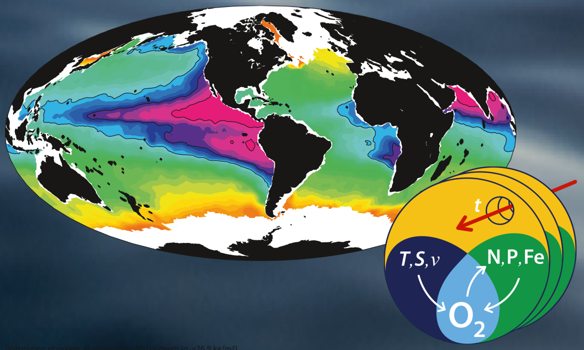
PIRATA 23, Marseilles
October 23, 2018



SFB 754

Ventilation of the eastern tropical North Atlantic oxygen minimum zone by latitudinally alternating zonal jets in a shallow water model

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HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

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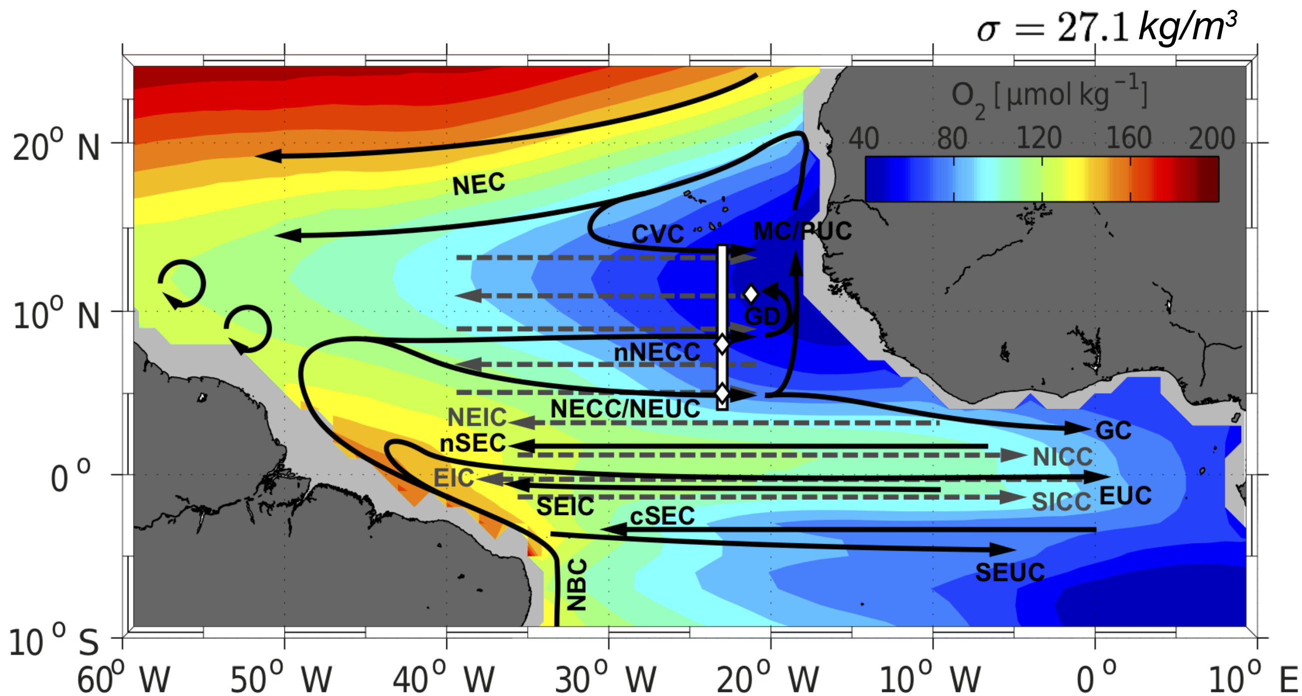
The oxygen minimum zone (OMZ) in the eastern tropical North Atlantic (ETNA)



Hahn et al. (2017), OS

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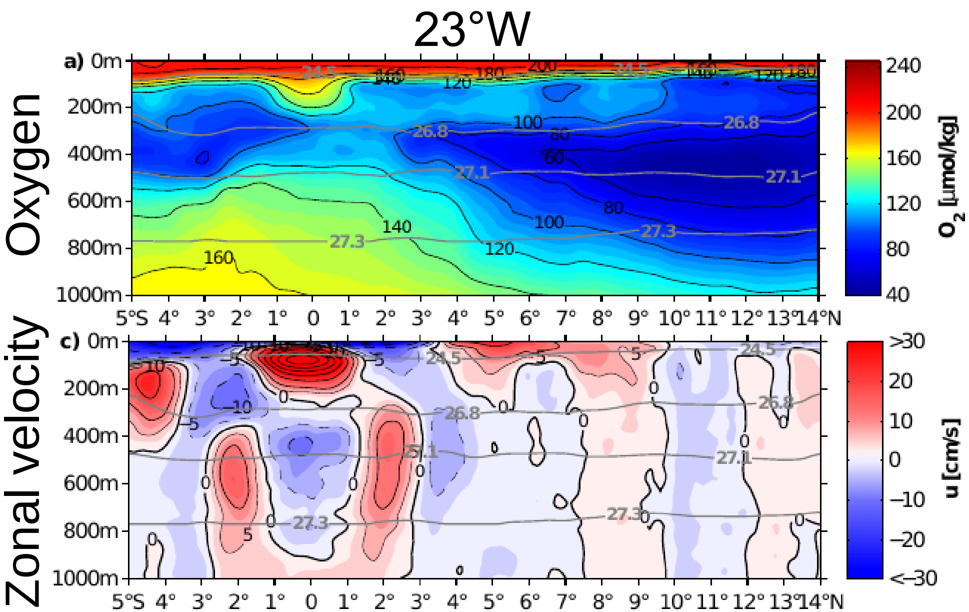
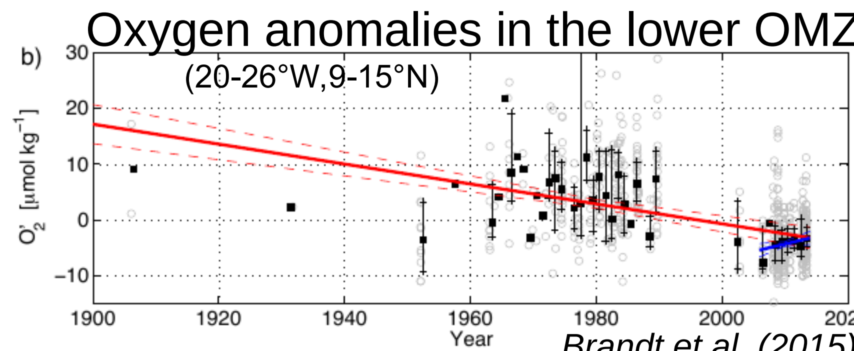
Ventilation of the ETNA OMZ by latitudinally alternating zonal jets (LAZJs)



Brandt et al. (2015), BG

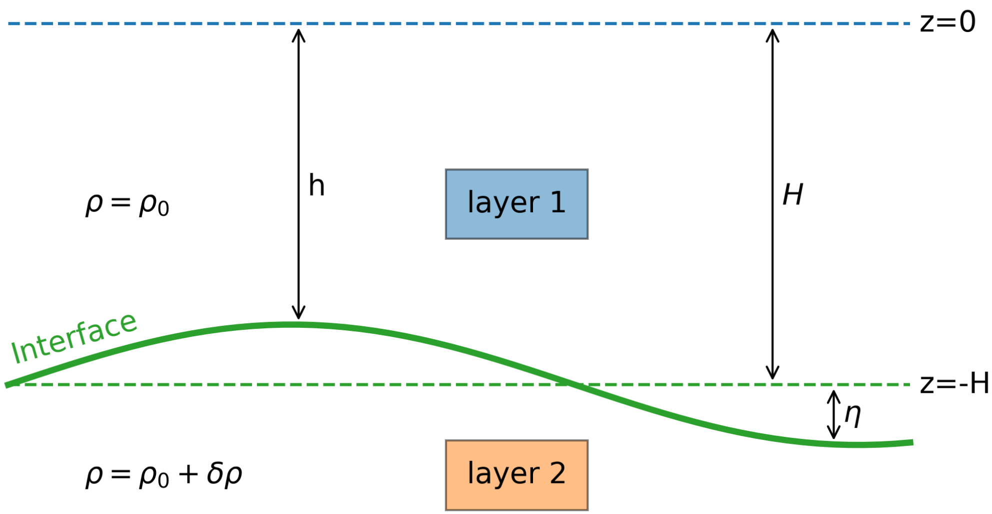


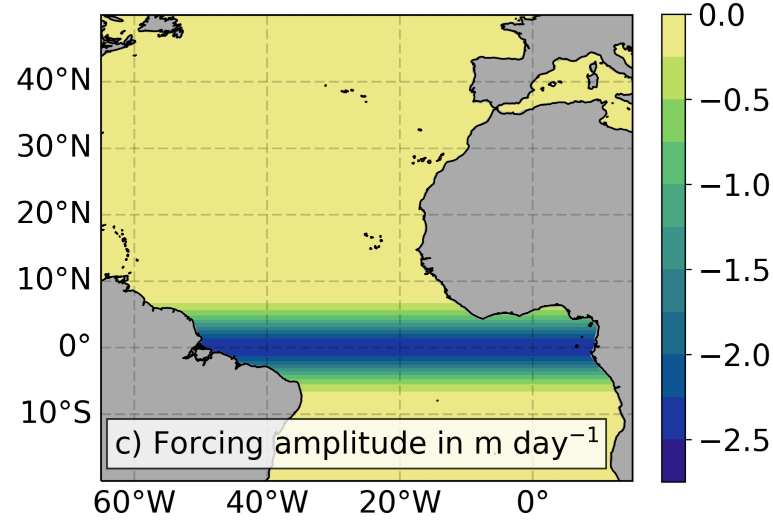
Brandt et al. (2015)

➡ LAZJs are suspected to matter for long term variability of OMZ ventilation (Brandt et al. 2015, BG)

➡ turn to non-linear shallow water model to study the LAZJ variability and its effect on the ETNA OMZ ventilation

Non-linear shallow water model





➡ coupled to an advection-diffusion model with tracer (C) set-up to mimic oxygen

$$\underbrace{\frac{\partial(Ch)}{\partial t}}_{1} + \underbrace{\nabla\cdot(Ch\mathbf{u})}_{2} = \underbrace{\nabla\cdot(\kappa_h h\nabla C)}_{3} - \underbrace{JCh}_{4} - \underbrace{h\gamma(C-C_0)}_{5} + \underbrace{CF_\eta}_{6}$$

$\gamma \approx 1/8$ day^{-1}

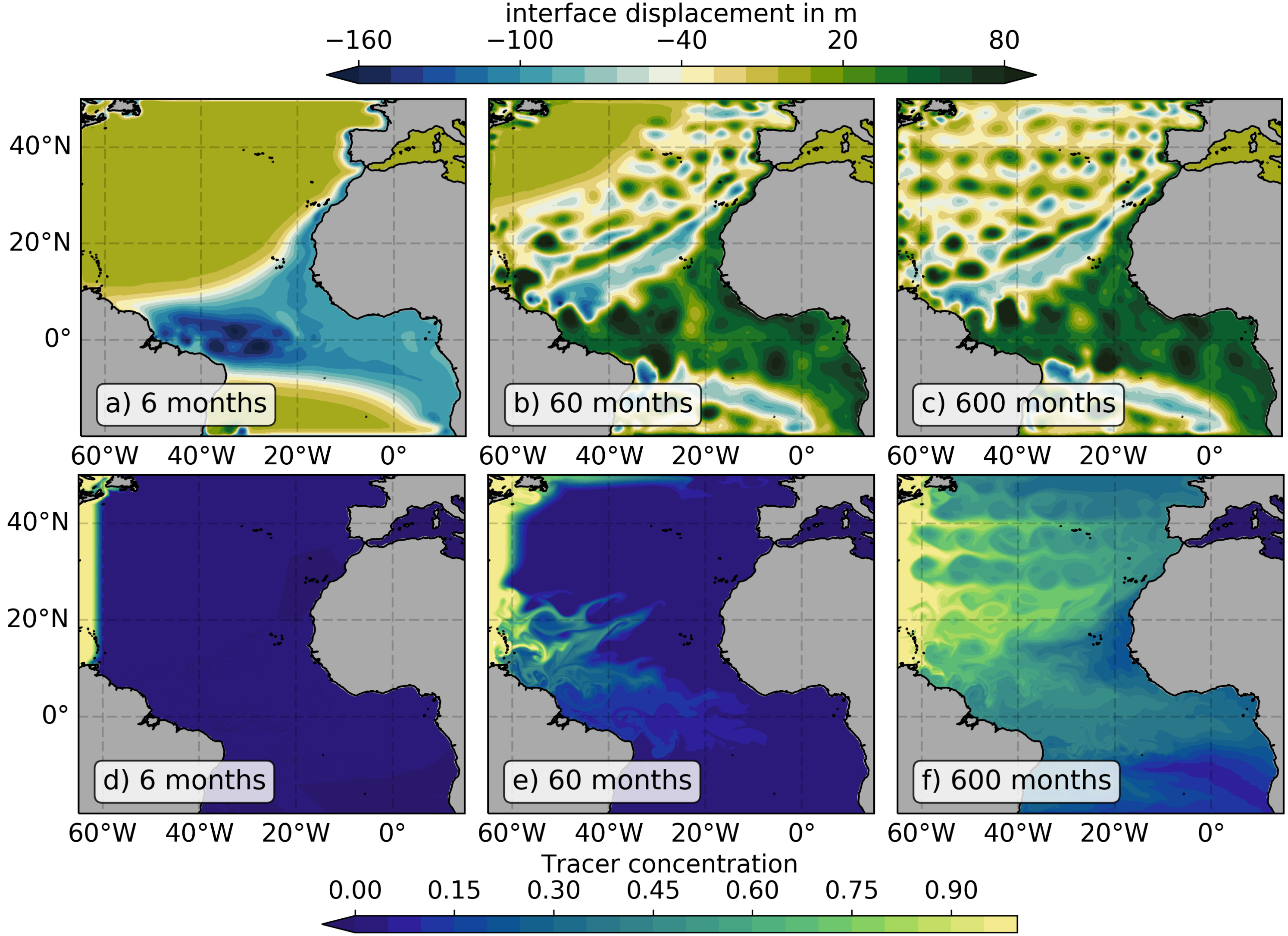
$J \approx 1/49$ year^{-1}

1) tendency 2) advective terms 3) diffusion 4) consumption 5) source (western boundary) 6) forcing

Spin-up

Interface displacement

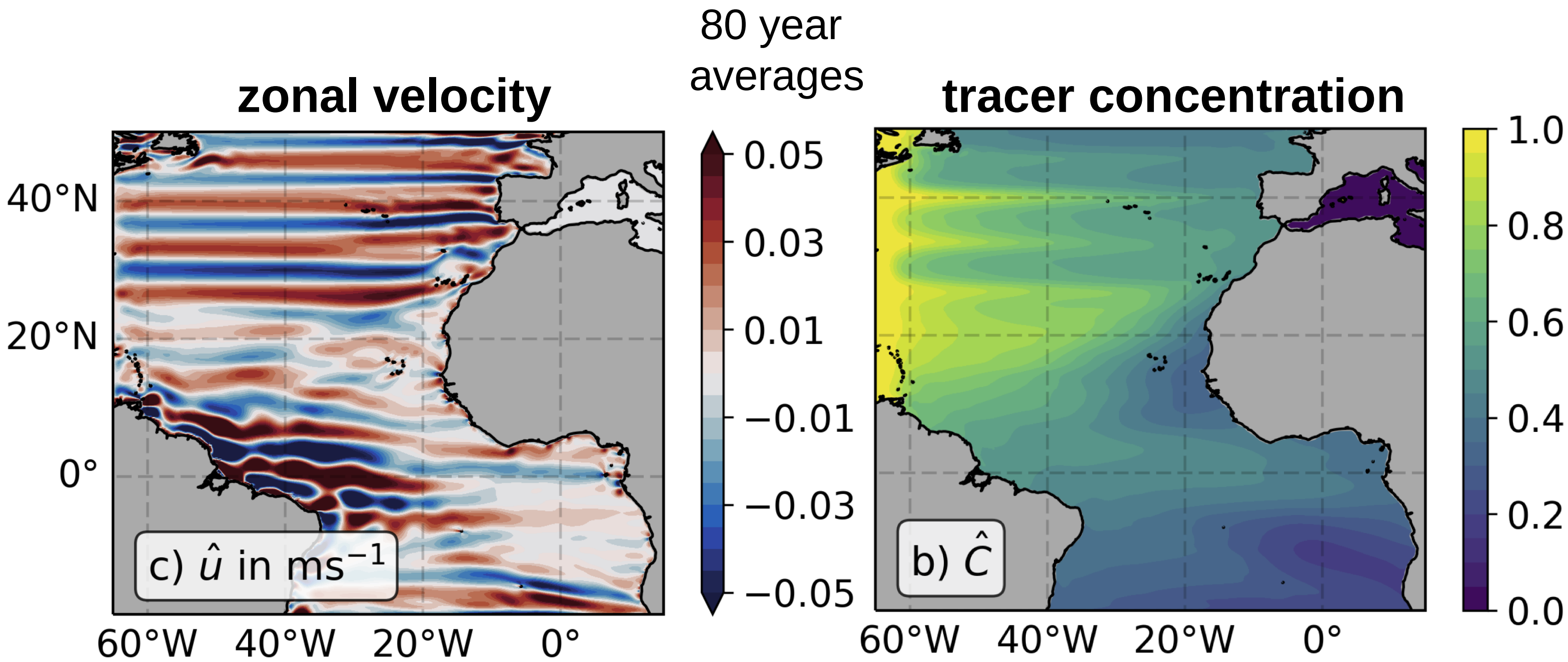
Tracer concentration



Statistical mean state features LAZJs and ETNA OMZ

Thickness weighted average:

$$\hat{\alpha} = \frac{\overline{\alpha h}}{\overline{h}}$$



- meridional scale of LAZJs is wider than Rossby radius and Rhines scale
- LAZJs mainly driven by eddies whose size is set by non-linear triad instability process (cf. Qiu et al. 2013, JPO)

