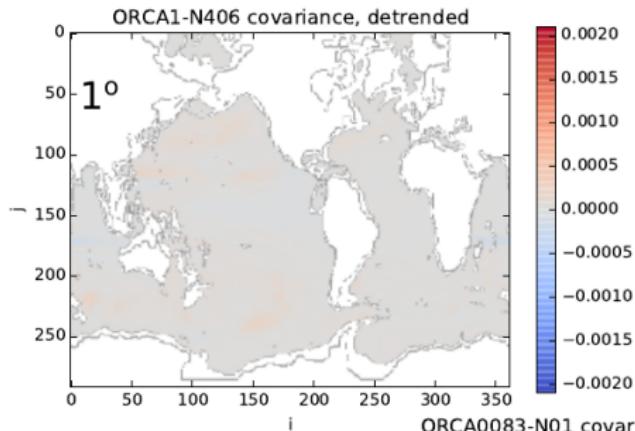
Steric variability



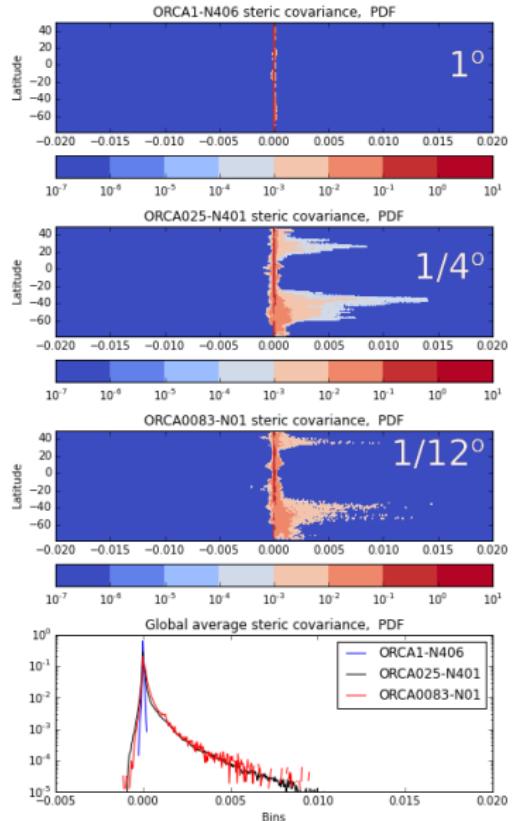
Steric variability PDF



Steric covariance



Steric covariance PDF



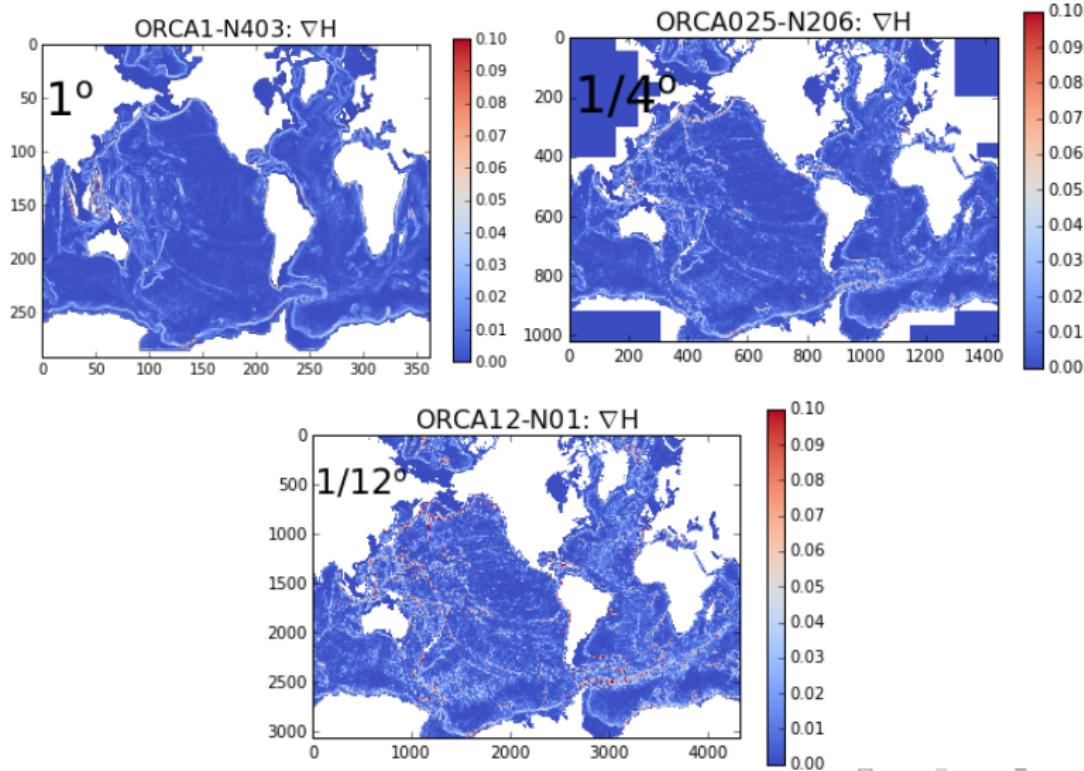
Interior: Summary

- Increase in surface<->deep covariance indicates allowing eddy-features changes information exchanges
- At 1° any covariance is confined to low temporal frequencies
- Inviscid assumption:
 - Our work does not assess the role of the interior explicitly, but suggests that the adjustment to surface fields could be affected...
- On to the interactions with topography...

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∇H : Bathymetry roughness



Bathymetry interactions:

Change in the balance of forces?

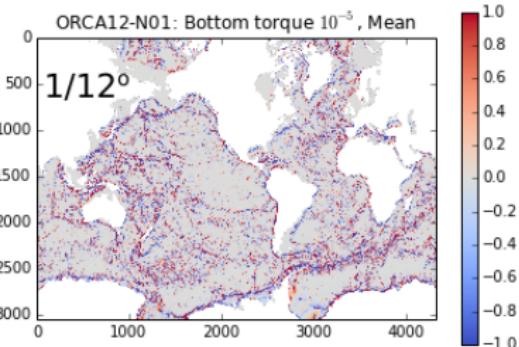
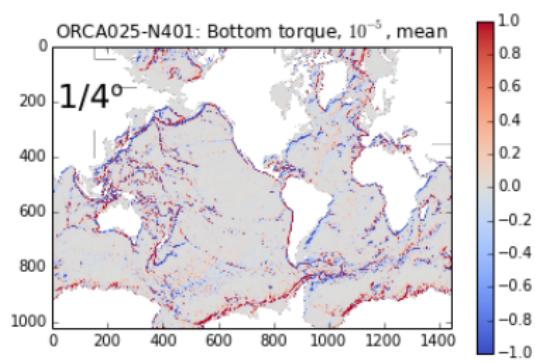
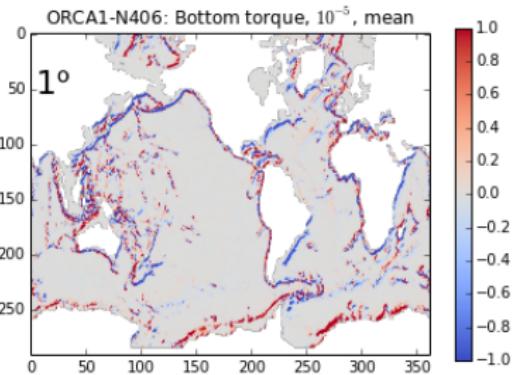
Conserving PV, wind driven gyre sees vorticity innput balanced by flow over f/H contours:

$$\beta\psi_x = \underbrace{-fw_B}_{\text{bottom velocity}} + \underbrace{\nabla \times \tau}_{\text{wind stress}} + \underbrace{R'}_{\text{Non-lin terms}}$$

