Diabatic processes controlling the growth of long baroclinic oceanic waves

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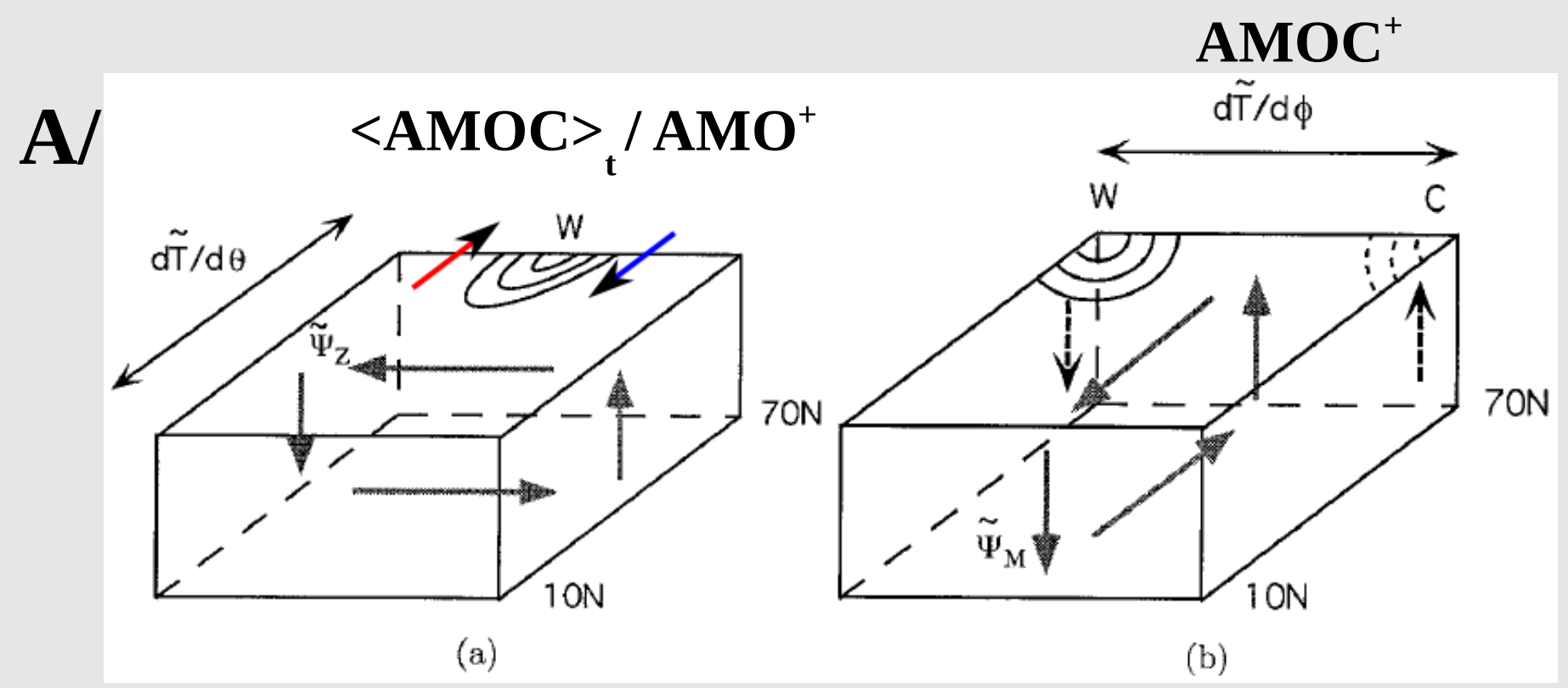
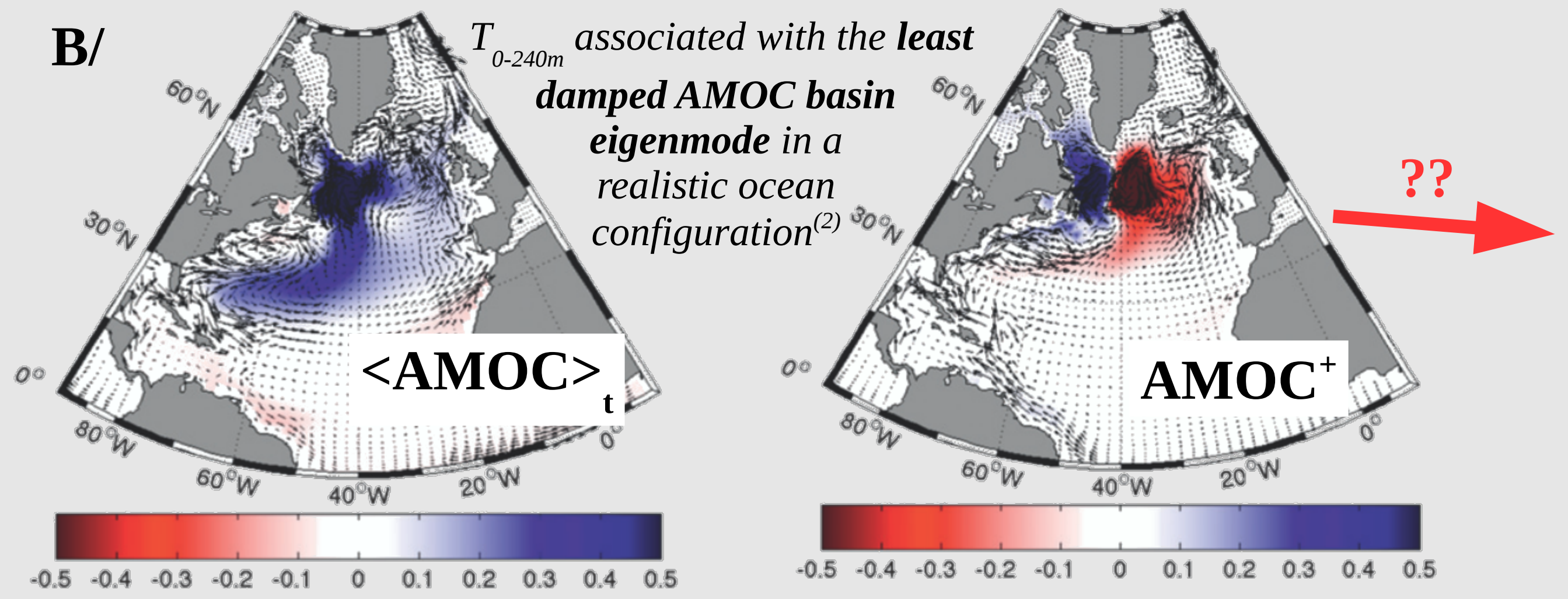
Motivation -- Hypotheses