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Results

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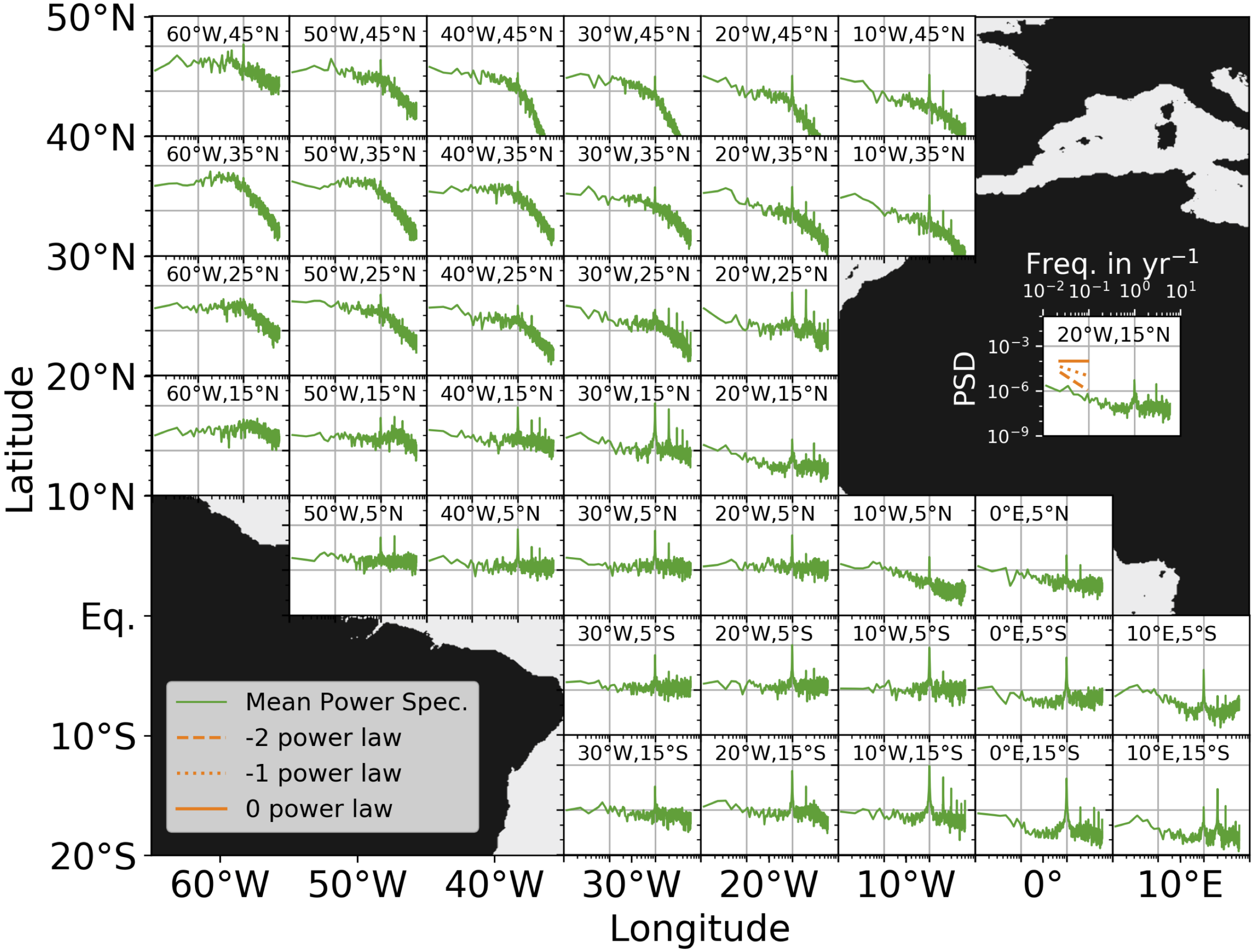
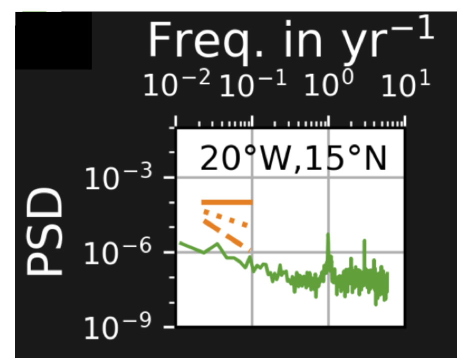
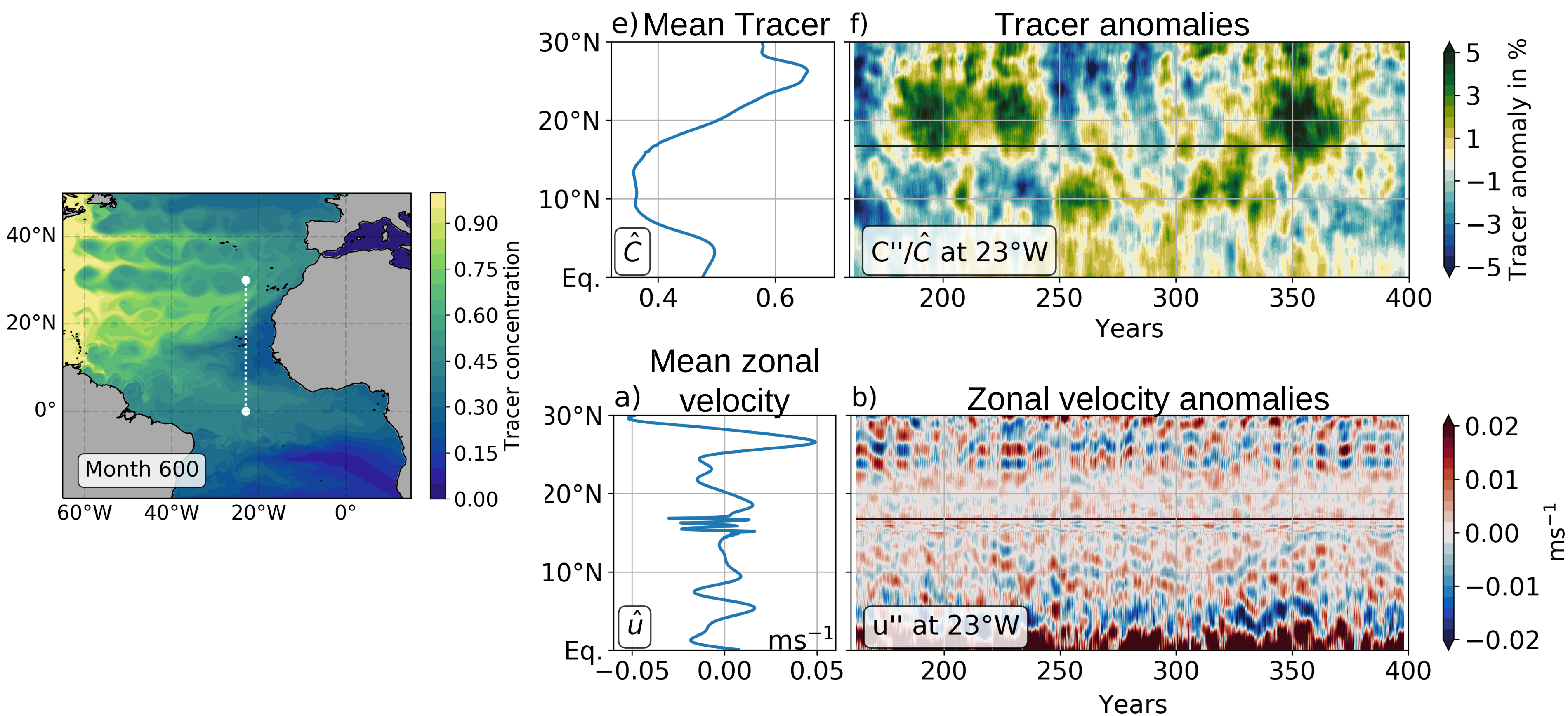
Tracer variability in the Atlantic basin



→ interannual to decadal tracer variability is exited off the equator by an annual period forcing

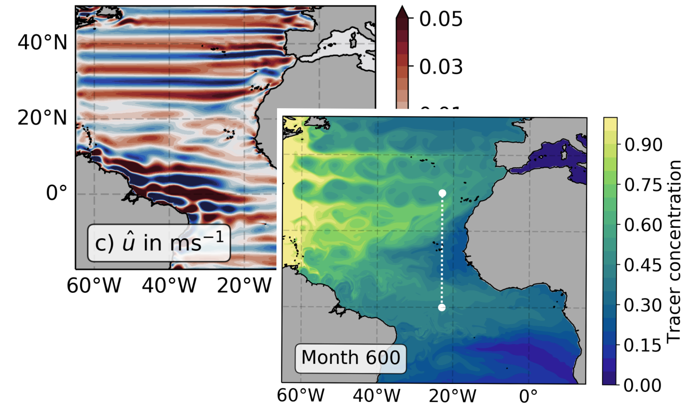


Connection between tracer variability and zonal velocity

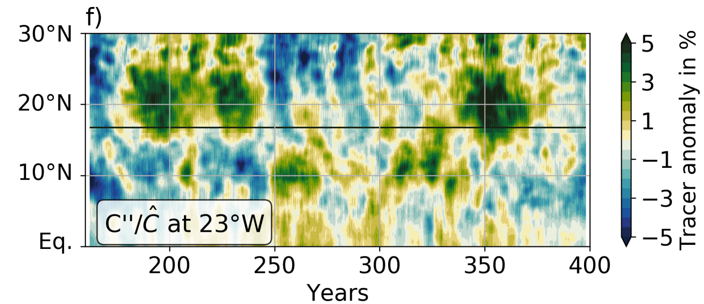


➡ multi-decadal tracer variability is accompanied by (multi-)decadal jet variability

Summary & Outlook



- the annually forced shallow water model features LAZJs, rectified by eddies and Rossby waves, that ventilate a more or less realistic ETNA OMZ



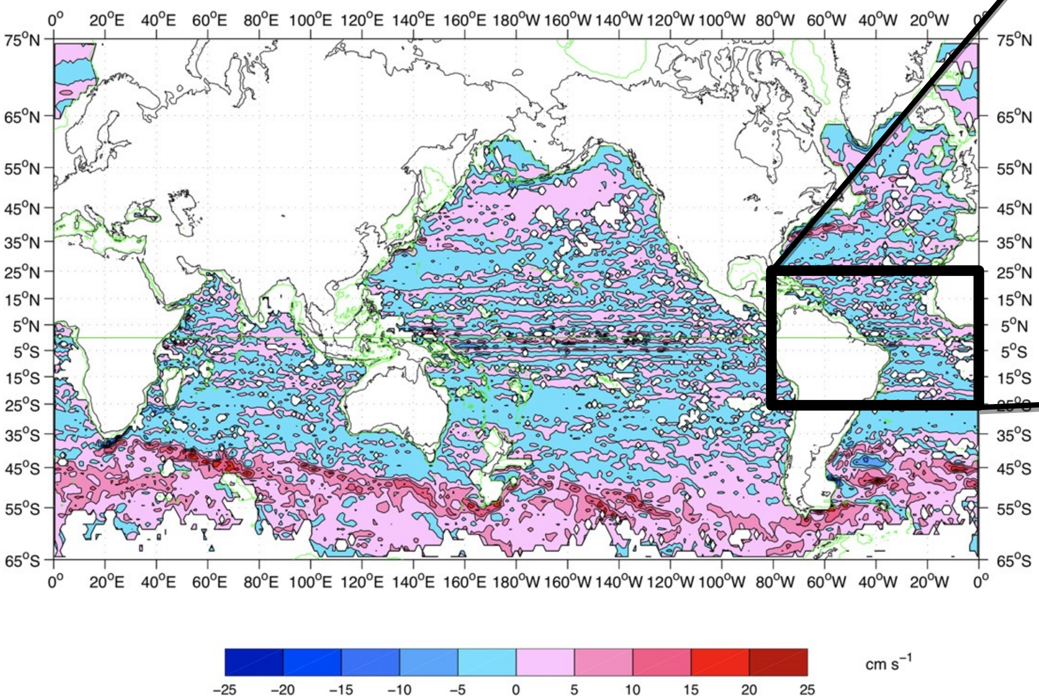
- inter-annual to multi-decadal variability of the tracer concentration is generated - it is accompanied by (multi-)decadal jet variability

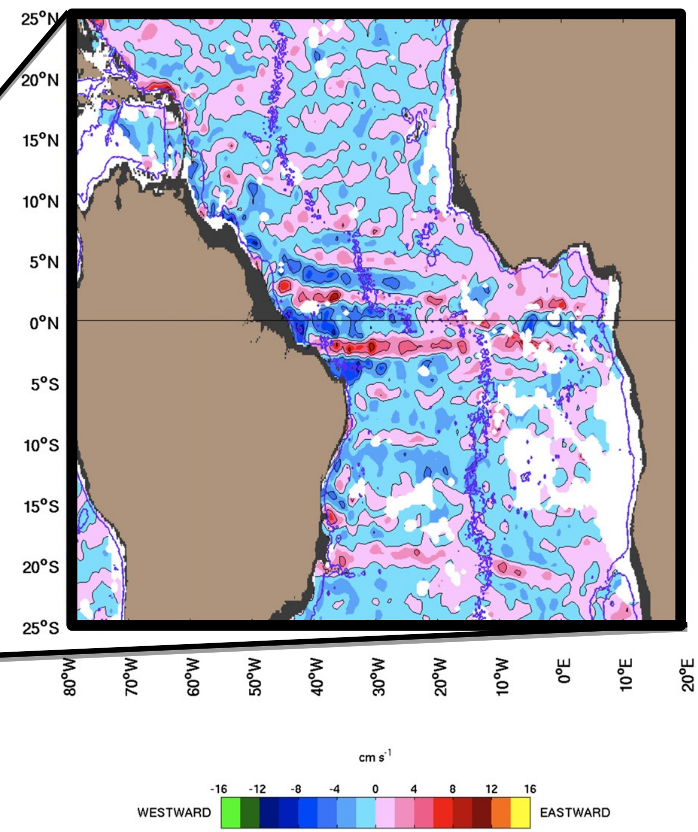
- obtain better understanding by turning to a more realistic model set-up (multi-layer model or GCM) and/or increasing the forcing complexity

Appendix

Latitudinally alternating zonal jets (LAZJs)

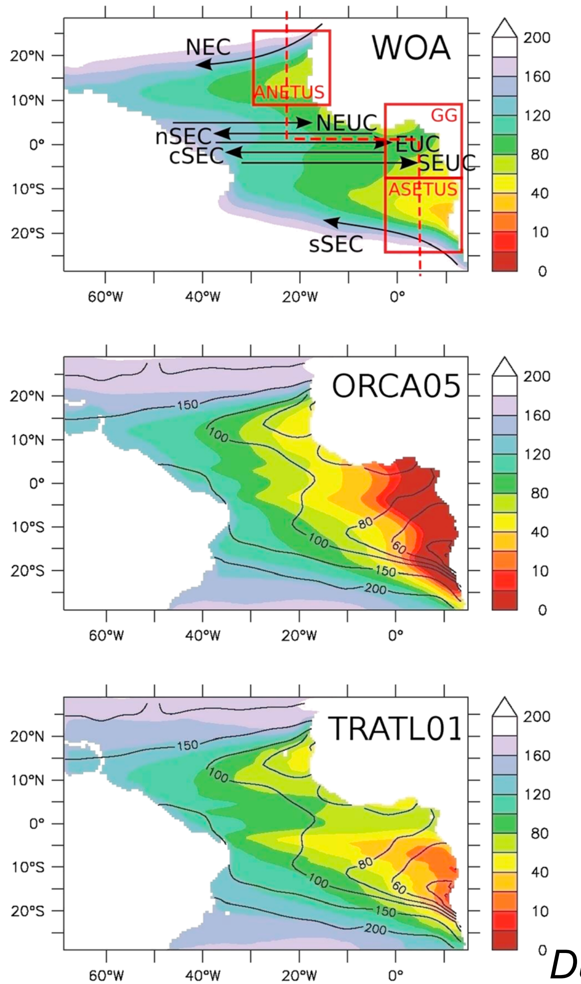
Zonal velocity at ~1000m depth





Ollitrault and Colin de Verdière (2014)

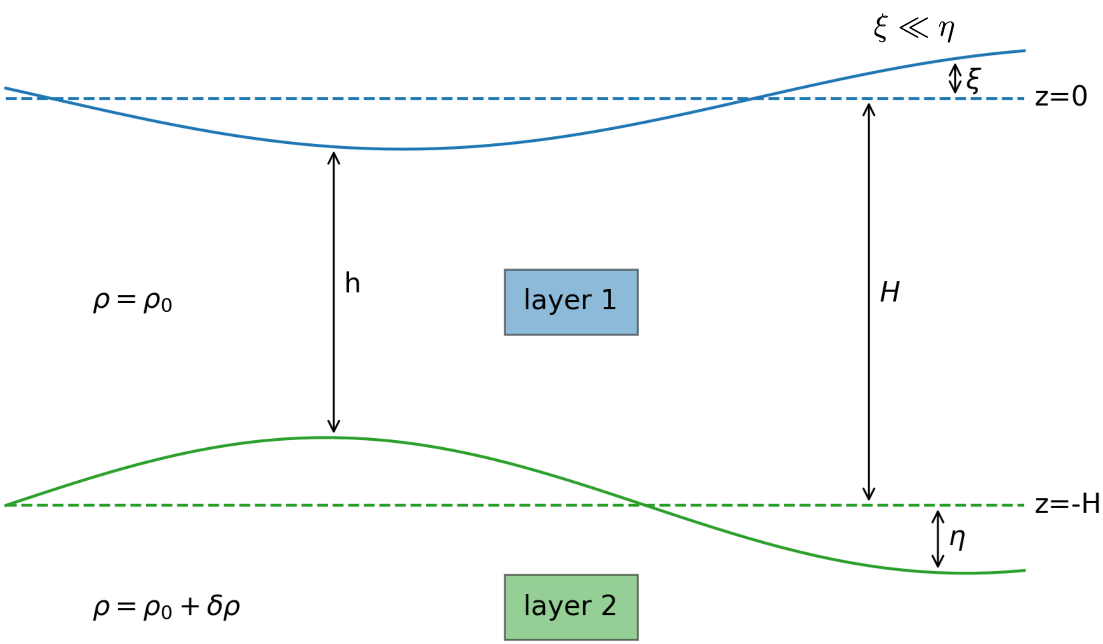
Modelling the ETNA OMZ



Duteil et al. (2014)