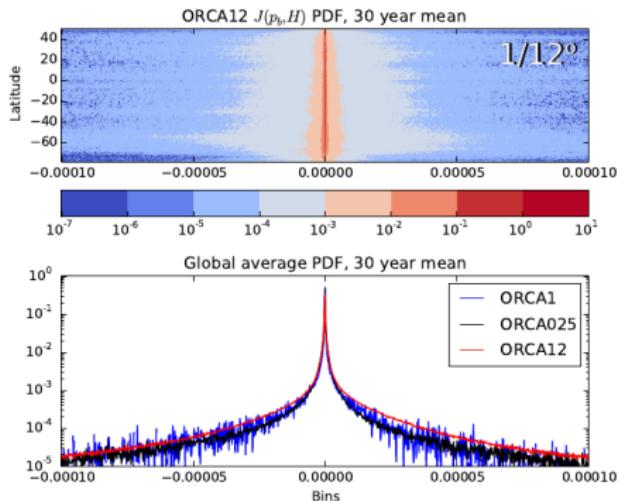
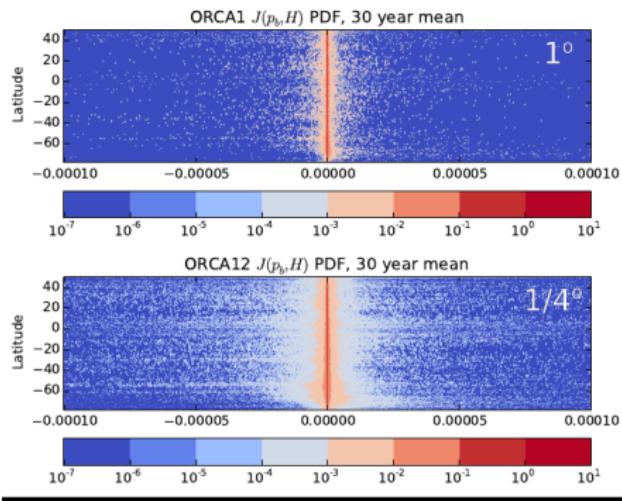
The link between H and vortex stretching:

$$w_B = u_B \cdot \nabla(H) \approx \frac{1}{\rho_0 f} J(p_B, H)$$

Bottom pressure torque ($J(p_B, H)$)



$J(p_B, H)$ PDF



Baroclinic contribution to bathymetry interaction: JEBAR

$J(p_B, H)$ does not seem to account for the change in ψ ?

$$\frac{1}{\rho_0} J(p_B, H) = f \mathbf{v}_{gb} \cdot \nabla H = \overbrace{H(JEBAR)}^{\text{Baroclinic}} + \overbrace{f \bar{\mathbf{v}}_g \cdot \nabla H}^{\text{Barotropic}}$$

Mertz and Wright (1992)

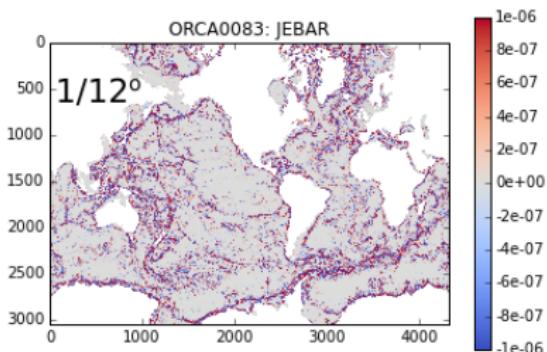
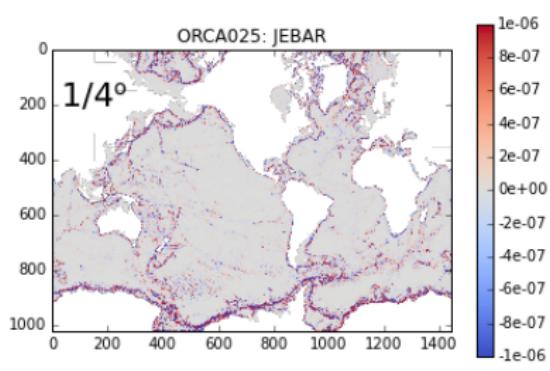
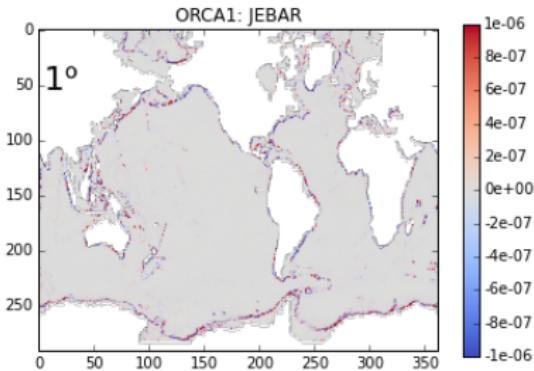
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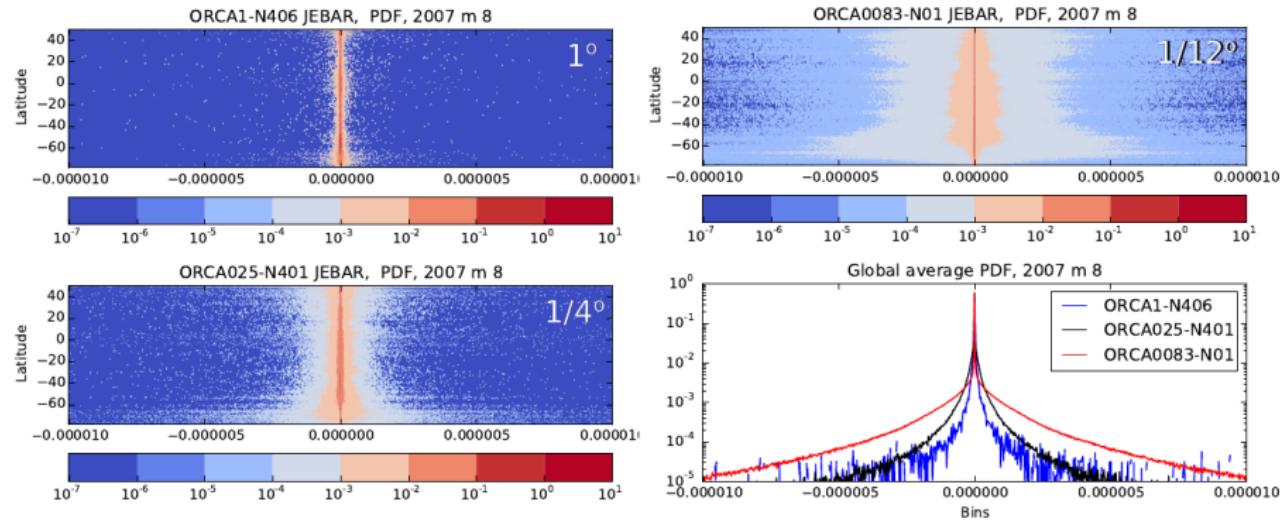
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Mertz and Wright (1992)