A/



*Schematic diagram of the interaction between **large scale Rossby waves** and **AMOC low frequency variability**[1]*

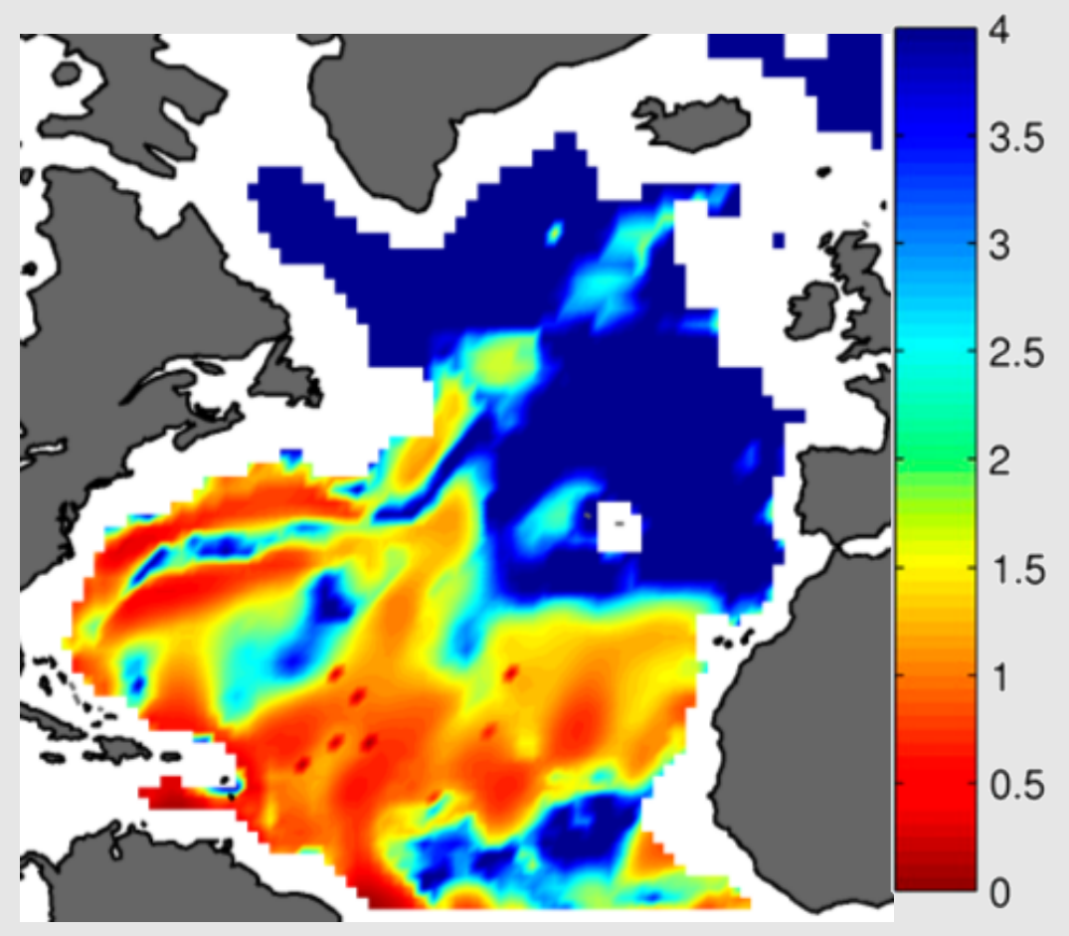
B/



*$T_{0\text{-}240m}$ associated with the **least damped AMOC basin eigenmode** in a realistic ocean configuration[2]*

C/

*Groth time of most **unstable local modes** of the observed oceanic mean state under the **Long Wave (LW) approximation**[3]*



What is the link between basin modes (B/)[2] and local unstable modes (C/)[3]?

Local linear Quasi-Geostrophic (QG) stability analysis

→ Linear theory of baroclinic instability[5,6] for a **local** problem, i.e. $\overline{N^2}=\overline{N^2}(z);\overline{\boldsymbol{u_g}}=\overline{\boldsymbol{u_g}}(z)$

- Linearizing the QG potential vorticity equation $(\partial_t+\boldsymbol{u_g}.\nabla_h)q=0$ with $q=\tilde{q}+f+\partial_z(\frac{f_0^2}{N^2}\partial_z\psi)$; $\tilde{q}=\nabla^2\psi$ **(1)** for perturbations of the form $\psi'=F(z)e^{i(kx+ly\boxed{-\omega t})}$

→ General eigenvalue problem

$$\begin{tikzcd} & \omega_i=0 \text{ Oscillatory mode} & \\ \boxed{\omega(k,l)\boldsymbol{A}F(z)=\boldsymbol{B}F(z)} \arrow[ur] \arrow[dr] & & \omega_i<0 \text{ Damped mode} \\ & \omega_i\neq0 \arrow[ur] \arrow[dr] & \\ & & \boxed{\omega_i>0} \text{ Unstable mode} \end{tikzcd}$$