- so far no good understanding of the long term variability of the ETNA OMZ
- Mesoscale dynamics play an important role in the ventilation of the ETNA OMZ
- Turn to a non-linear shallow water model coupled to an advection-diffusion model to get a conceptual understanding

Non-linear shallow water model



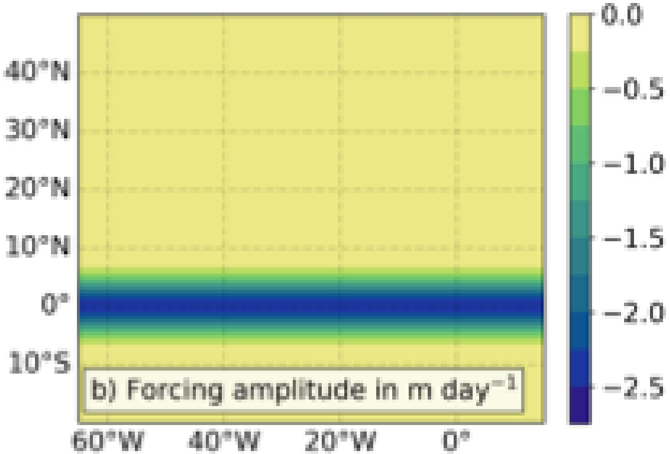
- Dynamical equations:

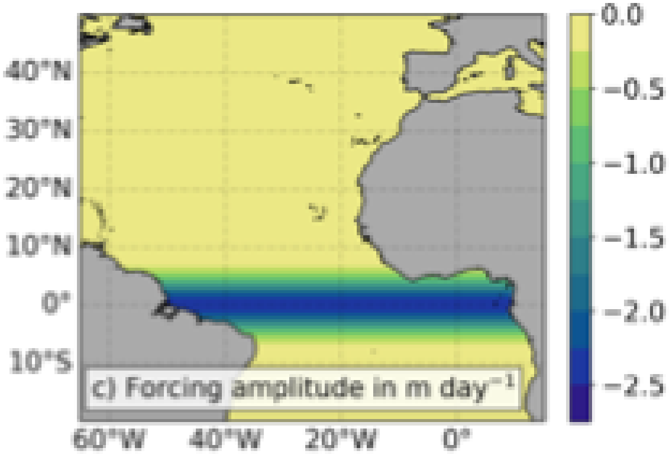
$$\frac{\partial u}{\partial t} = qhv - \frac{1}{r\cos\vartheta}\frac{\partial E}{\partial \lambda} + M_u + F_u$$
$$\frac{\partial v}{\partial t} = -qhu - \frac{1}{r}\frac{\partial E}{\partial \vartheta} + M_v + F_v$$
$$\frac{\partial \eta}{\partial t} = -\frac{1}{r\cos\vartheta}\left(\frac{\partial (hu)}{\partial \lambda} + \frac{\partial (hv\cos\vartheta)}{\partial \vartheta}\right) + F_\eta$$

- 1.5 layers - infinitely deep lower layer with vanishing velocities

- set to represent the first baroclinic mode with c = 2.7 ms^{-1} (H=500 m, g' = 1.5*10^{-2} ms^{-2})

Non-linear shallow water model





- rectangular and Atlantic basin (20°S-50°N, 65°W-15°E)

- 0.1° resolution
- viscosity set to 100 m^2s^{-1}
- run with no-slip boundary conditions

- annual period forcing

$$\frac{\partial u}{\partial t} = qhv - \frac{1}{r\cos\vartheta}\frac{\partial E}{\partial \lambda} + M_u + \cancel{F_u}$$
$$\frac{\partial v}{\partial t} = -qhu - \frac{1}{r}\frac{\partial E}{\partial \vartheta} + M_v + \cancel{F_v}$$
$$\frac{\partial \eta}{\partial t} = -\frac{1}{r\cos\vartheta}\left(\frac{\partial(hu)}{\partial \lambda} + \frac{\partial(hv\cos\vartheta)}{\partial \vartheta}\right) + \boxed{F_\eta}$$

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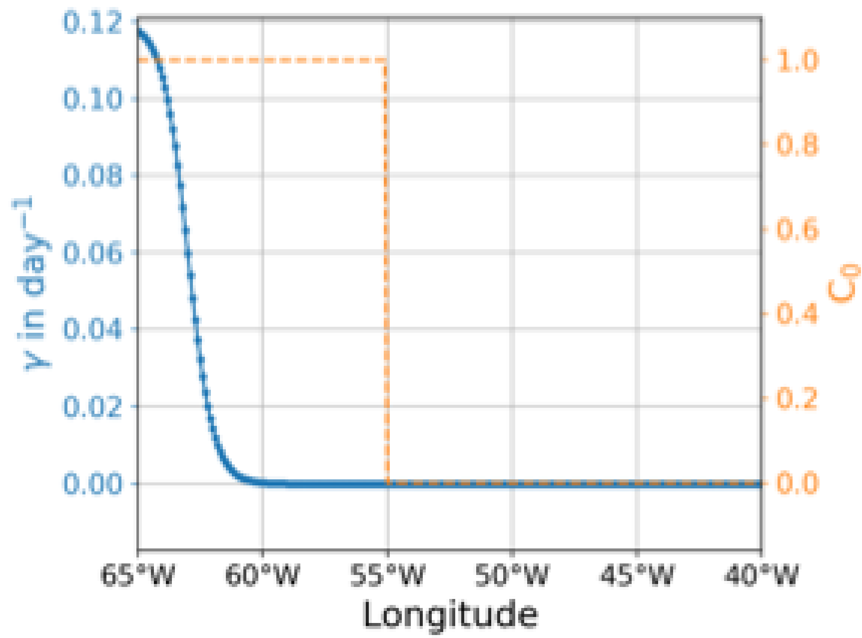
Advection-diffusion model

$$\underbrace{\frac{\partial(Ch)}{\partial t}}_{1} + \underbrace{\nabla\cdot(Ch\mathbf{u})}_{2} = \underbrace{\nabla\cdot(\kappa_h h\nabla C)}_{3} - \underbrace{JCh}_{4} - \underbrace{h\gamma(C - C_0)}_{5} + \underbrace{CF_\eta}_{6}$$

1. tendency
2. advective terms
3. diffusion
4. tracer sink (consumption, $J \approx 1/49\ \text{year}^{-1}$)
5. tracer source (relaxation at western boundary, $\gamma_0 \approx 1/8\ \text{day}^{-1}$)
6. forcing



➡ **Tracer set-up to mimic oxygen**

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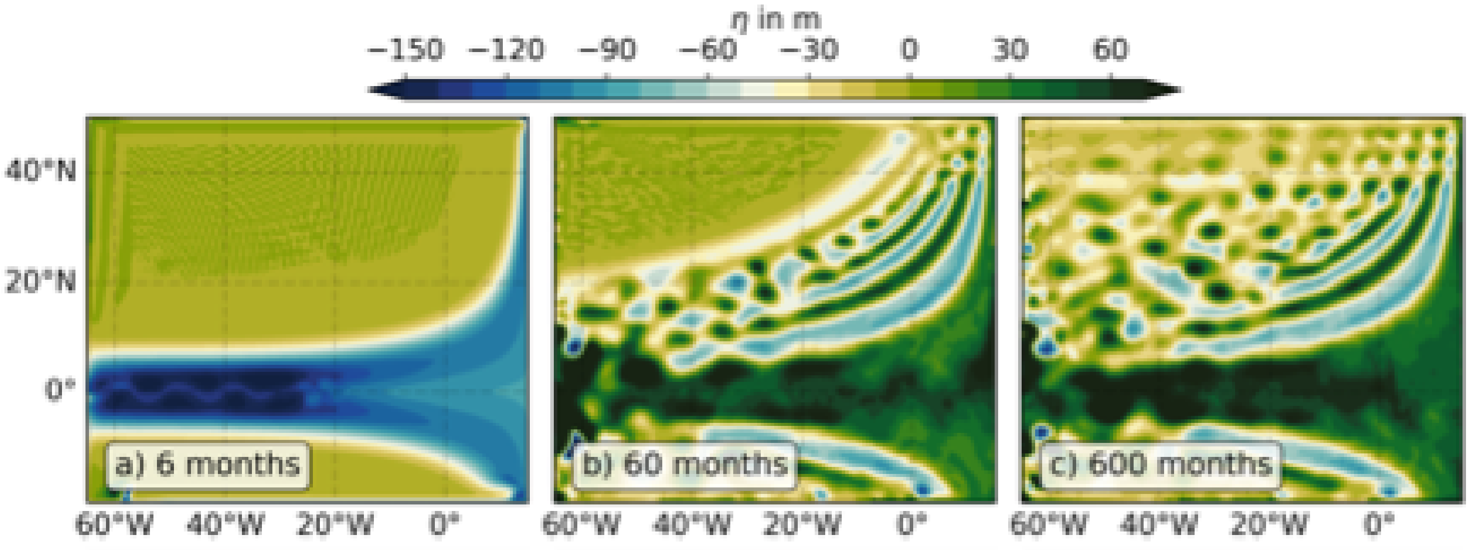
Spin-up

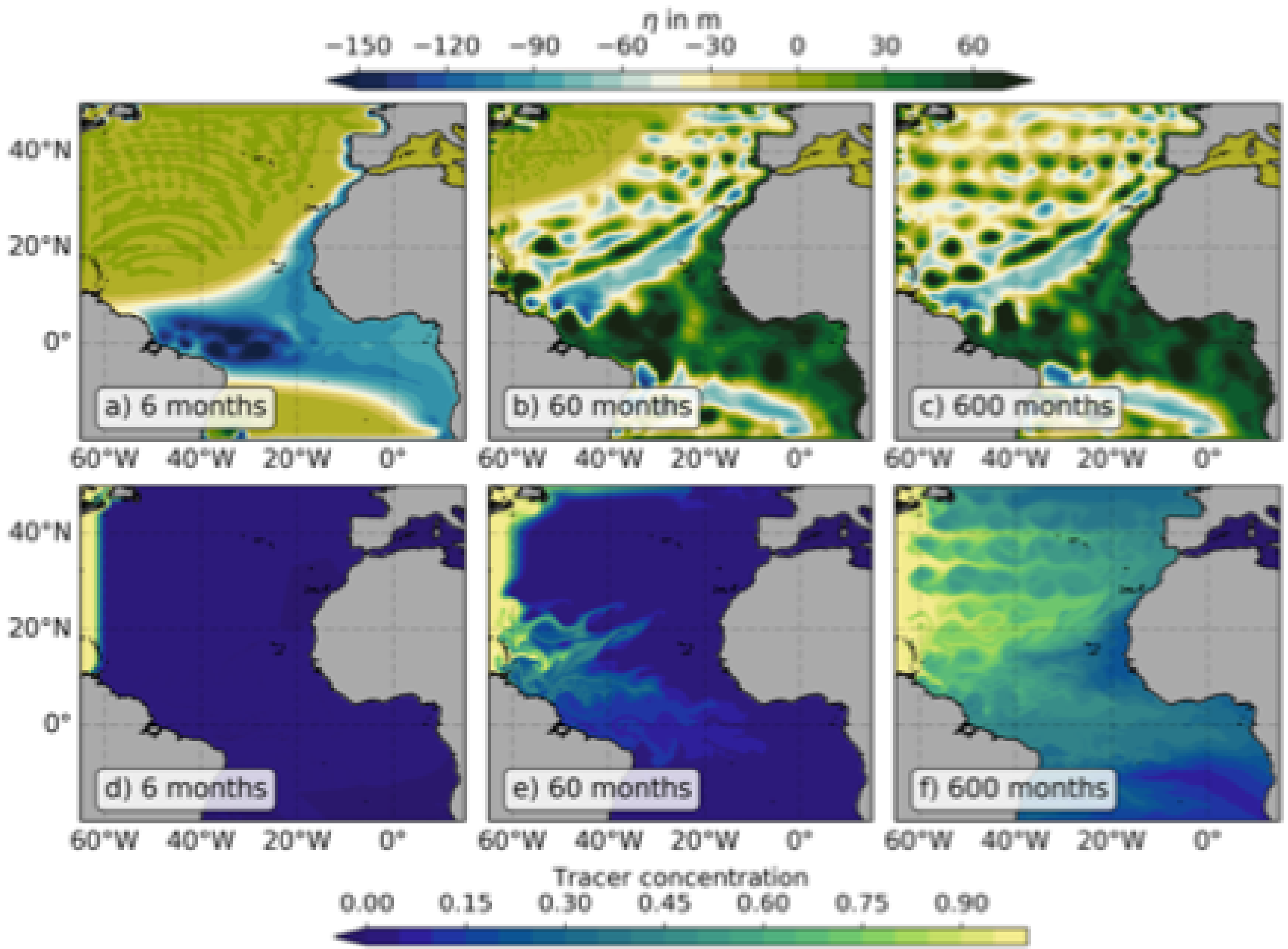
Interface displacement



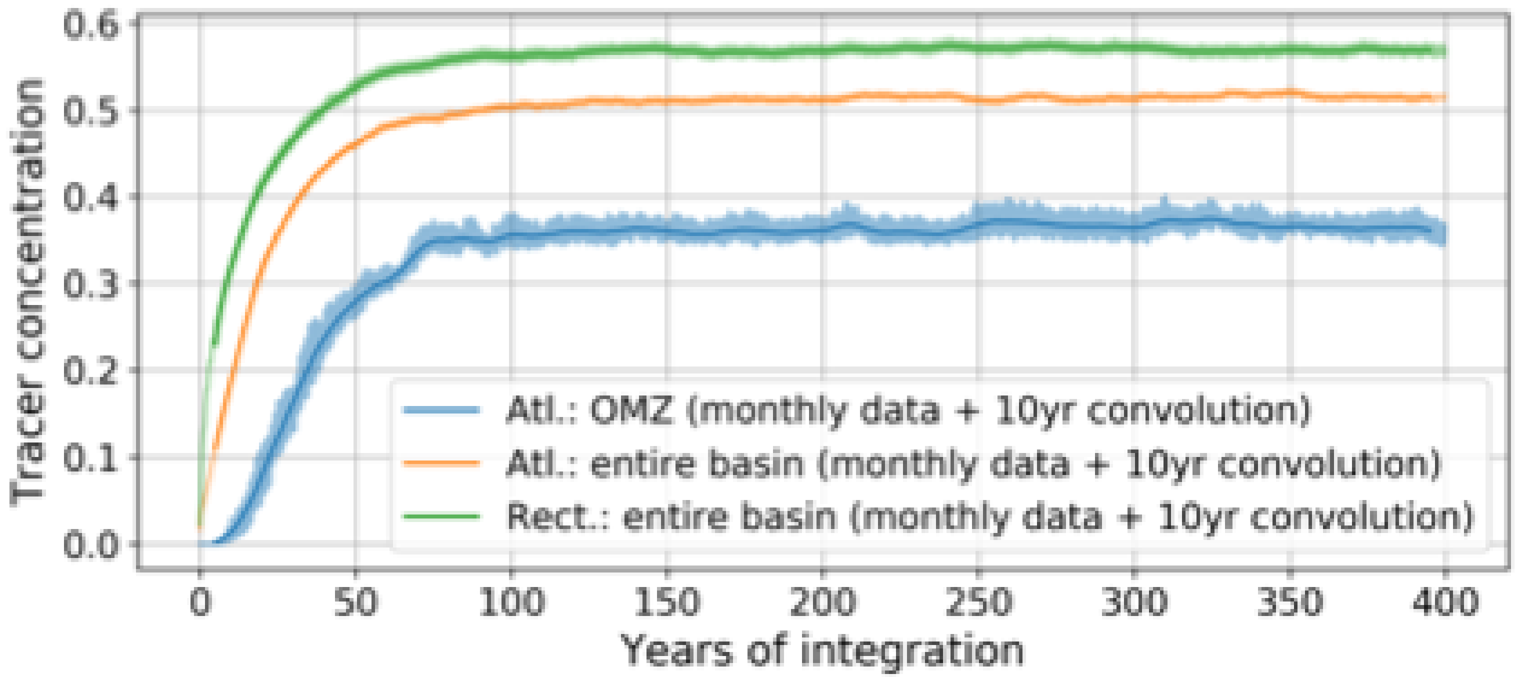
Spin-up

Interface displacement

Tracer concentration



Spin-up - Tracer content



0.7% std. dev.

0.51% std.dev.

2.88% std. dev.