Baroclinic bathymetry interaction: JEBAR

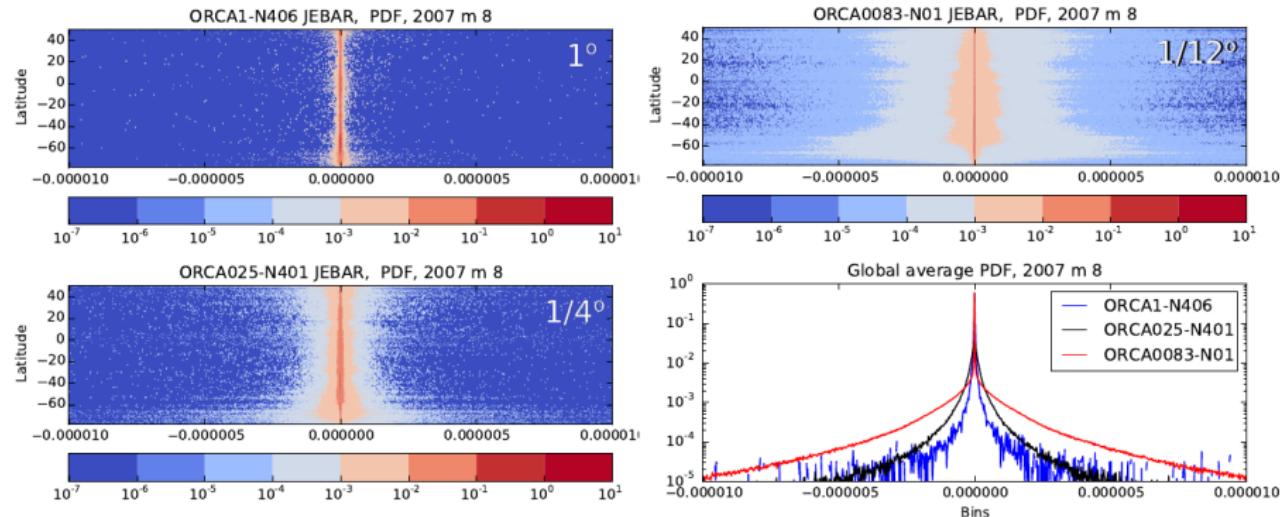


Baroclinic bathymetry interaction: JEBAR PDF



We see a large change in the distribution with resolution

Baroclinic bathymetry interaction: JEBAR PDF



We see a large change in the distribution with resolution

Summary: topography

- Stronger baroclinic contribution to overturning with resolution
- This happens mainly through changes in bathymetry interactions: JEBar
- Scotia ridge and Kuroshio case studies and further details: Sonnewald, M., Nurser, A.G. and Hirschi, J.J.-M. In Prep.

Change in energy dissipation happens baroclinically at depth

- Summarise our results for NEMO in terms of their “utility”

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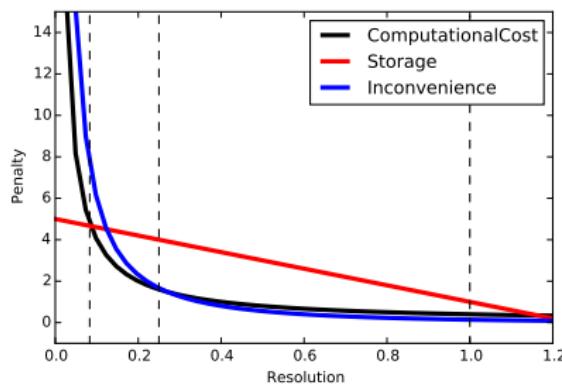
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Tools for comparing the model runs: Utility

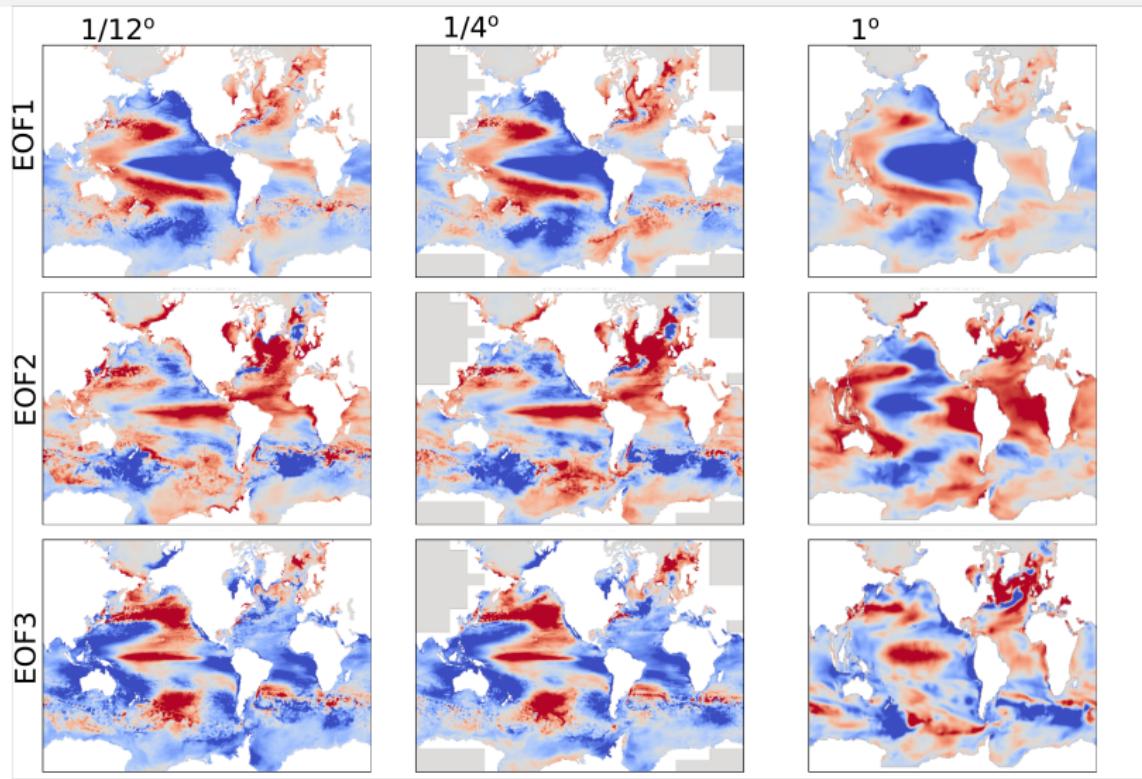
We explore “utility” using notional functions:

- Accuracy (A): $A = 100 - |\sigma_{EOFbaseline} - \sigma_{EOFmodel}|^c$
- Analysis inconvenience (I): $In = -0.2x^{-1} \ln\left(\frac{2}{x}\right)$
- Storage space (S): $S = -4x + 5$
- Computational cost (C): $C = -0.4x^{-1}$