Filtering Charney's modes

Long Wave (LW) approximation[3]

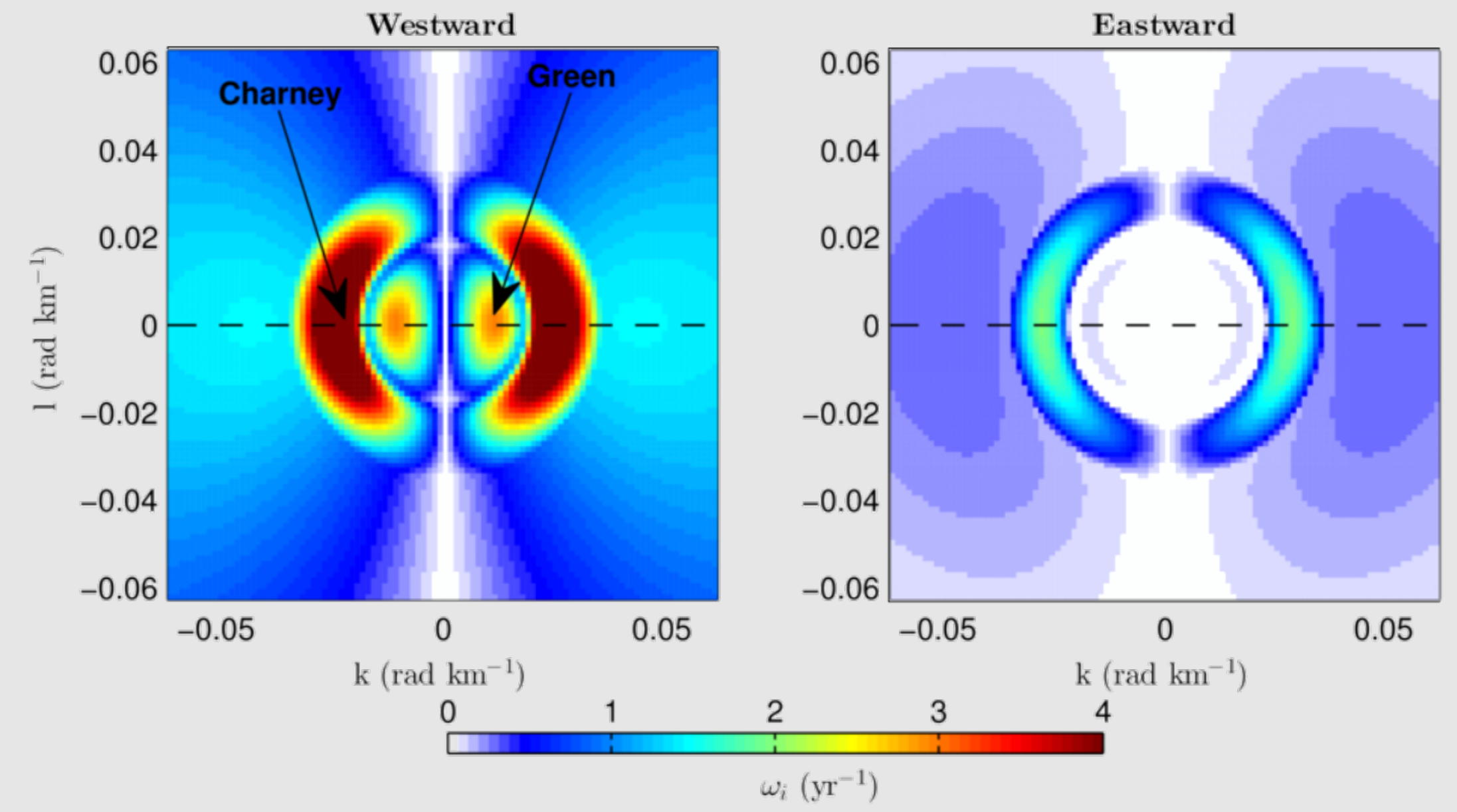
$$q=\cancel{\tilde{q}}+f+\partial_z(\frac{f_0^2}{N^2}\partial_z\psi)\quad \textbf{(2)} \longrightarrow C_i=\frac{\omega_i}{|\vec{k}|}$$