Statistical mean state

Thickness weighted average:

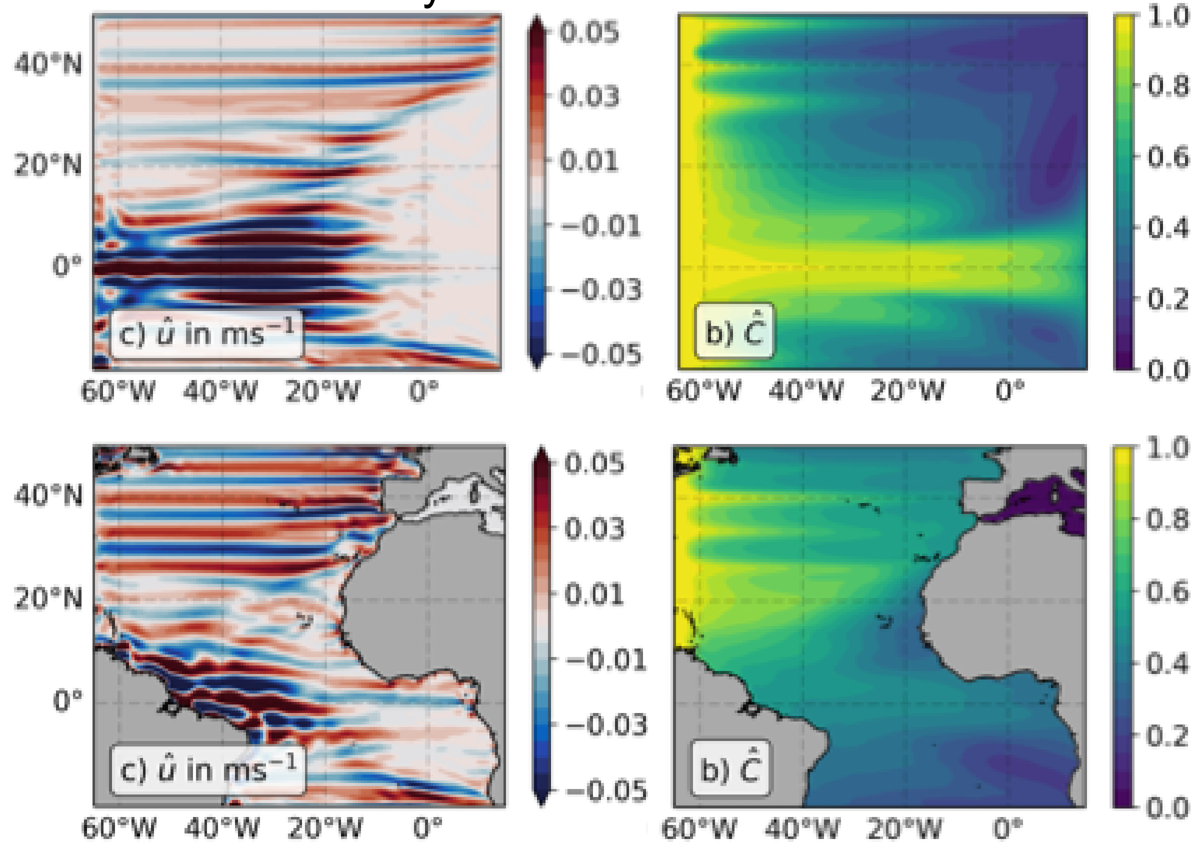
$$\hat{\alpha} = \frac{\overline{\alpha h}}{\overline{h}}$$

80 year averages

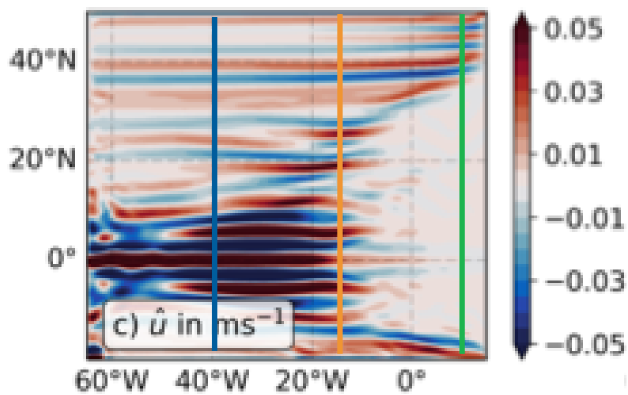
zonal velocity | tracer conc.

Rectangular basin

Atlantic basin



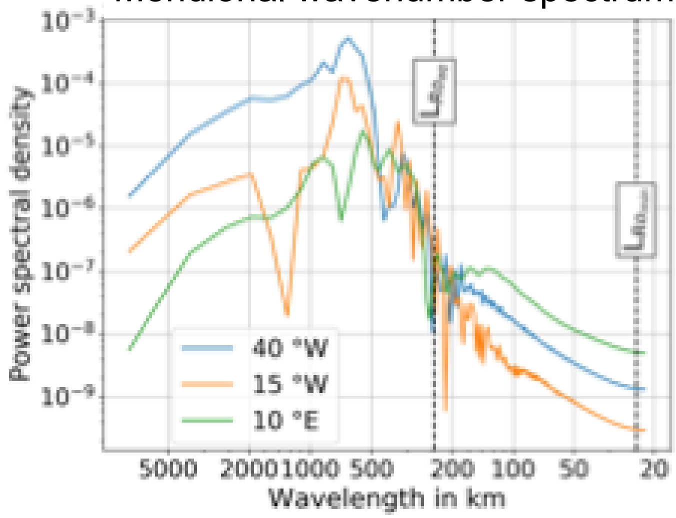
Meridional width of zonal jets



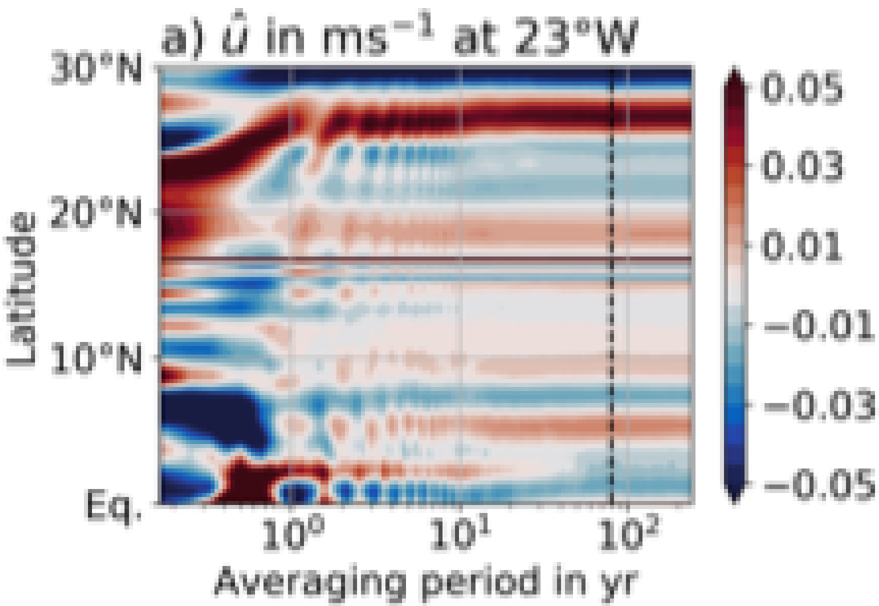
Rossby radius: $L_{\mathrm{Ro}} = \frac{(g'H)^{1/2}}{f}$, $L_{\mathrm{Ro}_{eq}} = \left(\frac{c}{2\beta}\right)^{1/2}$

- zonal jets are wider than both:
  1. Rossby radius
  2. Rhines scale

Meridional wavenumber spectrum



Meridional width of zonal jets



- eddies rectify the zonal jets
- hence, the eddy formation process plays a large role in setting the meridional width of the jets
- Resonant triad instability has been suggested to lead to break up of Rossby wave fronts (Qiu et al., 2013)

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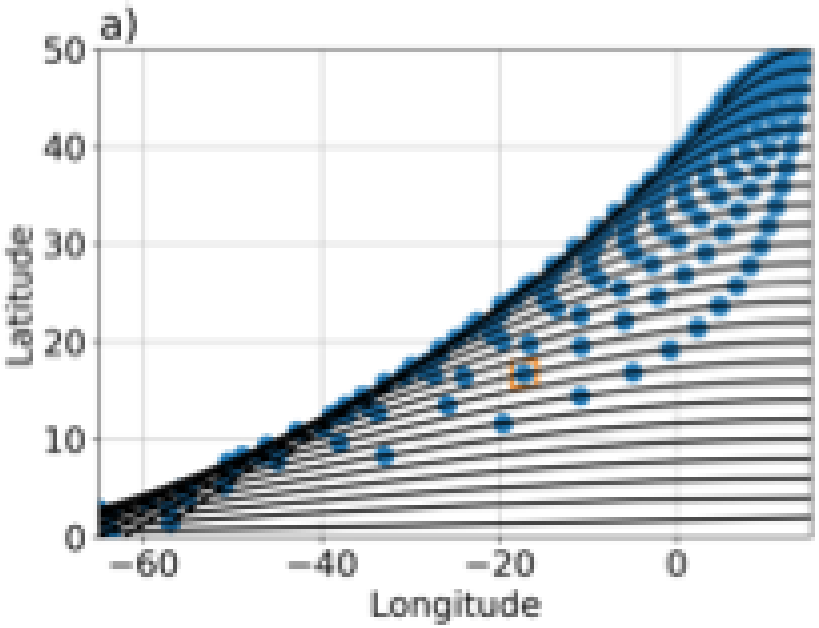
Zonal jet width - Non-linear triad instability

- Rossby wave ray theory (Schopf, 1981)
  - equatorial β-plane
  - purely meridional eastern boundary
  - initially vanishing meridional wavenumber
- dispersion relation: $$\omega = \frac{-\beta k}{(k^2 + l^2 + f^2 c^{-2})}$$
- the β-dispersion leads to the formation of the caustic
- along the ray paths, the triad instability mechanism can be analysed following Pedlosky (1987) and Qiu et al. (2013)



Zonal jet width - Non-linear triad instability

- for a resonant triad, three Rossby waves are required that fulfil the following condition:

$$k_1 + k_2 + k_3 = 0$$
$$l_1 + l_2 + l_3 = 0$$
$$\omega_1 + \omega_2 + \omega_3 = 0$$

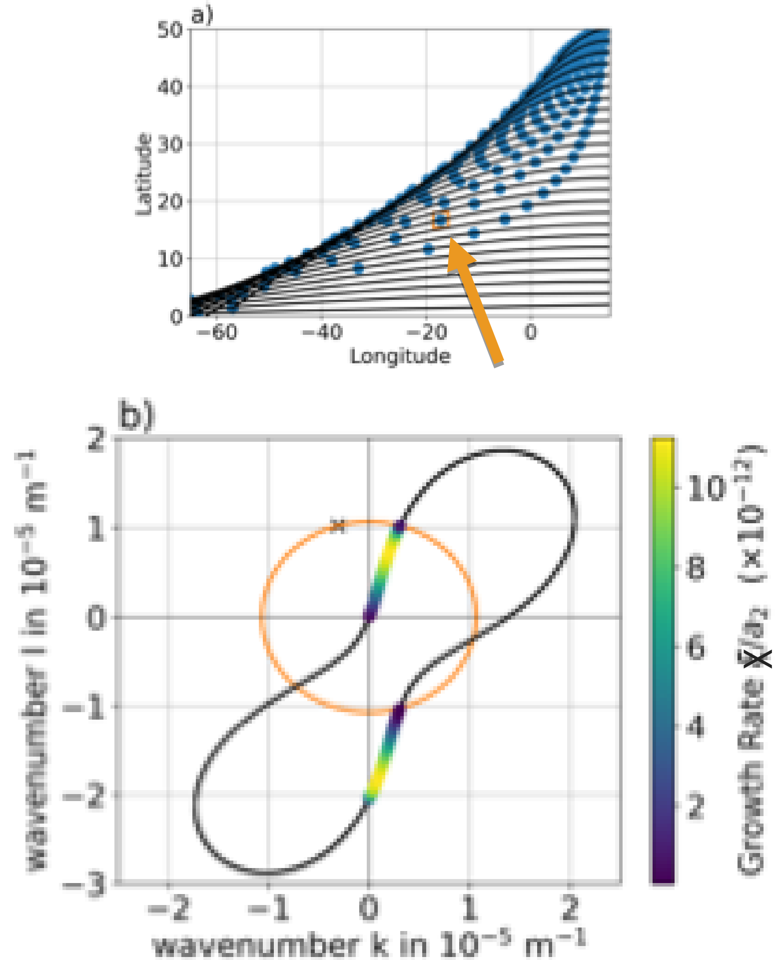
- assuming k_2, l_2, ω_2 etc. to be associated with the primary wave, the necessary instability criterion is given by $K_1 < K_2 < K_3$

- the growth rate for the secondary waves is given by:

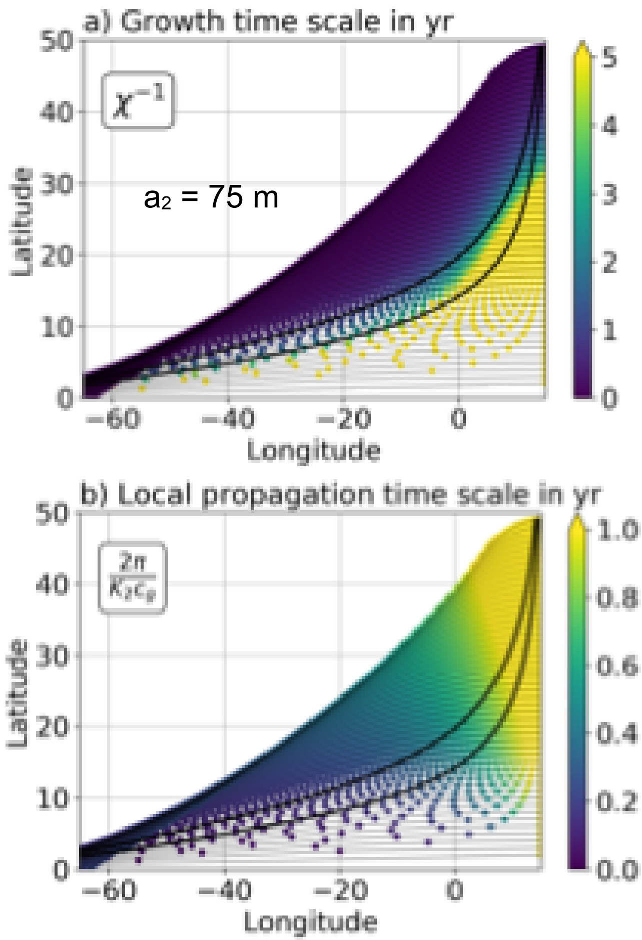
$$\chi = a_2 \left[\frac{B(K_2, K_3) B(K_1, K_2)}{(K_1^2 + f^2 c^{-2})(K_3^2 + f^2 c^{-2})} \right]^{1/2}$$

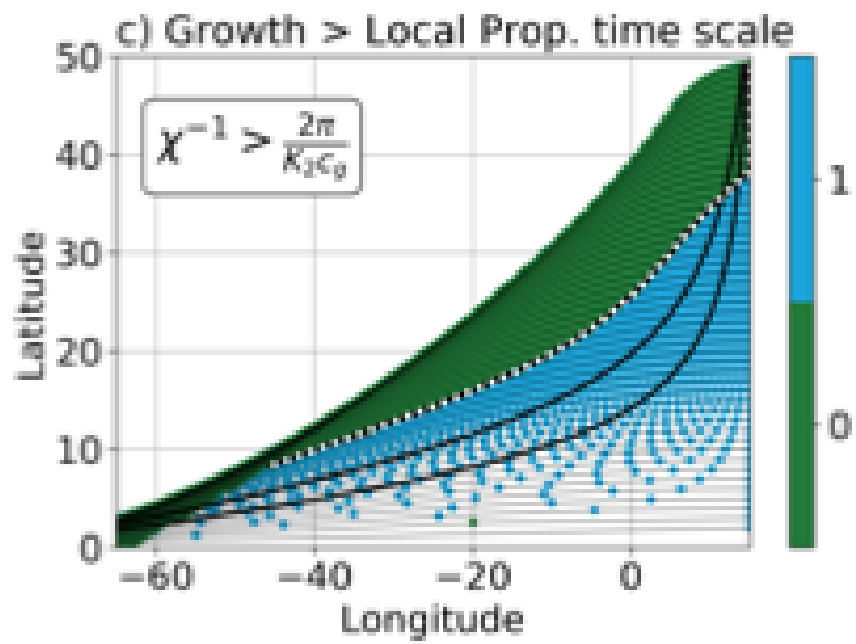
with

$$B(K_m, K_n) = (K_m^2 - K_n^2)(k_m l_n - k_n l_m)$$



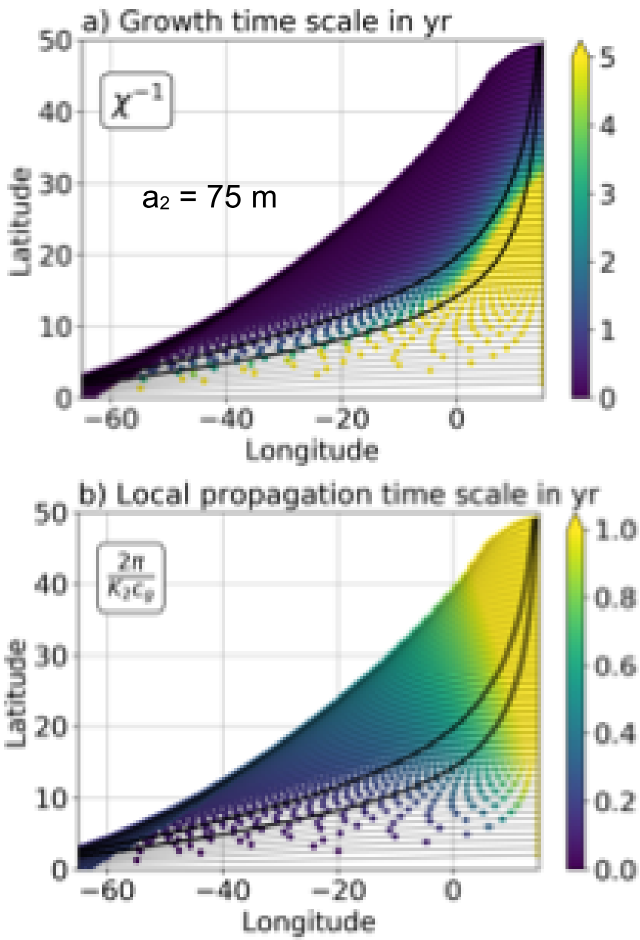
Zonal jet width - Non-linear triad instability