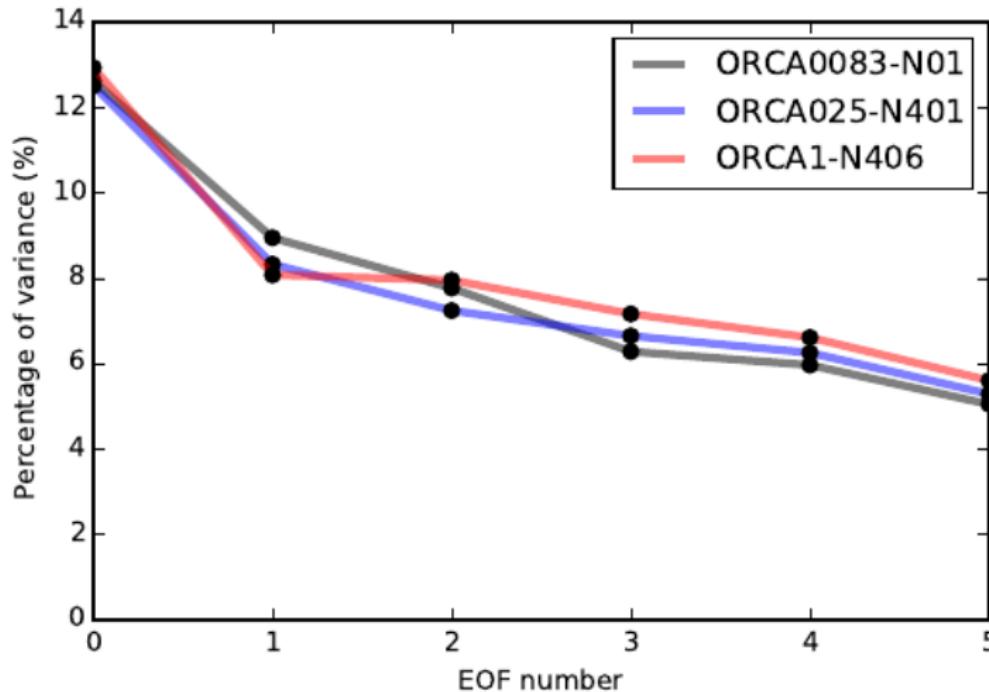
$$\text{Utility} = A + (In + C + S) I$$



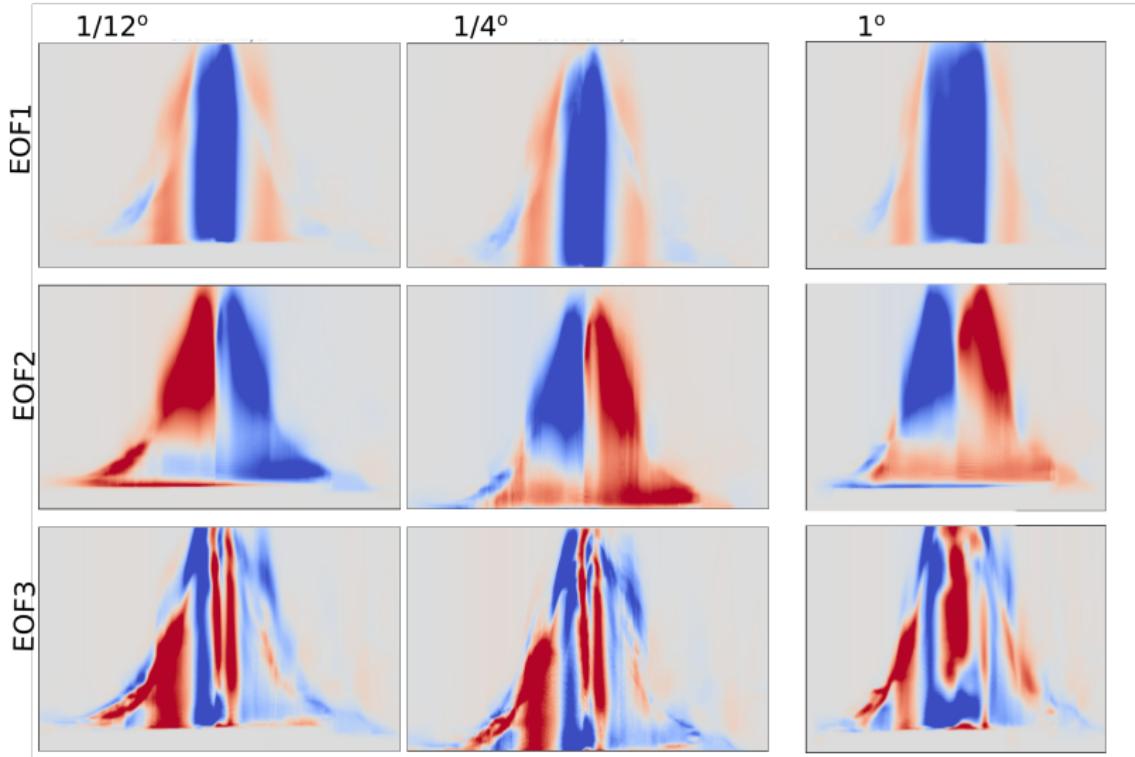
Utility: SST



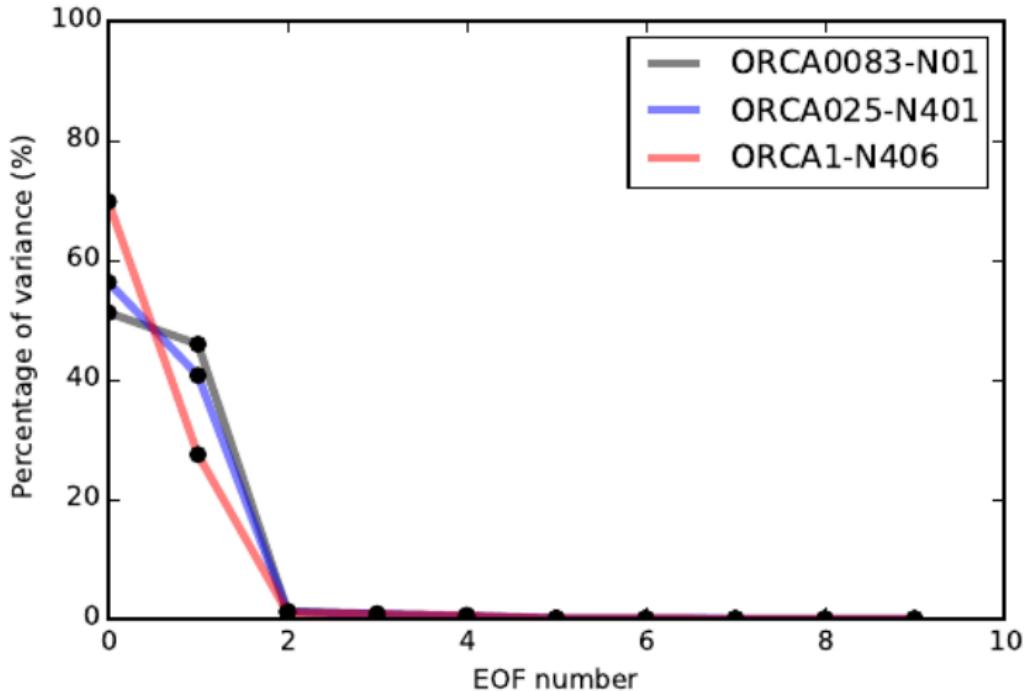
Utility: SST

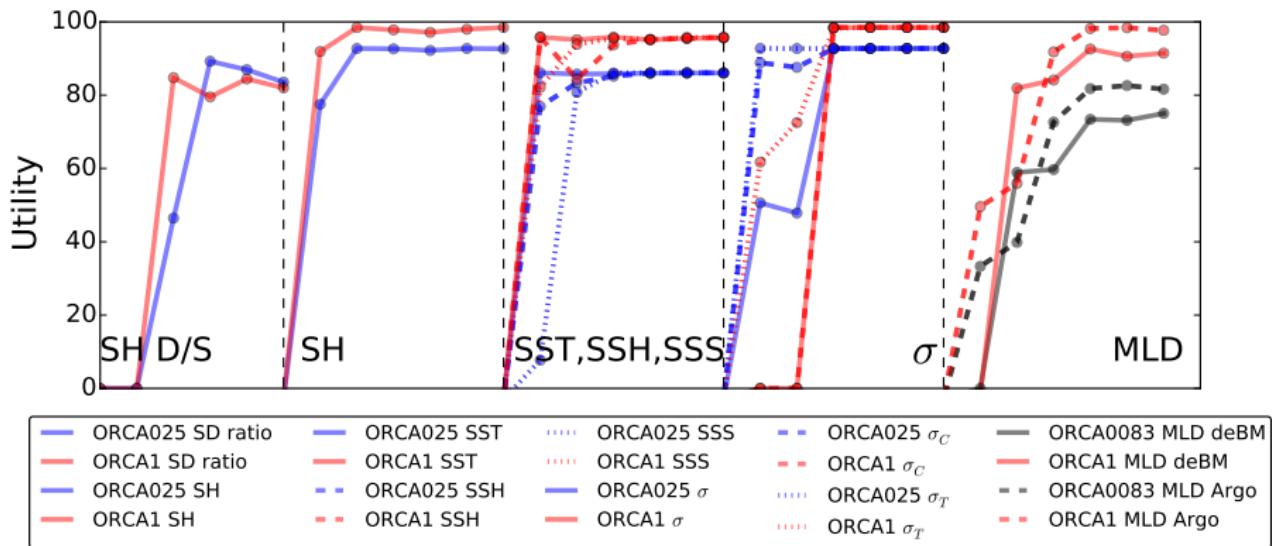


Utility: $\psi(\sigma, y)$



Utility: $\psi(\sigma, y)$





Conclusion and further work

- The changes in utility in NEMO highlight that certain fields are well captured even at low resolution (MLD) while others require higher resolution.
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Selected references:

- Brodeau, L., Barnier, B., Treguier, A.M., Penduff, T. and Gulev, S.: An ERA40-based atmospheric forcing for global ocean circulation models, *Ocean Modelling*, 31 (3-4), 88-104, 2010.
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- Jackson, L., Hughes, C.W. and Williams, R.G.: Topographic Control of Basin and Channel Flows: The Role of Bottom Pressure Torques and Friction, *J. Phys. Oceanogr.