Diabatic processes

$$(\partial_t+\boldsymbol{u_g}.\nabla_h)q=\underbrace{A_h\nabla^2\tilde{q}}_{\text{Kinematic Eddy Viscosity (KEV)}}-\underbrace{\gamma\partial_z(\frac{f_0^2}{N^2}H(z-z_m)\partial_z\psi)}_{\text{Surface Restoring (SR)}}\quad \textbf{(3)}$$

Analytical experiments

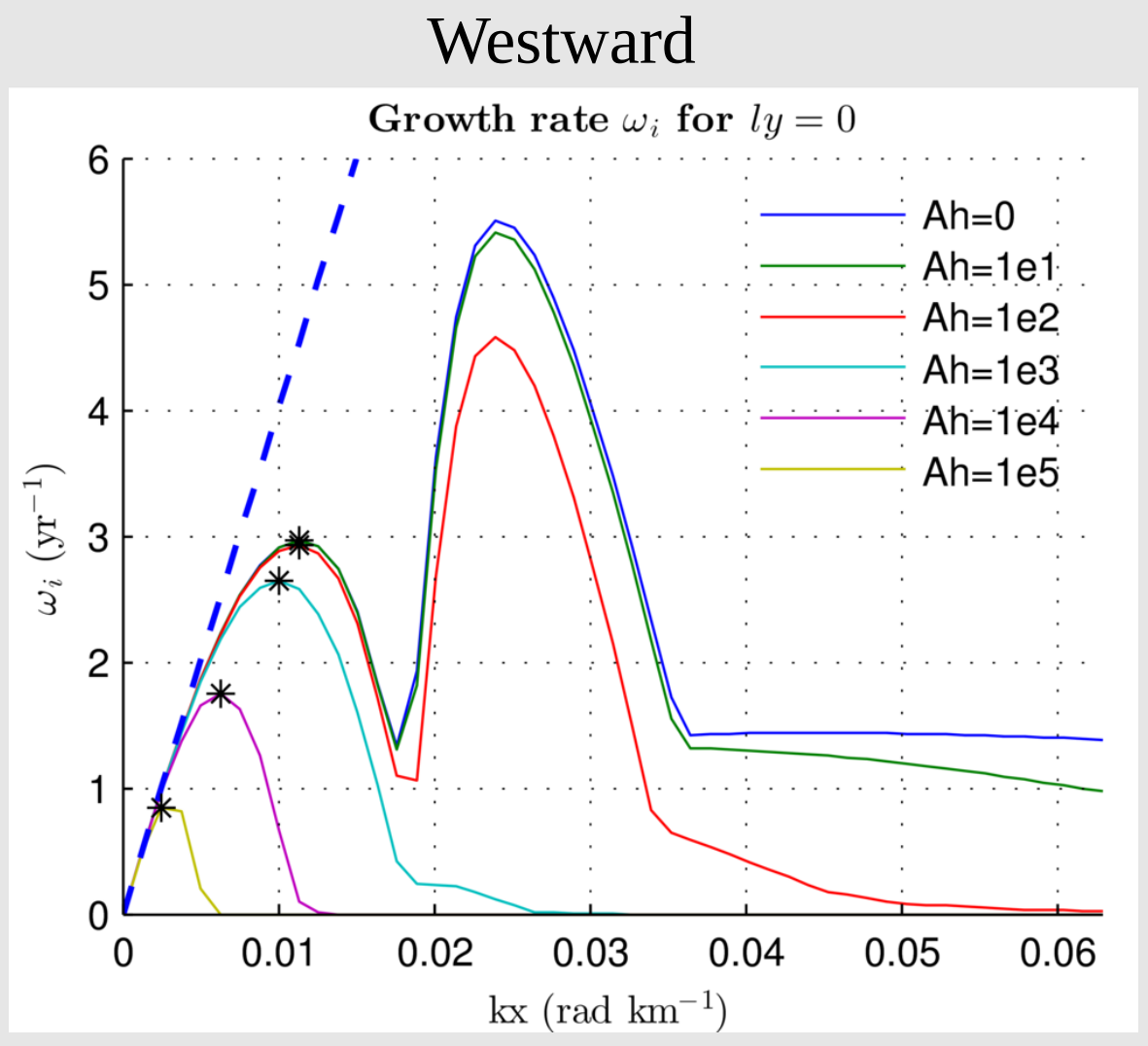
Adiabatic case



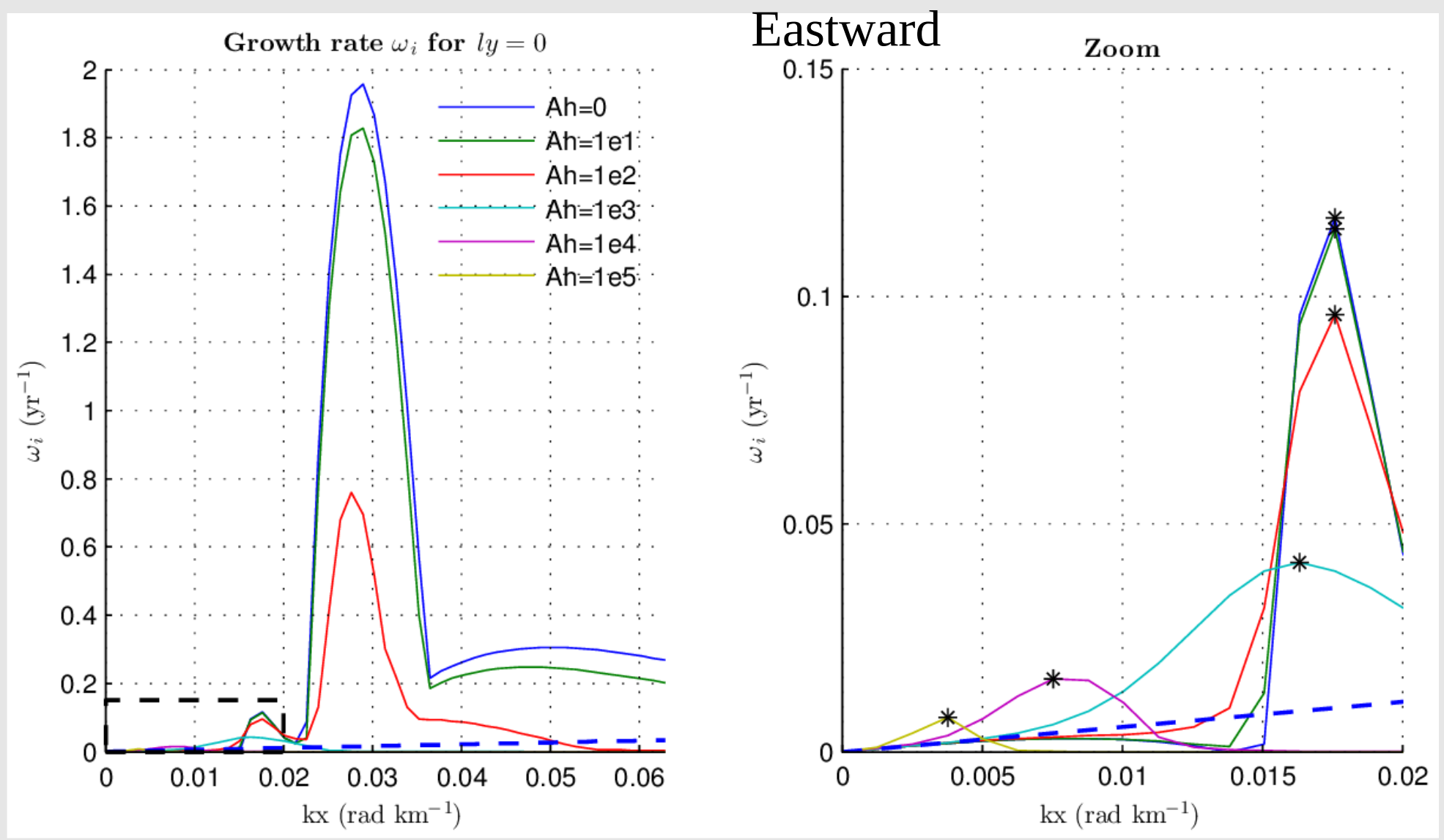
Growth rate $\omega_i(k,l)$ [yr^{-1}] of most unstable modes for an analytical stratification profile (N^2) balanced by a purely westward (left) and eastward (right) velocity shear.