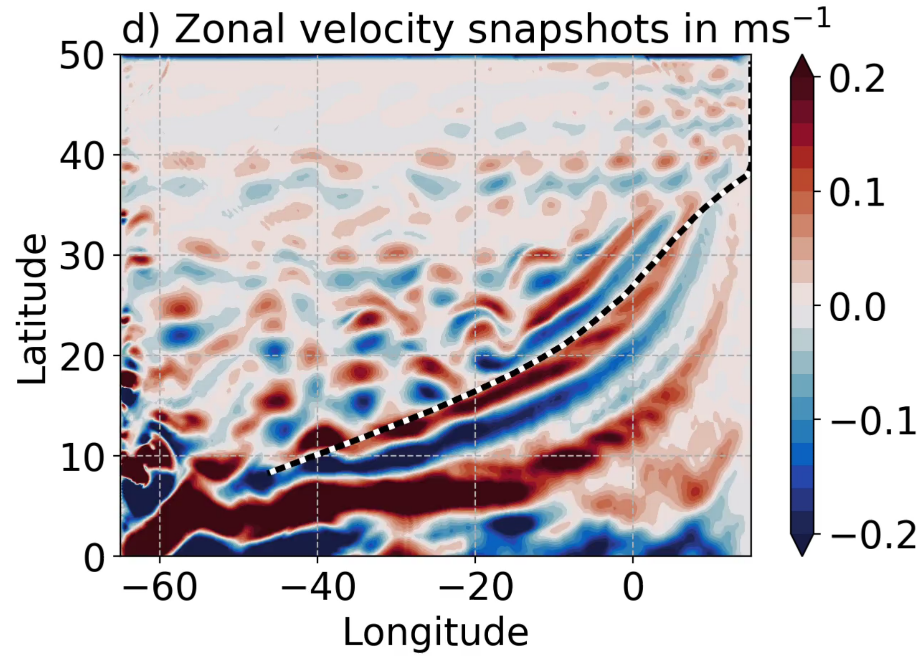




Physically one can expect the breakdown to occur where $\chi^{-1} = \frac{2\pi}{K_2 c_g}$

Zonal jet width - Non-linear triad instability





Projection onto the modelled field in spherical coordinates

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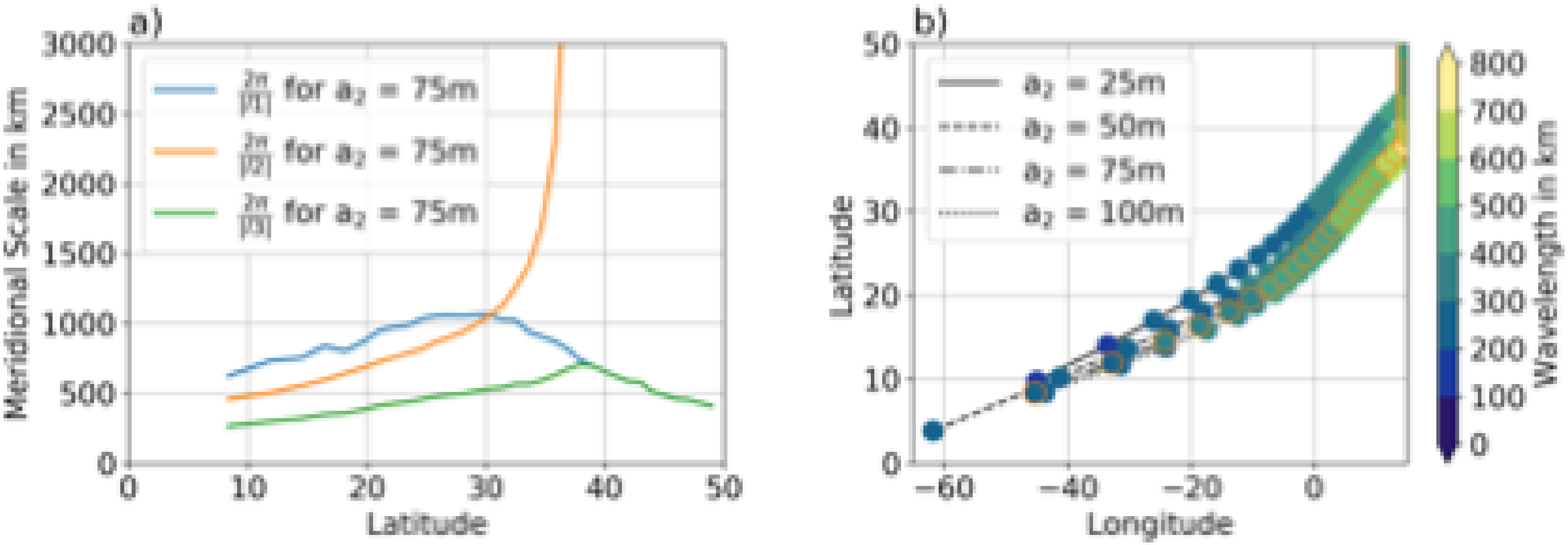
Zonal jet width - Non-linear triad instability

$$\chi = a_2 \left[\frac{B(K_2, K_3)B(K_1, K_2)}{(K_1^2 + f^2 c^{-2})(K_3^2 + f^2 c^{-2})} \right]^{1/2}$$



- inter-annual modulation of primary Rossby wave strength could lead to variability in zonal jet strength, width and position

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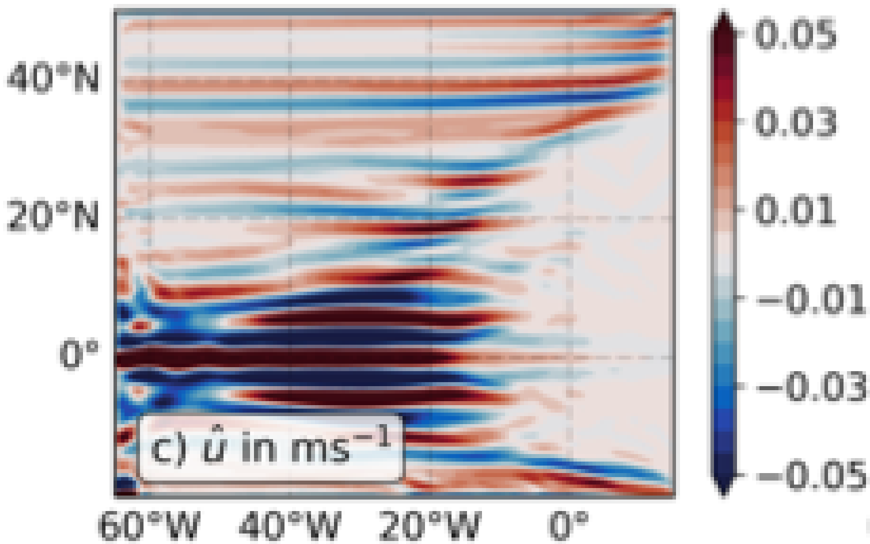
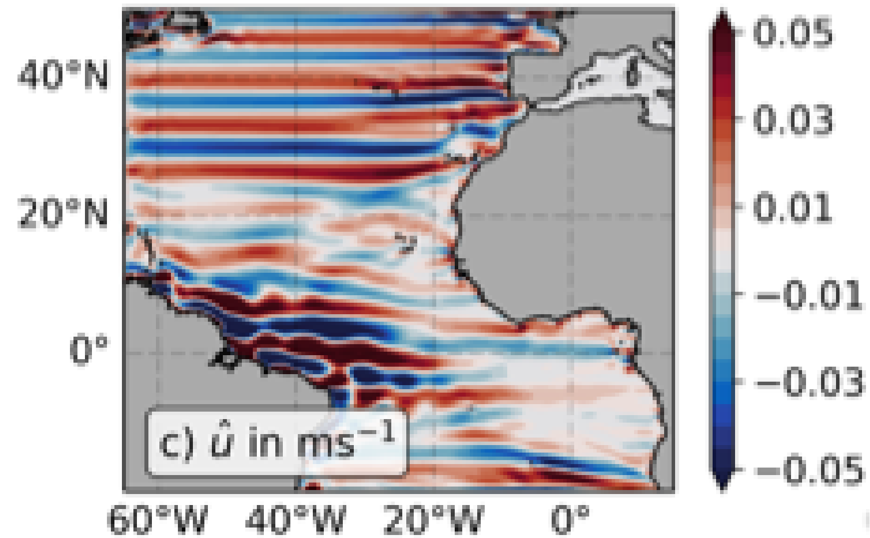
Zonal jets - origin





- zonal jets rectify through eddies after non-linear triad instability

- coastline has some effect on the jet generation - jets reach into ETNA OMZ

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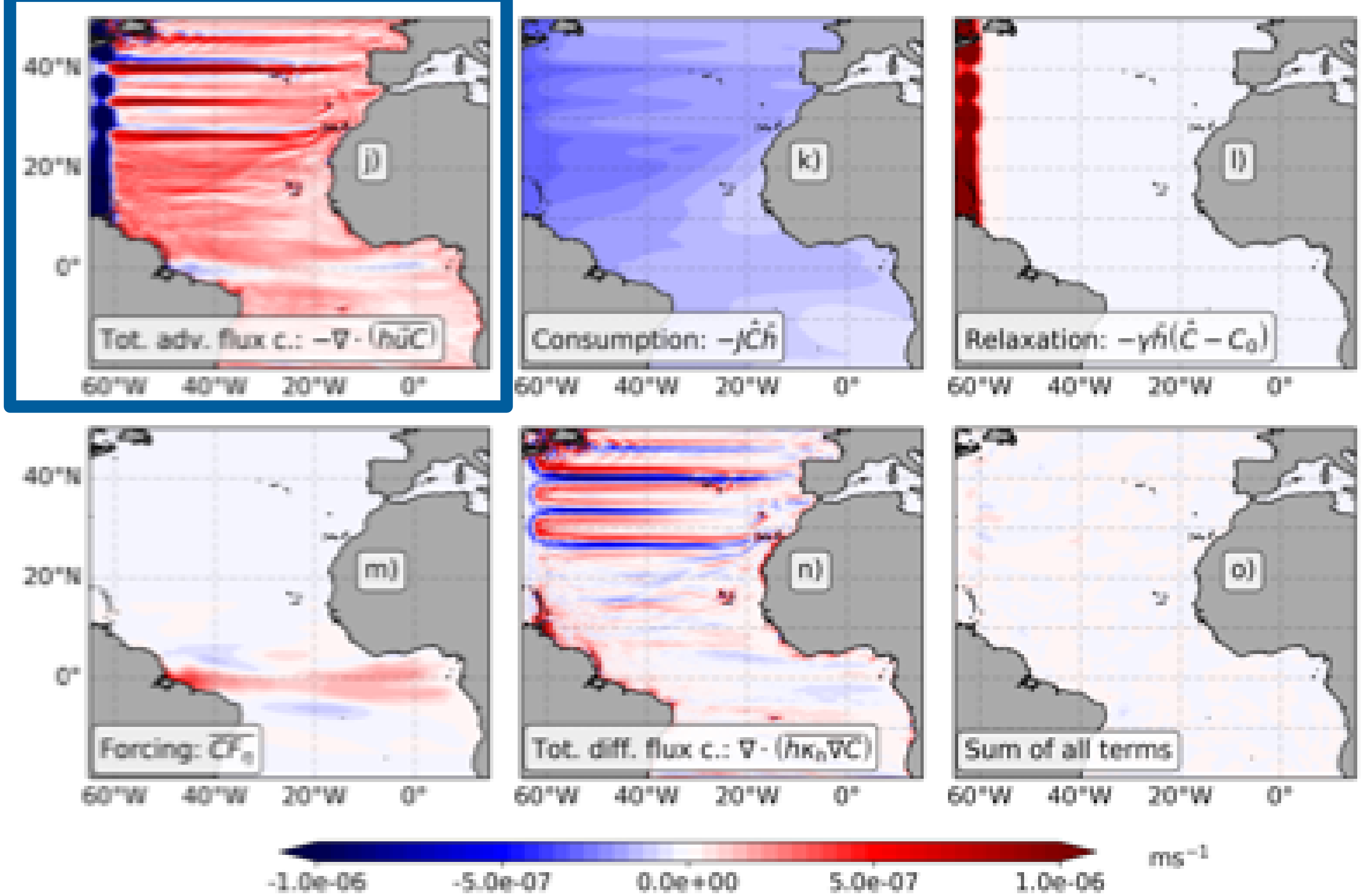
Tracer budget

$$\frac{\partial\left(\hat{C}\bar{h}\right)}{\partial t} = -\nabla\cdot\left(\overline{Ch\mathbf{u}}\right) + \nabla\cdot\left(\overline{h\kappa_h\nabla C}\right) - J\hat{C}\bar{h} - \gamma\bar{h}\left(\hat{C} - C_0\right) + \overline{CF_\eta}$$



Thickness weighted average:

$$\hat{\alpha} = \frac{\overline{\alpha h}}{\bar{h}}$$

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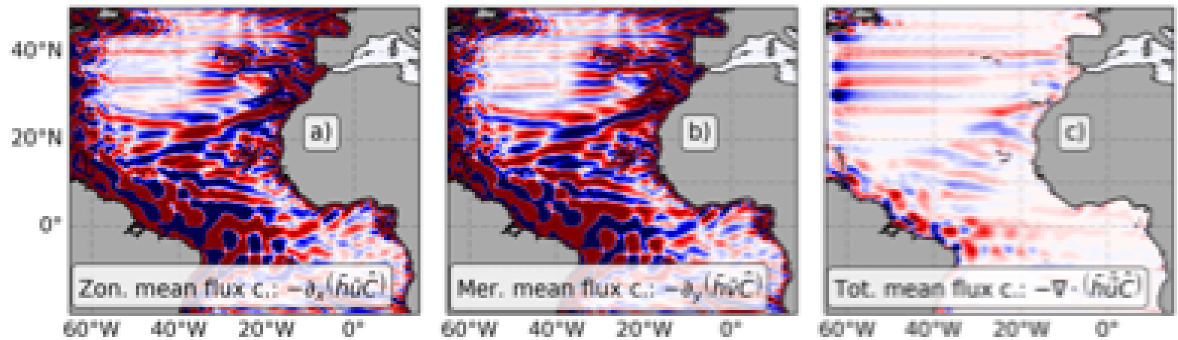
Analysis of advective flux convergence



$$-\nabla \cdot \overline{(Chu)} =$$

mean flux convergence

eddy flux c.

$$-\nabla \cdot \left(\hat{h}\hat{\mathbf{u}}\hat{C}\right) - \nabla \cdot \left(\hat{h}\mathbf{u}^{*}\hat{C}\right) - \nabla \cdot \left(\overline{h\mathbf{u}''C''}\right)$$

"eddy mixing"

with

$$\alpha = \hat{\alpha} + \alpha''$$

and bolus velocity

$$\mathbf{u}^{*} = \hat{\mathbf{u}} - \overline{\mathbf{u}} = \frac{\overline{\mathbf{u}'h'}}{\overline{h}}$$

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Analysis of advective flux convergence

$-\nabla \cdot \overline{(Ch\mathbf{u})}$ =

mean flux convergence

eddy flux c.