*, 36, 1786-1805. doi: <http://dx.doi.org/10.1175/JPO2936.1>, 2006.
- Hughes, C.W.; de Cuevas, B.A.. 2001 Why western boundary currents in realistic oceans are inviscid: a link between form stress and bottom pressure torques. *Journal of Physical Oceanography*, 31 (10). 2871-2885. doi: [http://dx.doi.org/10.1175/1520-0485\(2001\)031<2871:WWBCIR>2.0.CO;2](http://dx.doi.org/10.1175/1520-0485(2001)031<2871:WWBCIR>2.0.CO;2)
- Yeager, S. 2015: Topographic coupling of the Atlantic overturning and gyre circulations. *J. Phys. Oceanogr.*, 45, 1258-1284. doi: <http://dx.doi.org/10.1175/JPO-D-14-0100.1>

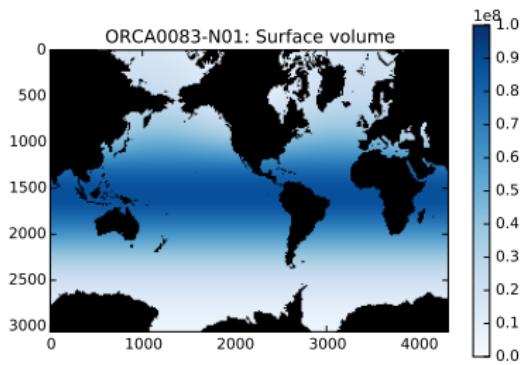
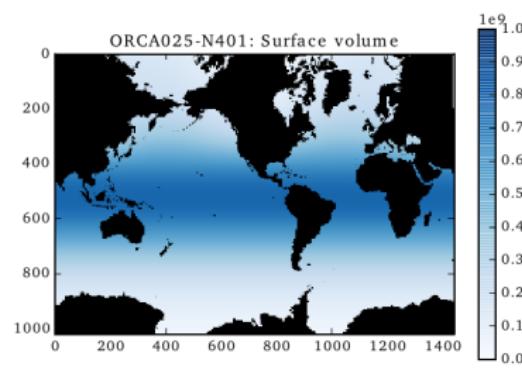
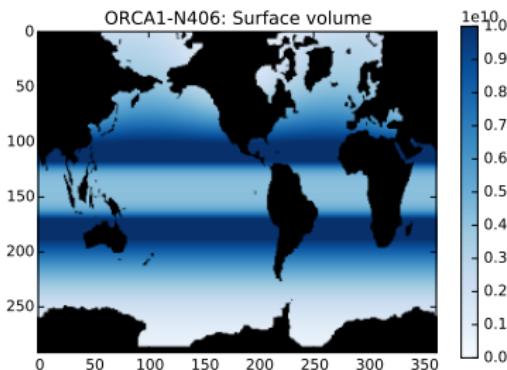
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Selected references:

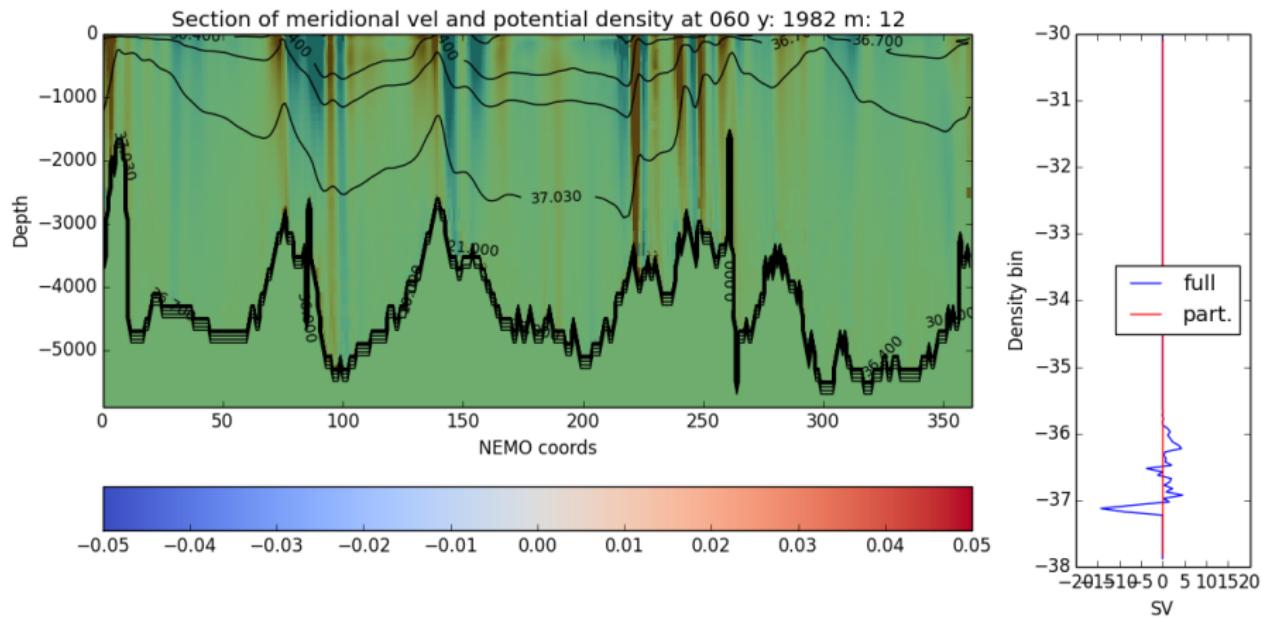
- Brodeau, L., Barnier, B., Treguier, A.M., Penduff, T. and Gulev, S.: An ERA40-based atmospheric forcing for global ocean circulation models, *Ocean Modelling*, 31 (3-4), 88-104, 2010.
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Thank you!

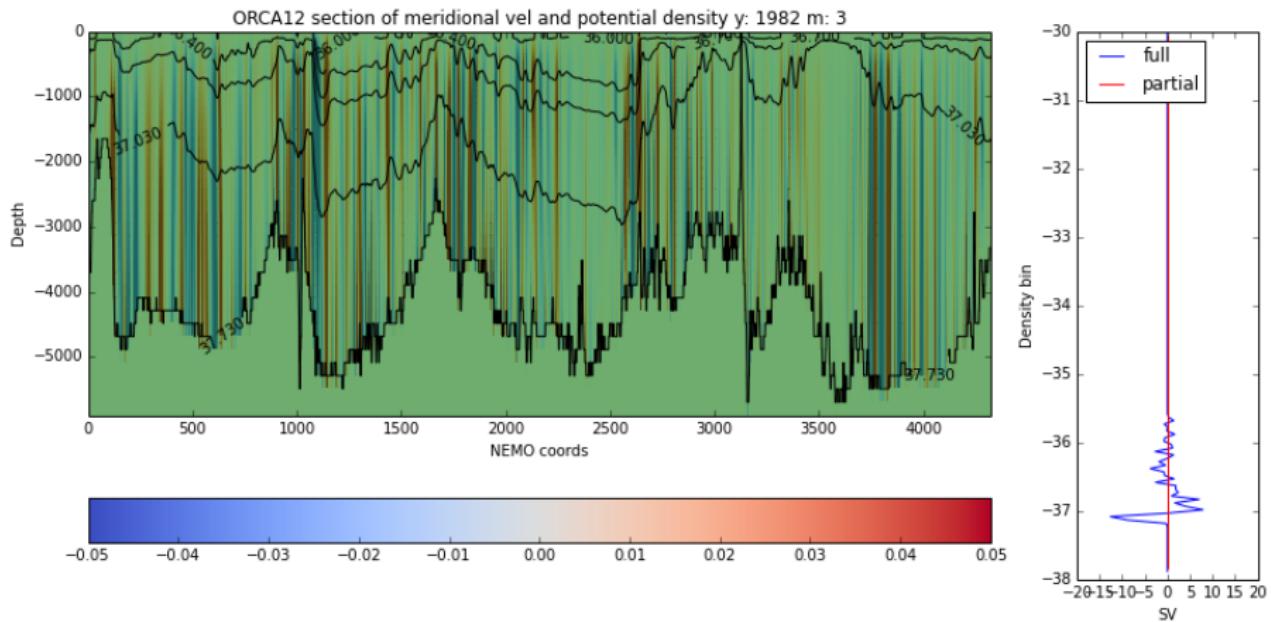
Model grid: Surface volume (m^3)



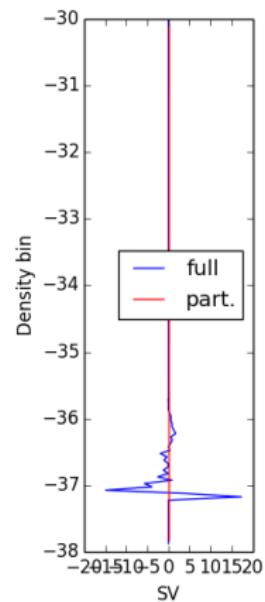
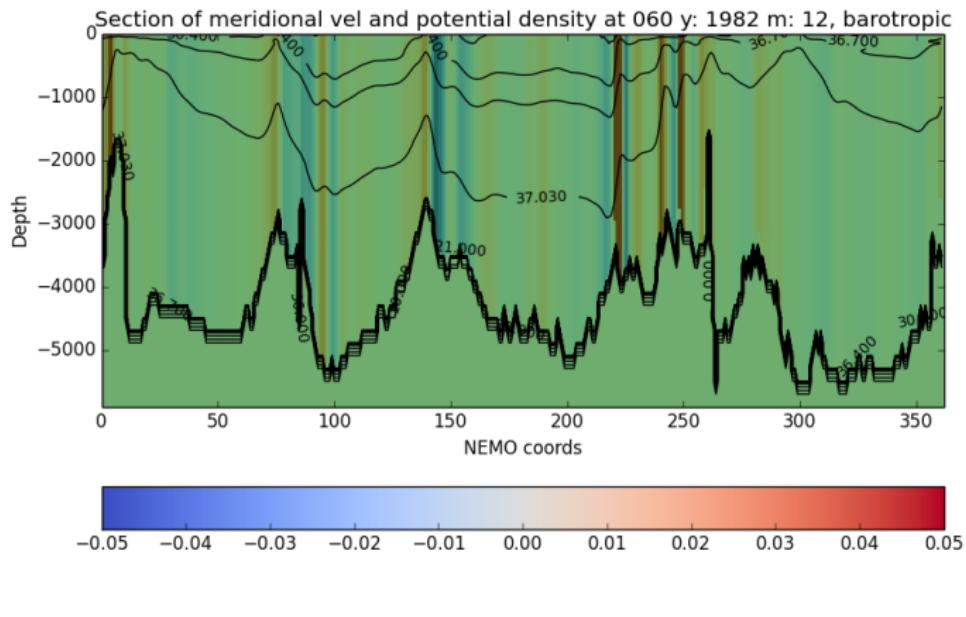
Cumulative density transport 57S: ORCA1