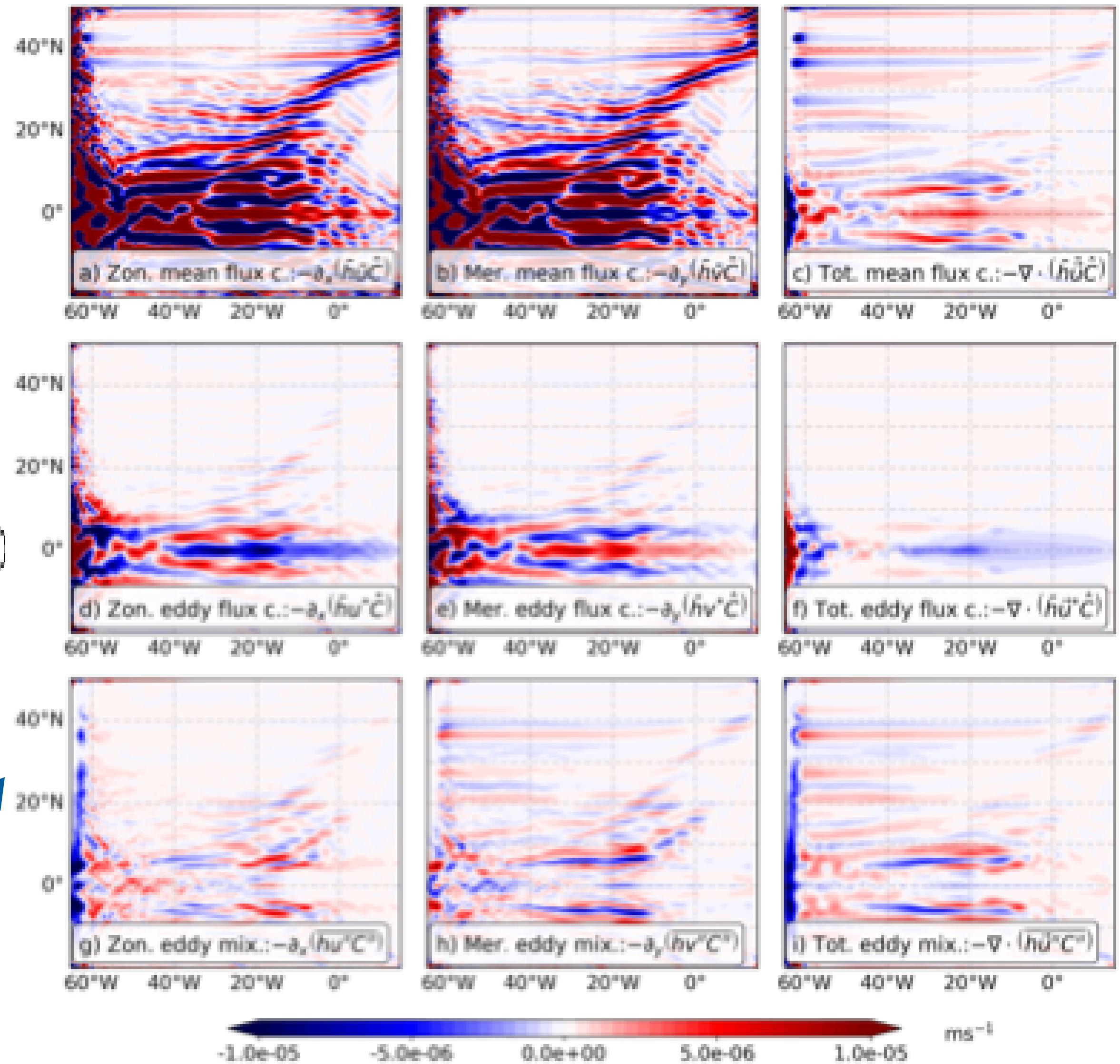
$-\nabla \cdot \left(\bar{h}\hat{\mathbf{u}}\hat{C}\right) - \nabla \cdot \left(\bar{h}\mathbf{u}^{*}\hat{C}\right) - \nabla \cdot \left(\overline{h\mathbf{u}''C''}\right)$

"eddy mixing"

with

$\alpha = \hat{\alpha} + \alpha''$

and bolus velocity $\mathbf{u}^{*} = \hat{\mathbf{u}} - \overline{\mathbf{u}} = \dfrac{\overline{\mathbf{u}'h'}}{\bar{h}}$



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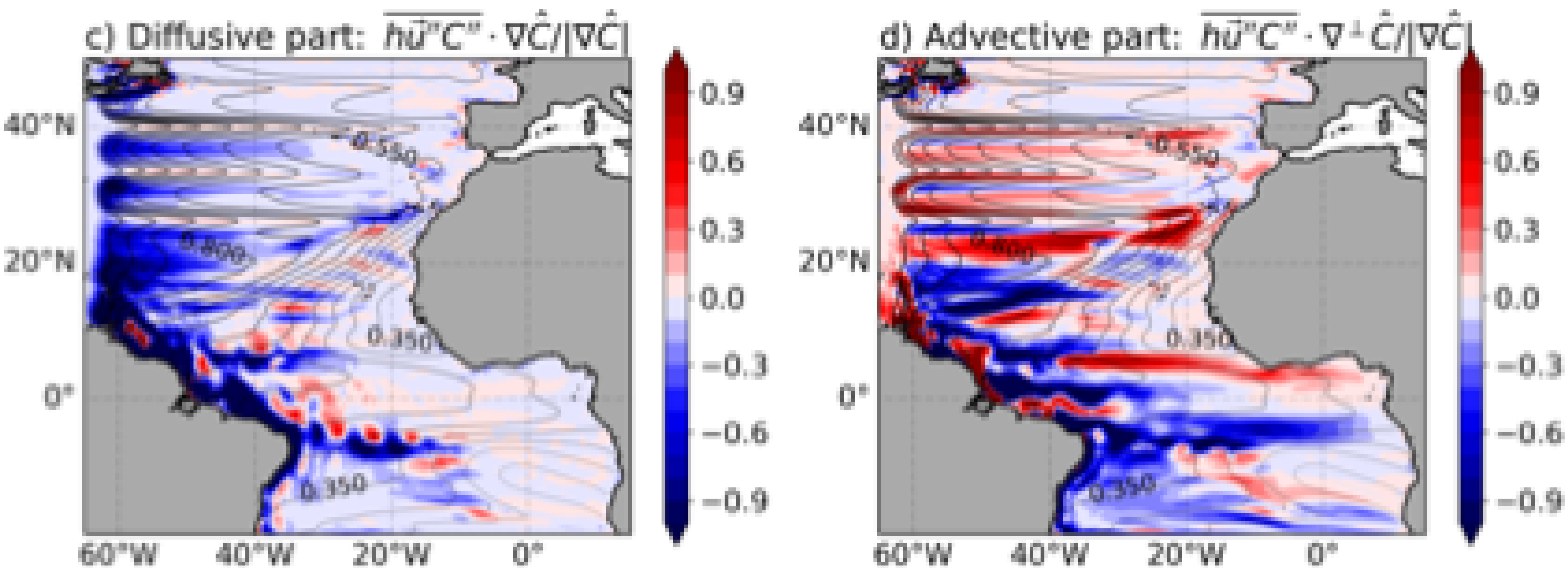
Nature of the “eddy mixing” term



- mostly down the tracer gradient
  - i.e. a genuine diffusive flux
- along lines of equal tracer concentrations

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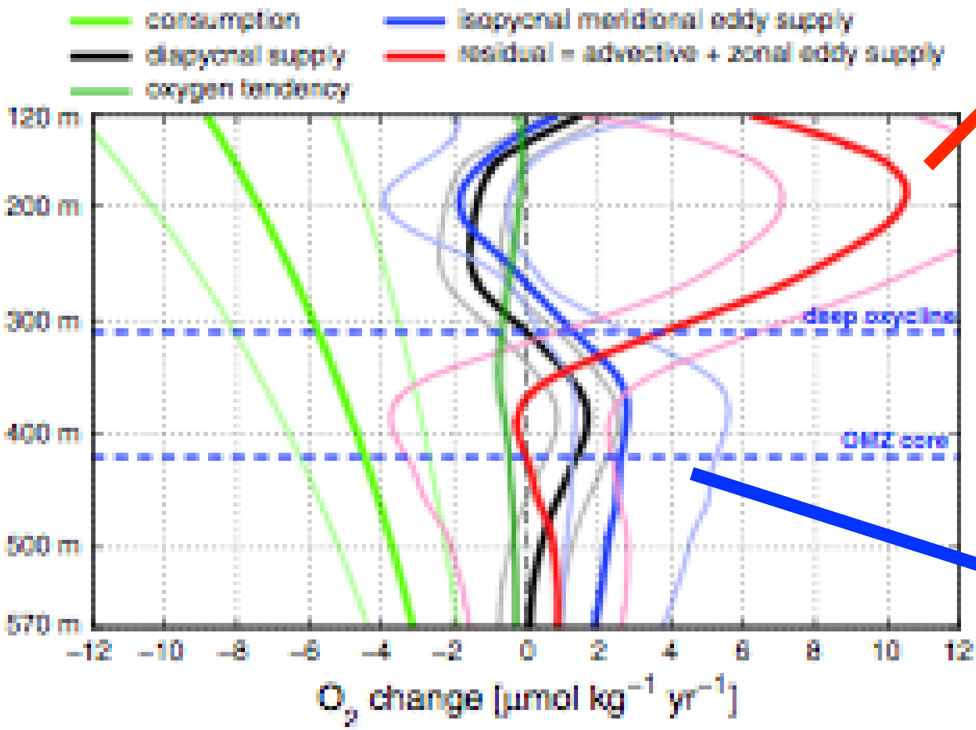
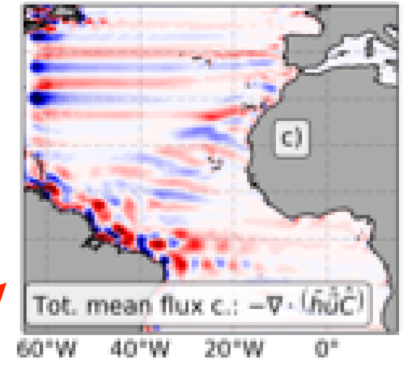
Budget of the ETNA OMZ at 23°W

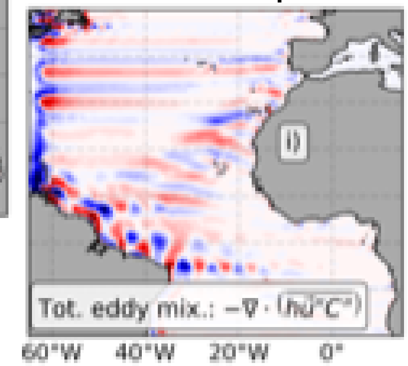


Hahn et al. (2014)

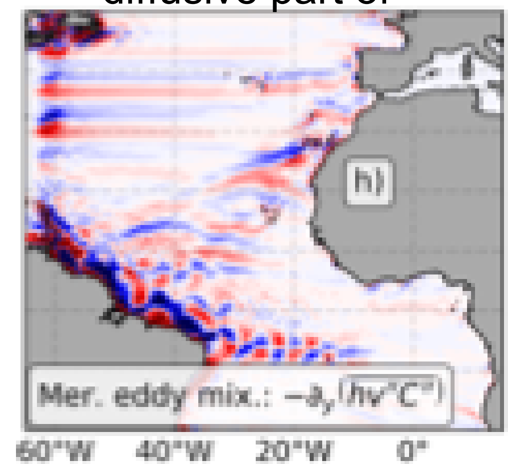
$$aOUR + O_{2,dia} + O_{2,y,eddy} + R_{O_2} = \partial_t O_2$$



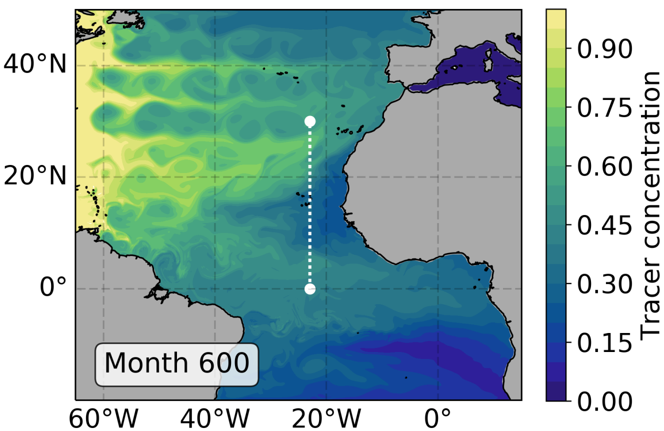
+ advective part of

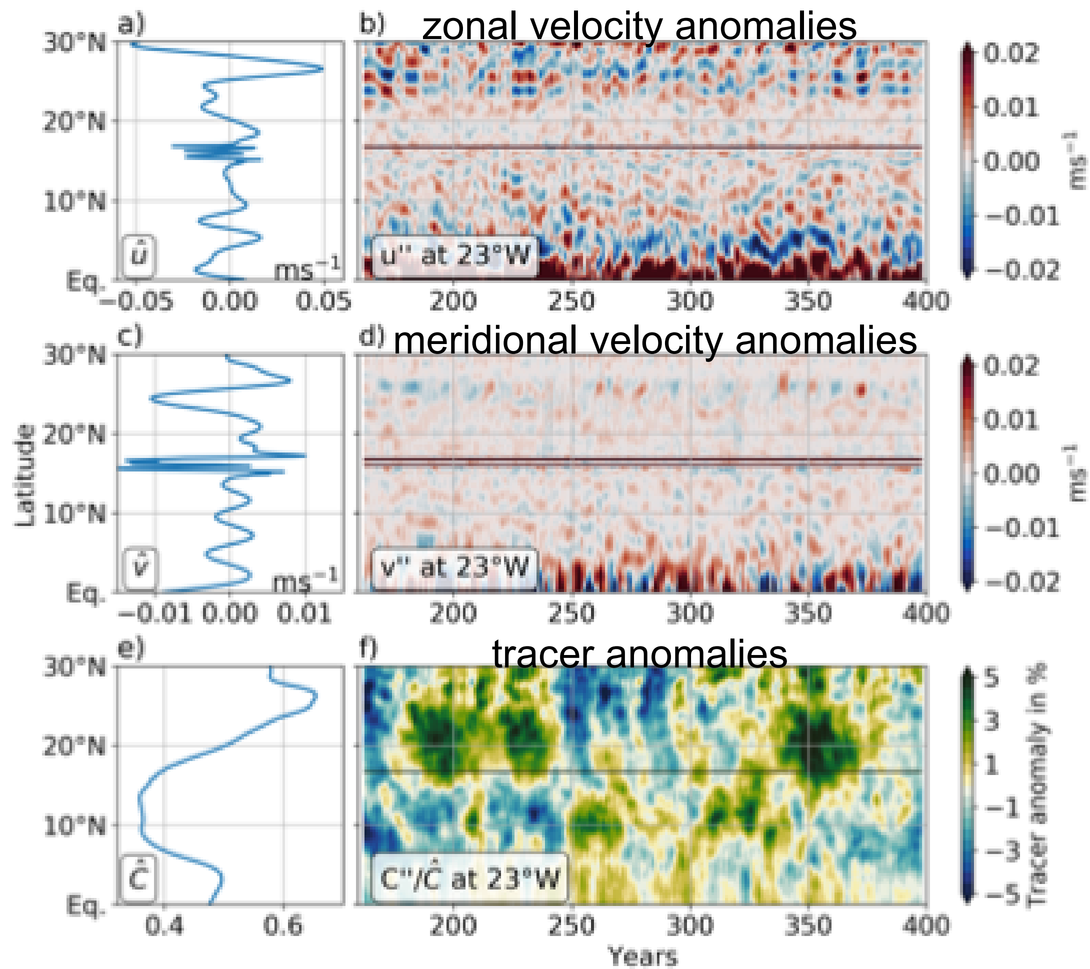


diffusive part of



Connection between zonal jet and tracer variability





- interannual jet variability and interdecadal tracer variability are hard to link

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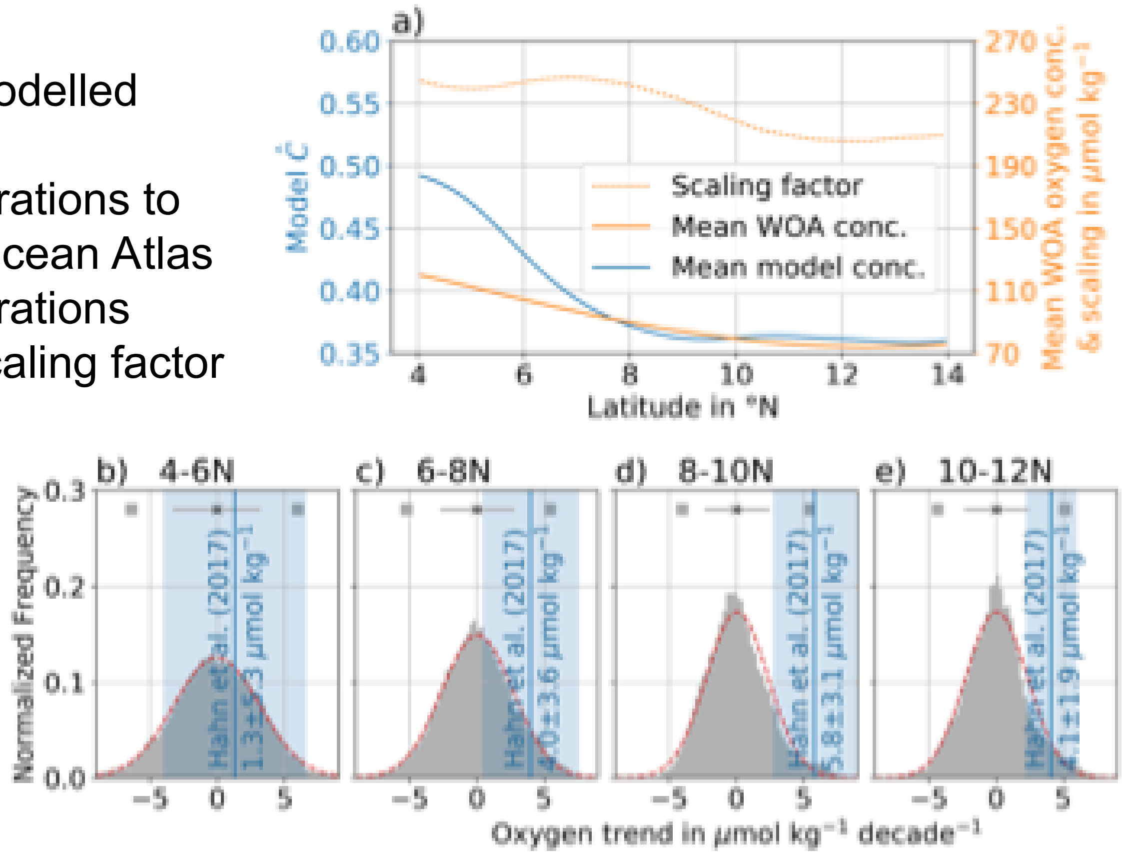
Comparison of modelled decadal trends at 23°W with observations

- scale modelled tracer concentrations to World Ocean Atlas concentrations using scaling factor



Observed decadal trends from Hahn et al. (2017) are possible realisations of modelled trends

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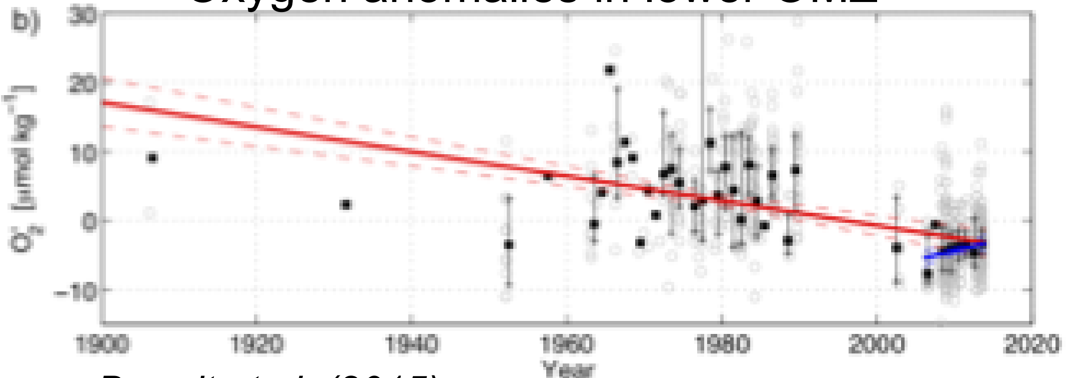
GEOMAR SFB 754