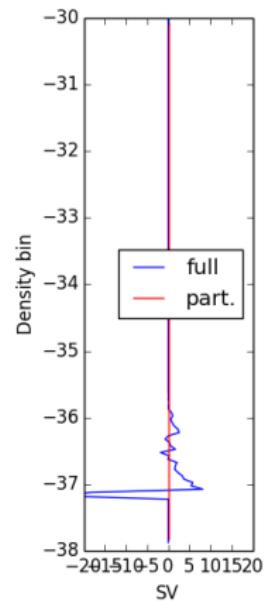
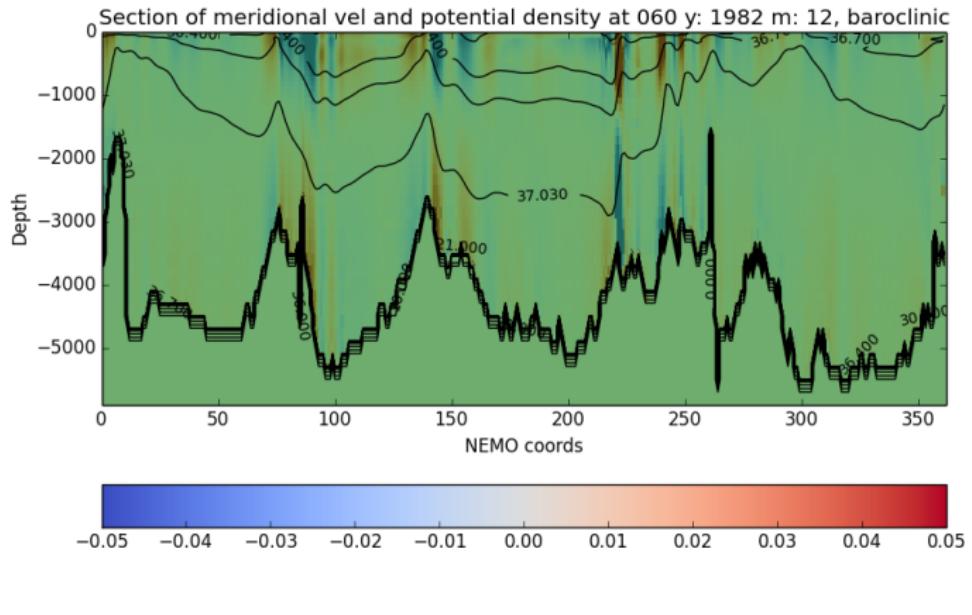
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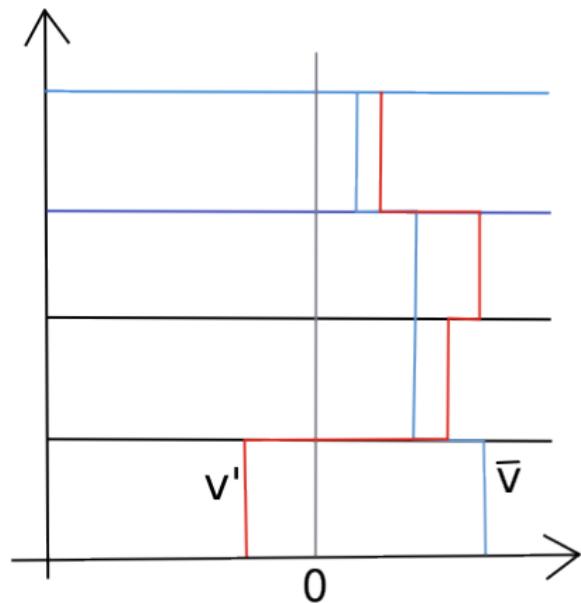
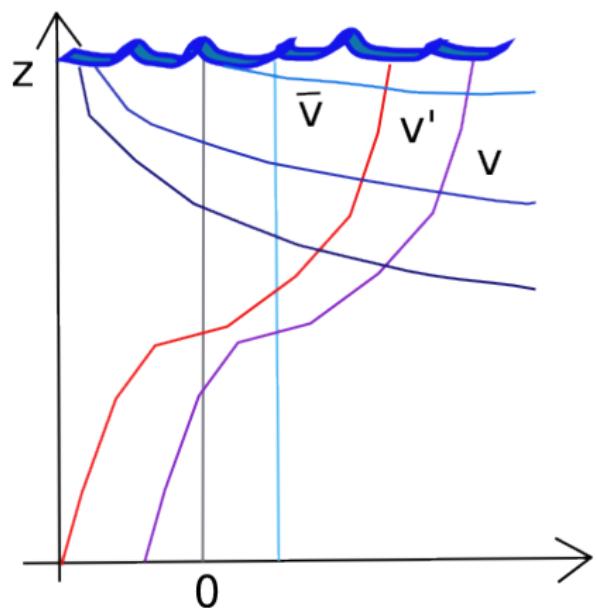
Cumulative density transport 57S: ORCA1 barotropic



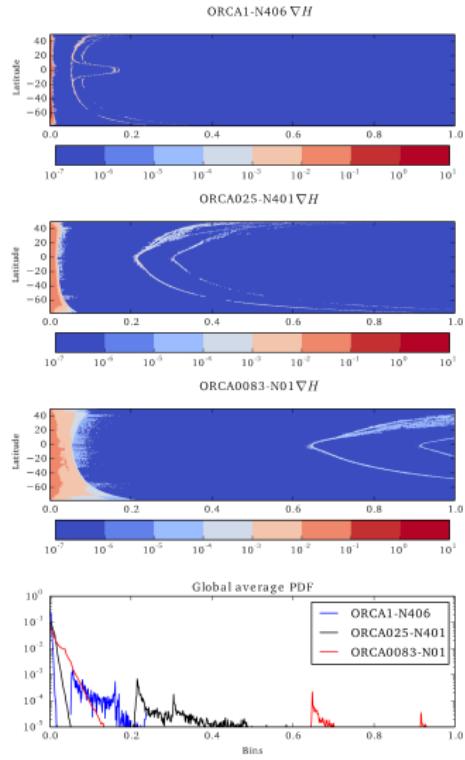
Cumulative density transport 57S: ORCA1 baroclinic

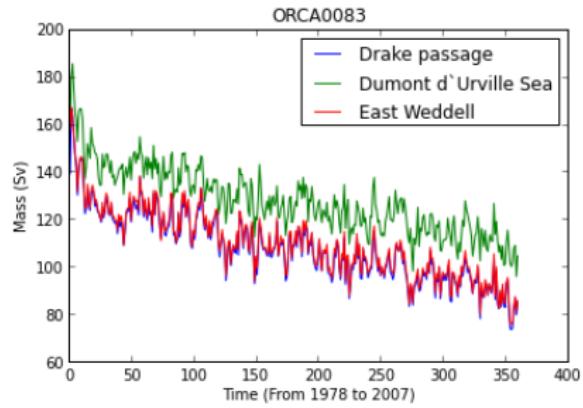
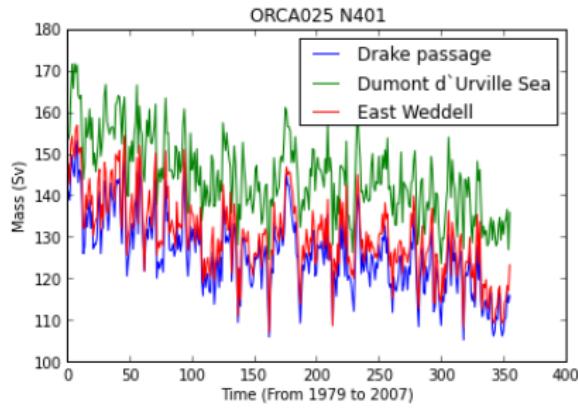
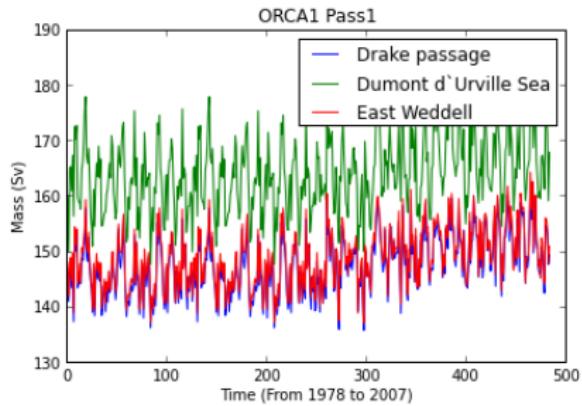


How do we interpret this...?

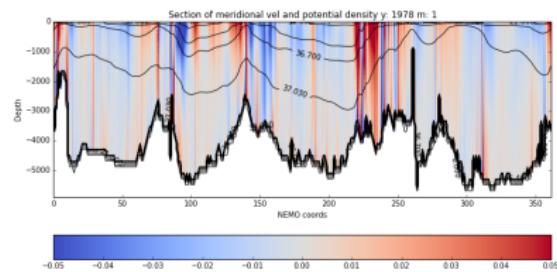
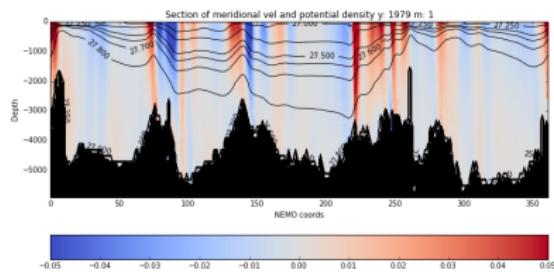


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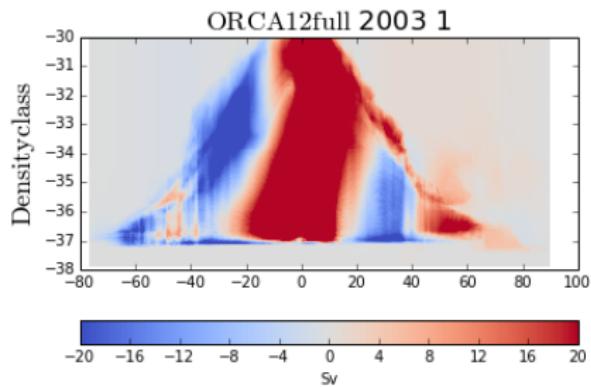
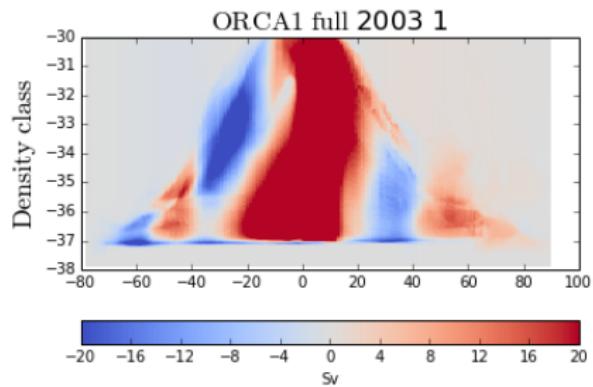




Transport section



OVERTURNING: Density space



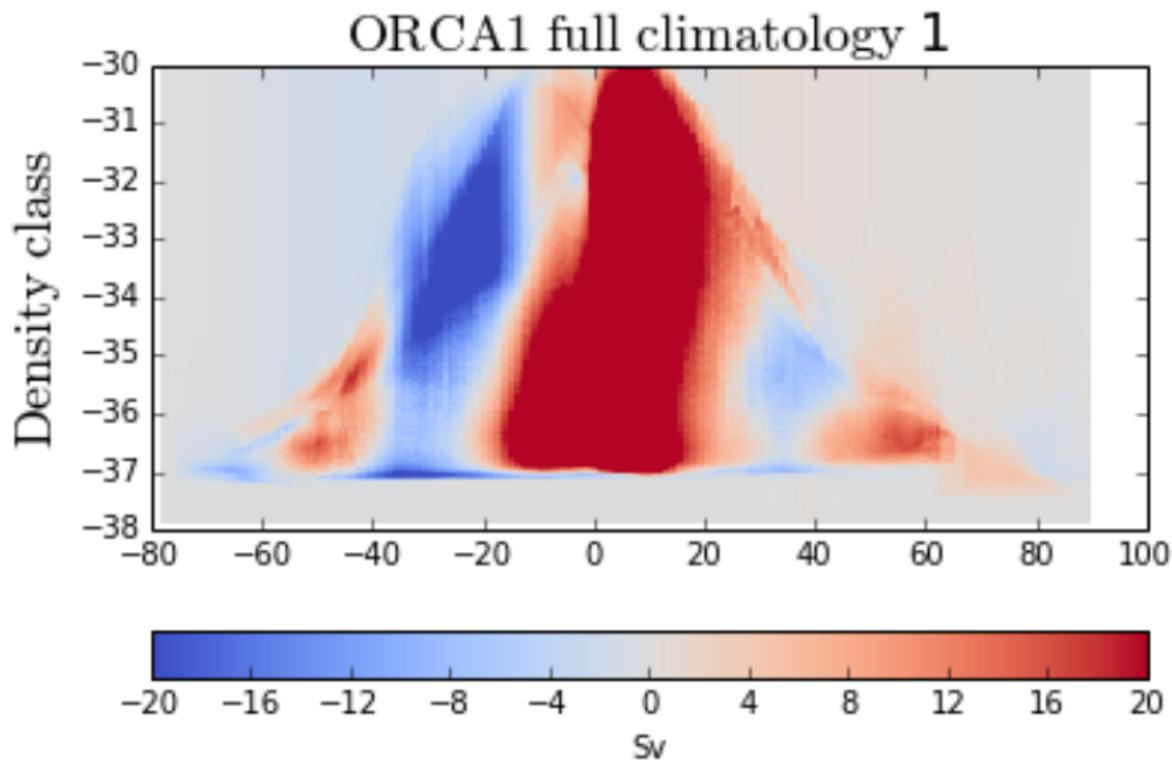
Density space overturning: Baroclinic

mergedmocsigORCA12_baroc_300.png

Density space overturning: Barotropic

mergedmocsigORCA12_barot_300.png

ORCA1-N406: Climatology 1978-2007



ORCA025-N401: Climatology 1978-2007