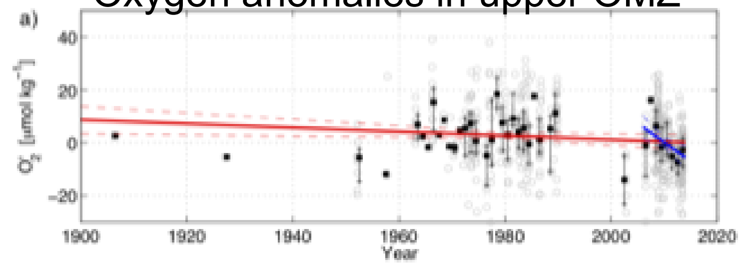
Compare trends for entire OMZ (9-15°N, 26-20°W)

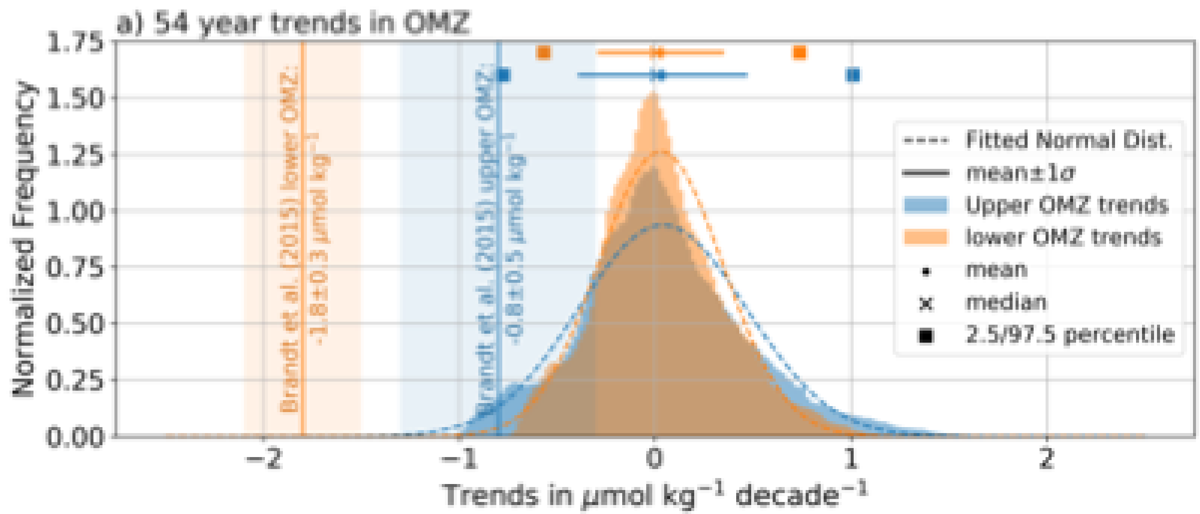
Oxygen anomalies in lower OMZ



Brandt et al. (2015)

Oxygen anomalies in upper OMZ

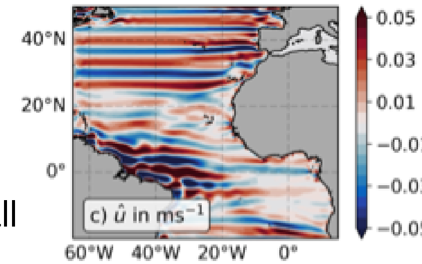


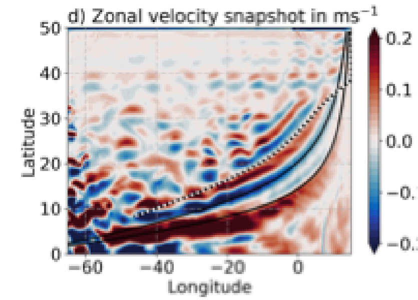


- Observed multi-decadal trends in lower OMZ are not captured by modelled tracer field

Summary

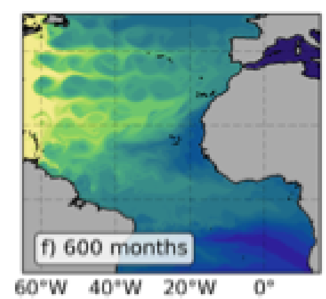
- the non-linear shallow water model is able to produce latitudinall alternating zonal jets by imposing an annual period forcing on the equator



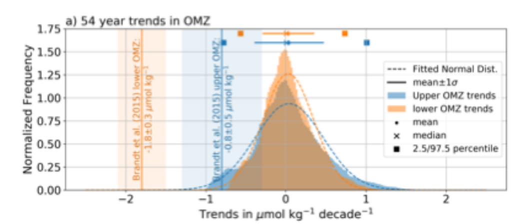


- non-linear triad resonance is the likely Rossby wave front instability mechanism

- a more or less realistic “oxygen minimum zone” is established, which is mainly ventilated by a mean advective flux convergence and the meridional component of the eddy mixing term



- interannual to interdecadal variability of the tracer concentration is generated - the observed long term decrease in oxygen is however not reproduced



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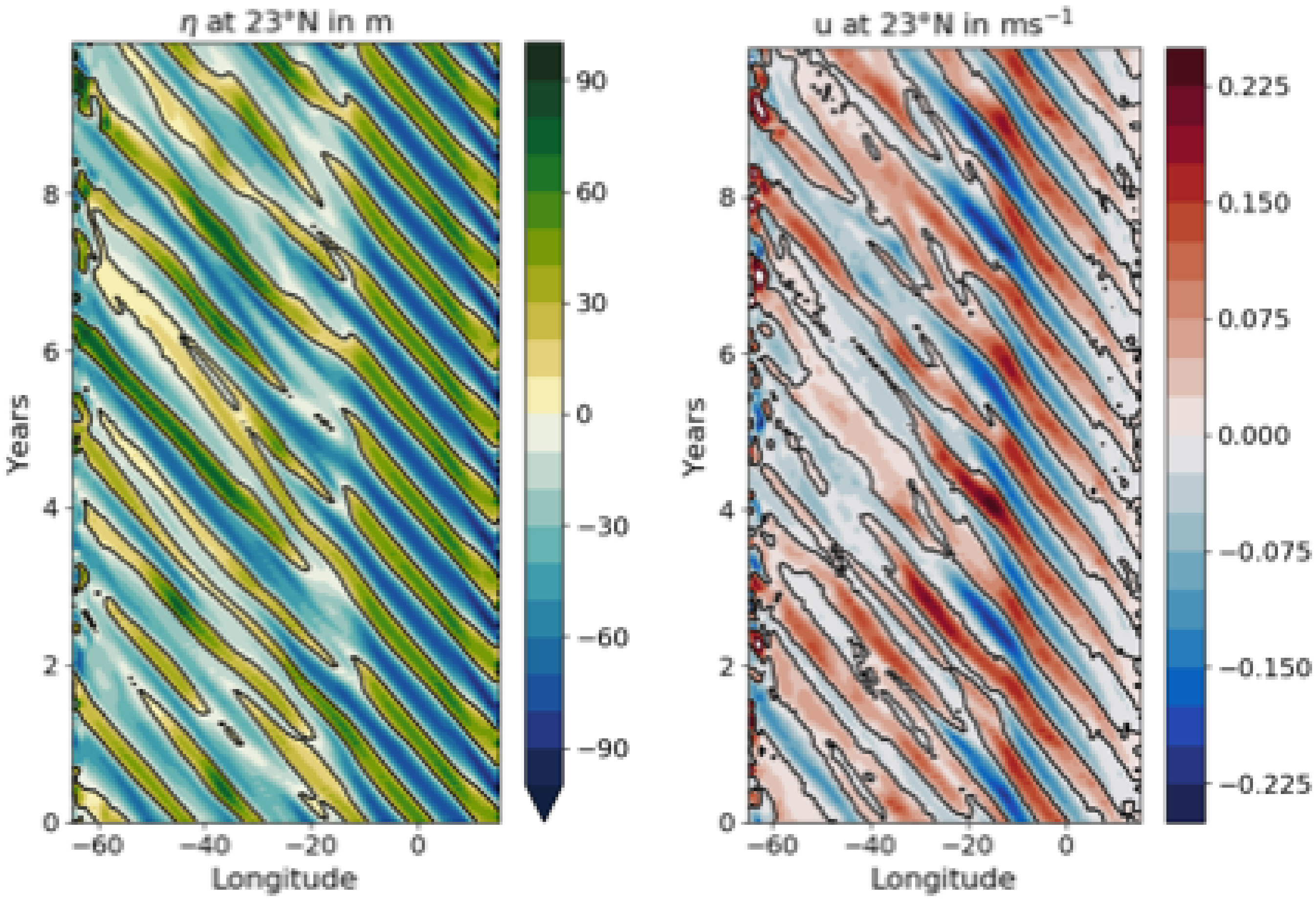
Zonal eddy propagation



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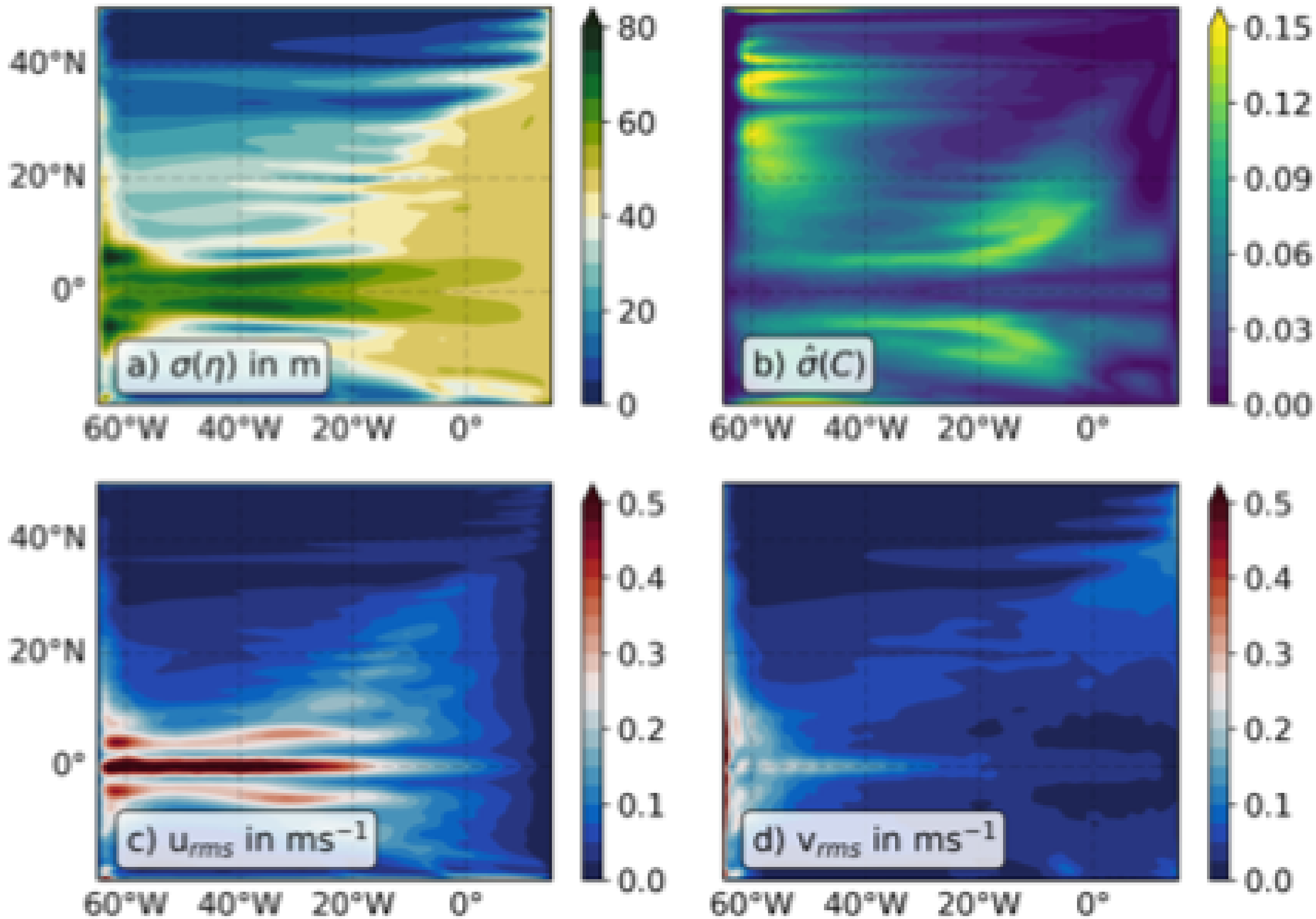
Variance



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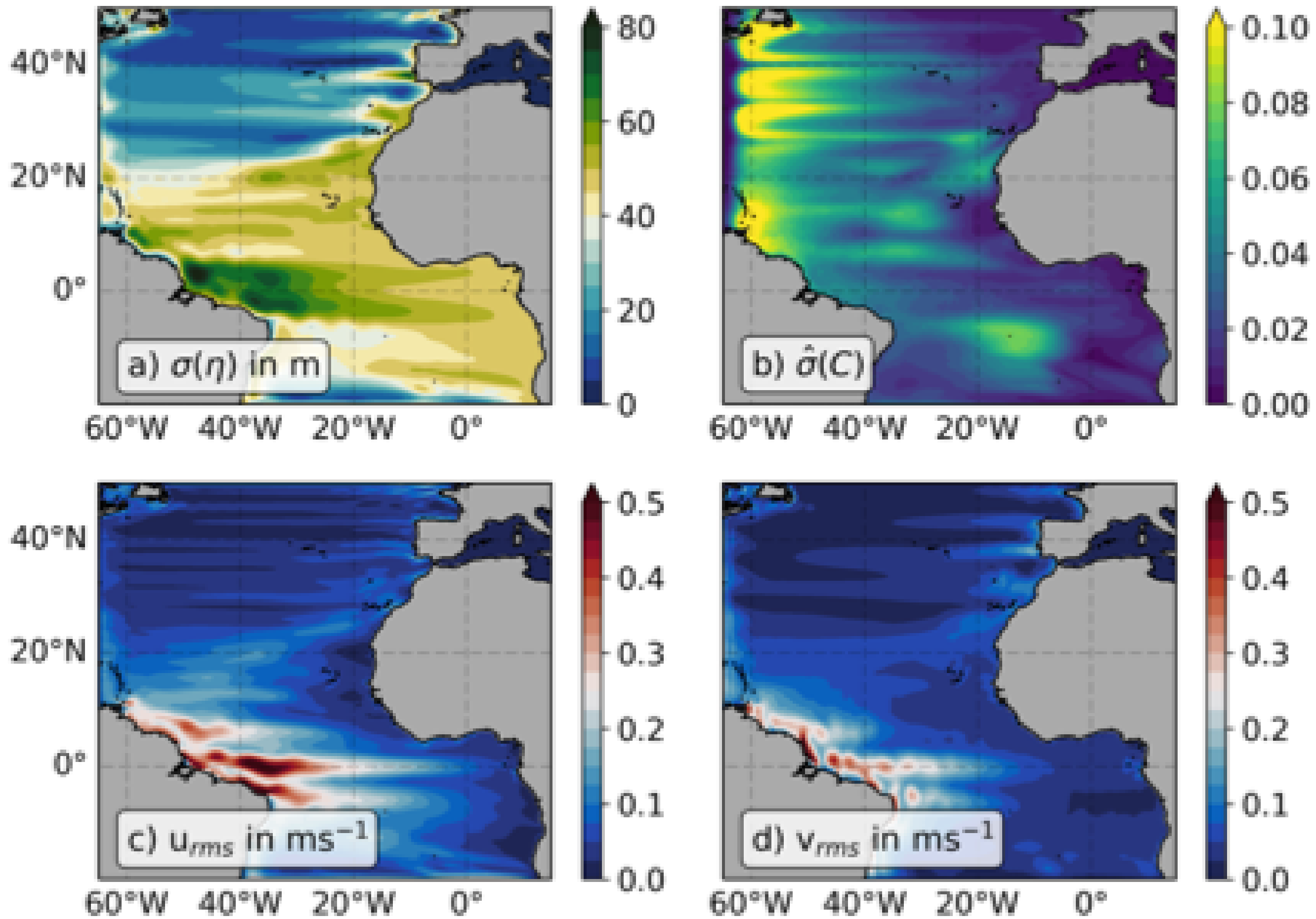
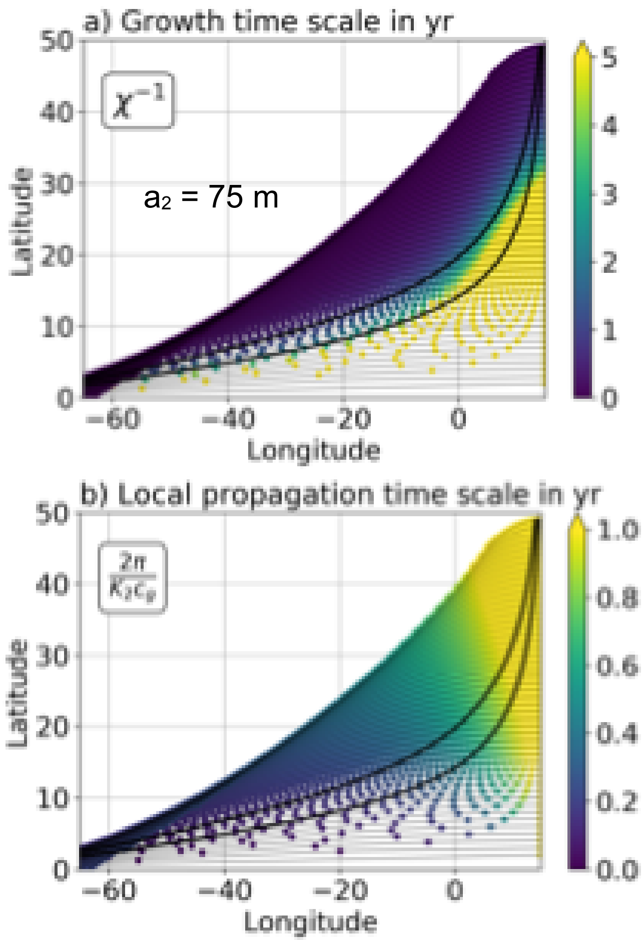
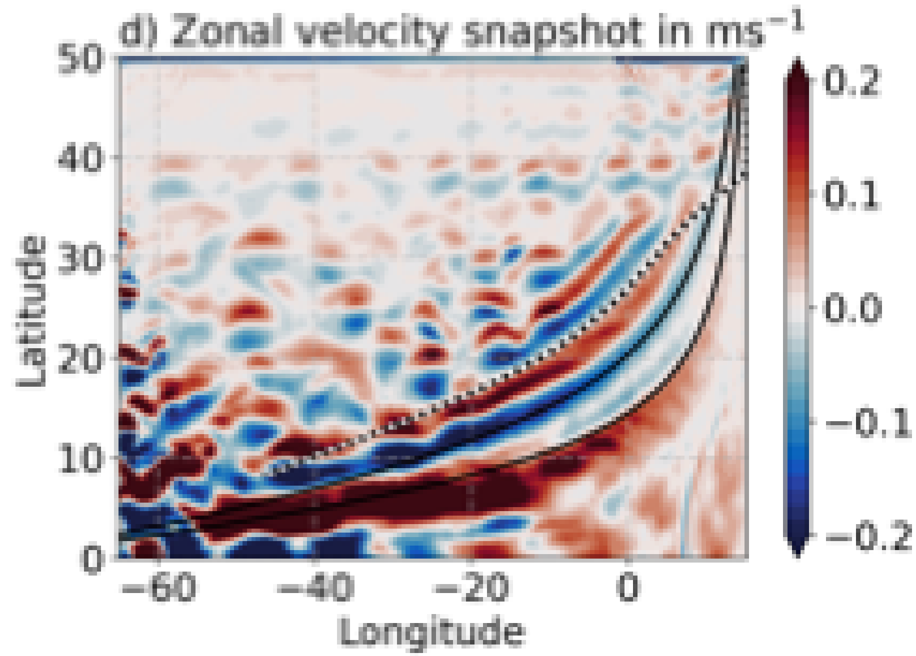
Variance



40°N
20°N
0°
60°W
40°W
20°W
0°
a) σ(η) in m
0
20
40
60
80
b) σ̂(C)
0.00
0.02
0.04
0.06
0.08
0.10
c) u_rms in ms⁻¹
d) v_rms in ms⁻¹
0.0
0.1
0.2
0.3
0.4
0.5

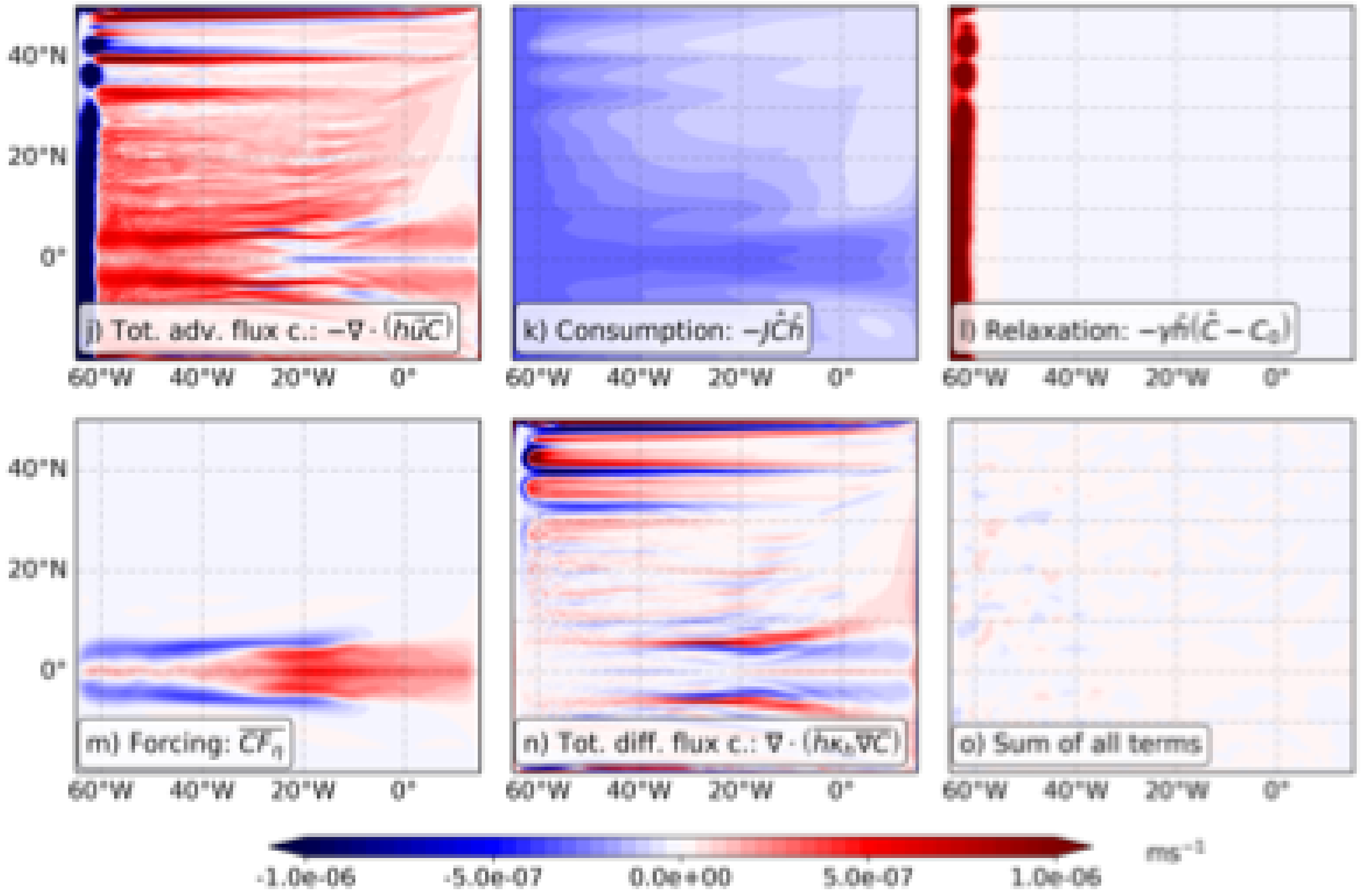
Zonal jet width - Non-linear triad instability



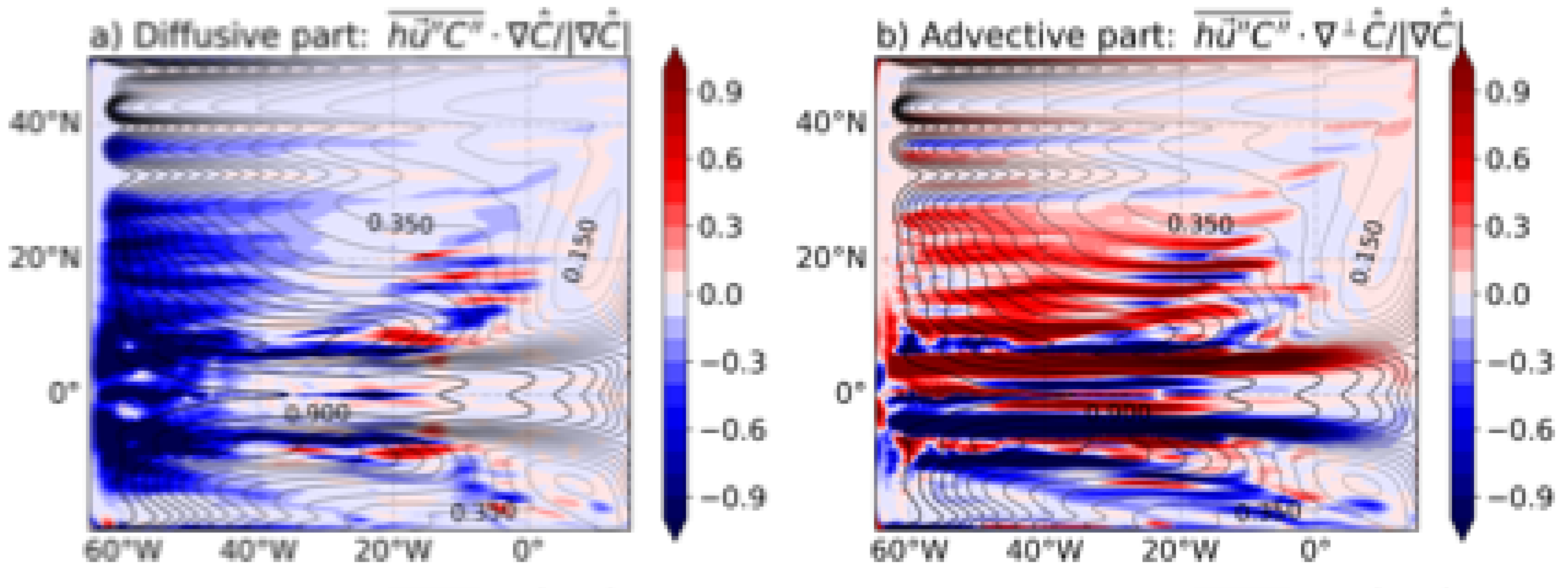


Projection onto the modelled field in spherical coordinates

Budget rectangle



Eddy mixing rectangle



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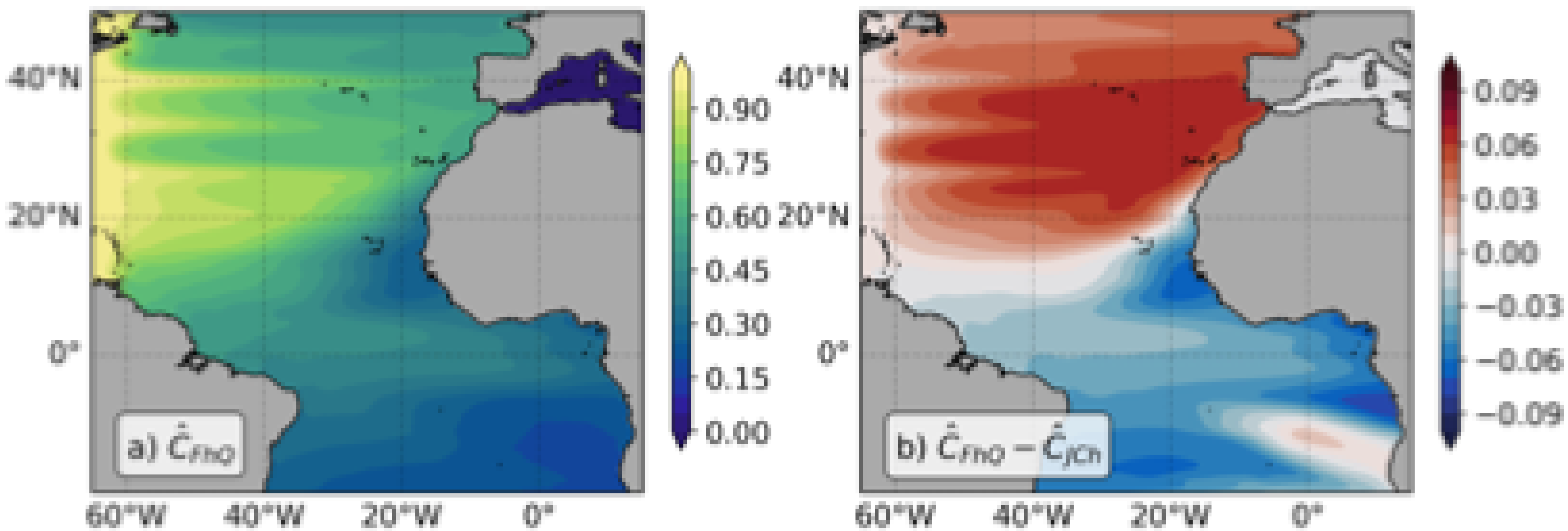
Different consumption scheme

consumption = -FhQ
F = 1 if C > 0.2
F = 0 else

as opposed to
consumption = -JCh



Different consumption scheme

consumption = -FhQ
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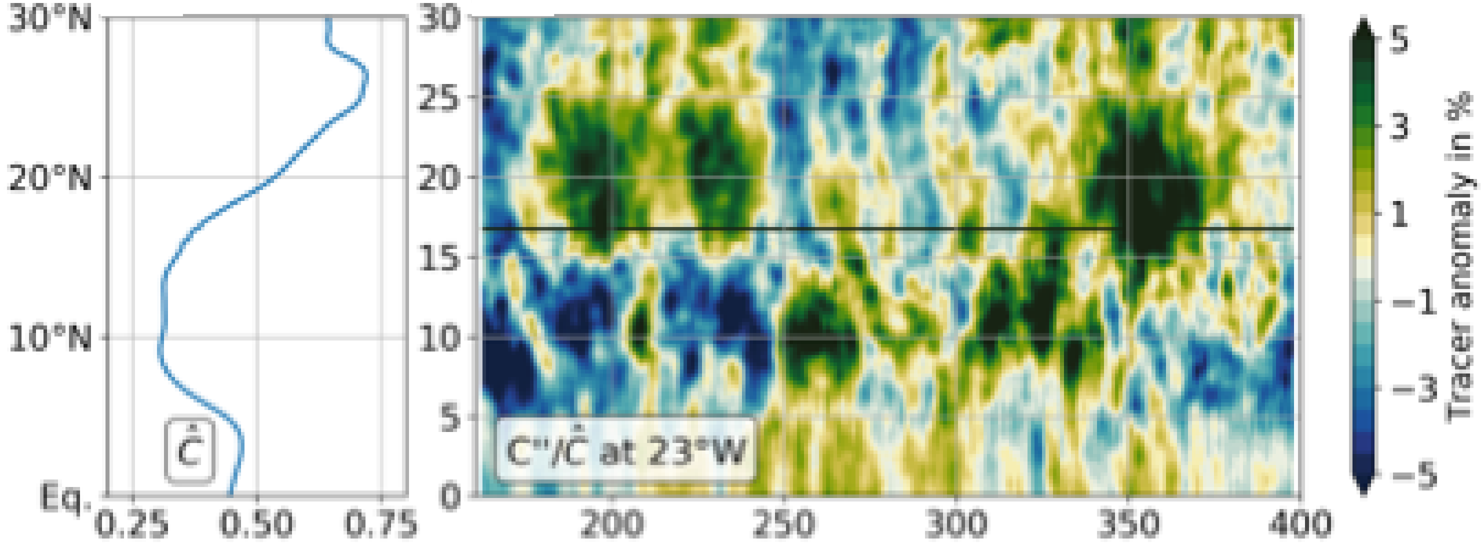
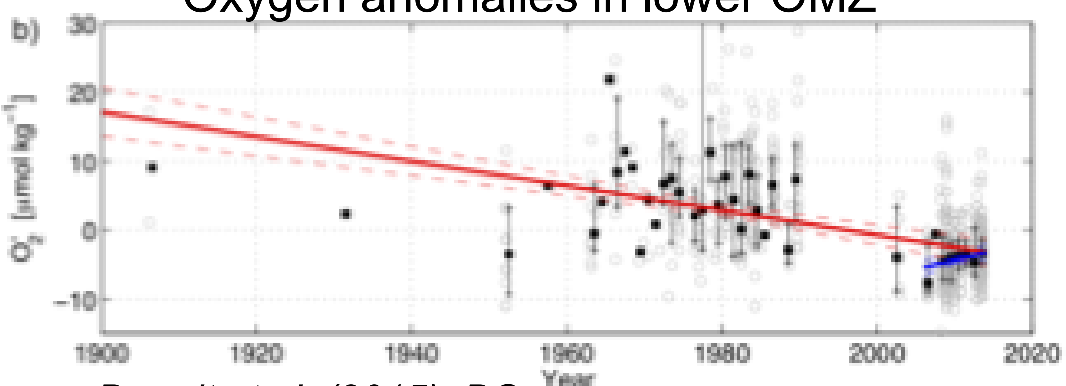
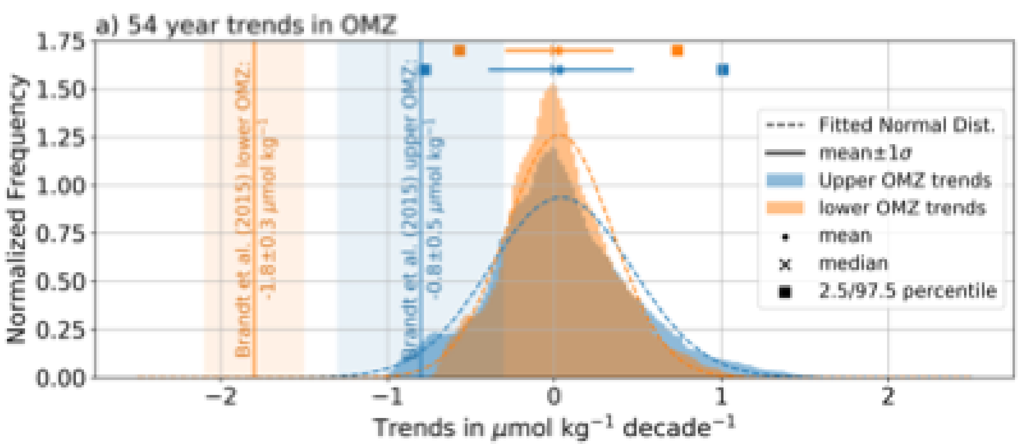


Compare trends for entire OMZ (9-15°N, 26-20°W)

Oxygen anomalies in lower OMZ



Brandt et al. (2015), BG



- ➡ to facilitate a comparison scale modelled tracer concentrations to World Ocean Atlas concentrations
- ➡ Observed multi-decadal trends in lower OMZ are not captured by modelled tracer field

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Merci beaucoup pour votre attention