Unstable modes grow about 3 times faster for a westward shear at meso-scale (Charney's modes[5]), consistent with a weaker negative mean PV meridional gradient at subsurface (not shown)

Kinematic eddy viscosity .vs. LW approximation

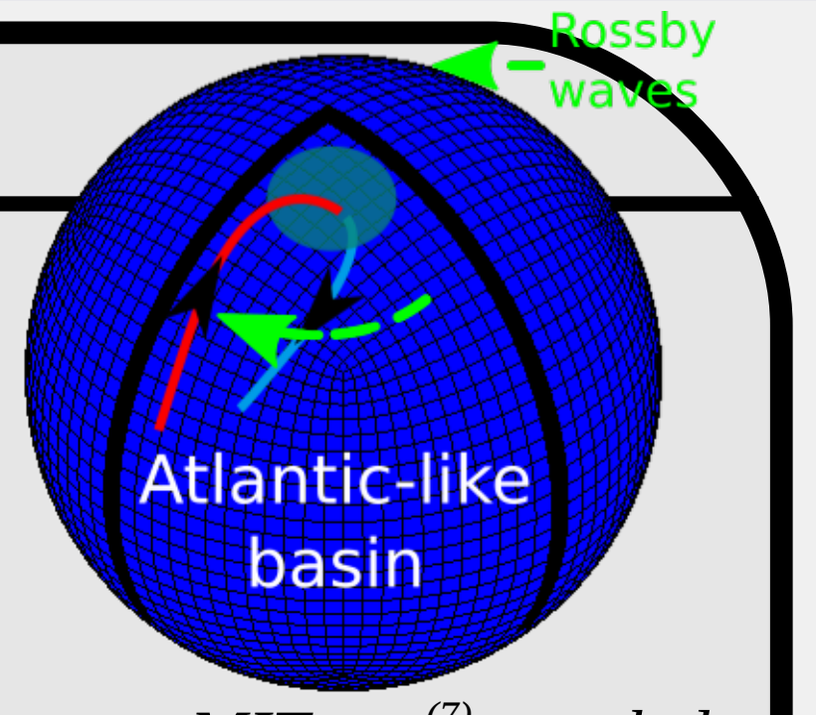


Growth rate $\omega_i(k,l=0)$ for l=0, for a westward (left) and an eastward (right) shear for various kinematic eddy viscosity coefficients (solid lines) and for the LW approx. (dashed lines; computed as $\omega_i=C_i*|k|$ with $|k|=2\pi/1000$ rad km^{-1})



- Unstable modes grow about 1000 times faster for a westward shear at large-scale (Green's modes[6]), consistent with a much larger imaginary part of the longwave eigenvalue C_i
- The kinematic eddy viscosity effect:
  - Westward shear: **damping** at all |k|
  - → Eastward shear: **increase growth rate for small wavenumbers**
- Result reproduced in a **2.5 layers QG model** and under the **Planetary-Geostrophic** (PG) appx.
  - → Does not rely on the **vertical resolution** nor the **QG approximation**

Application to a numerical model



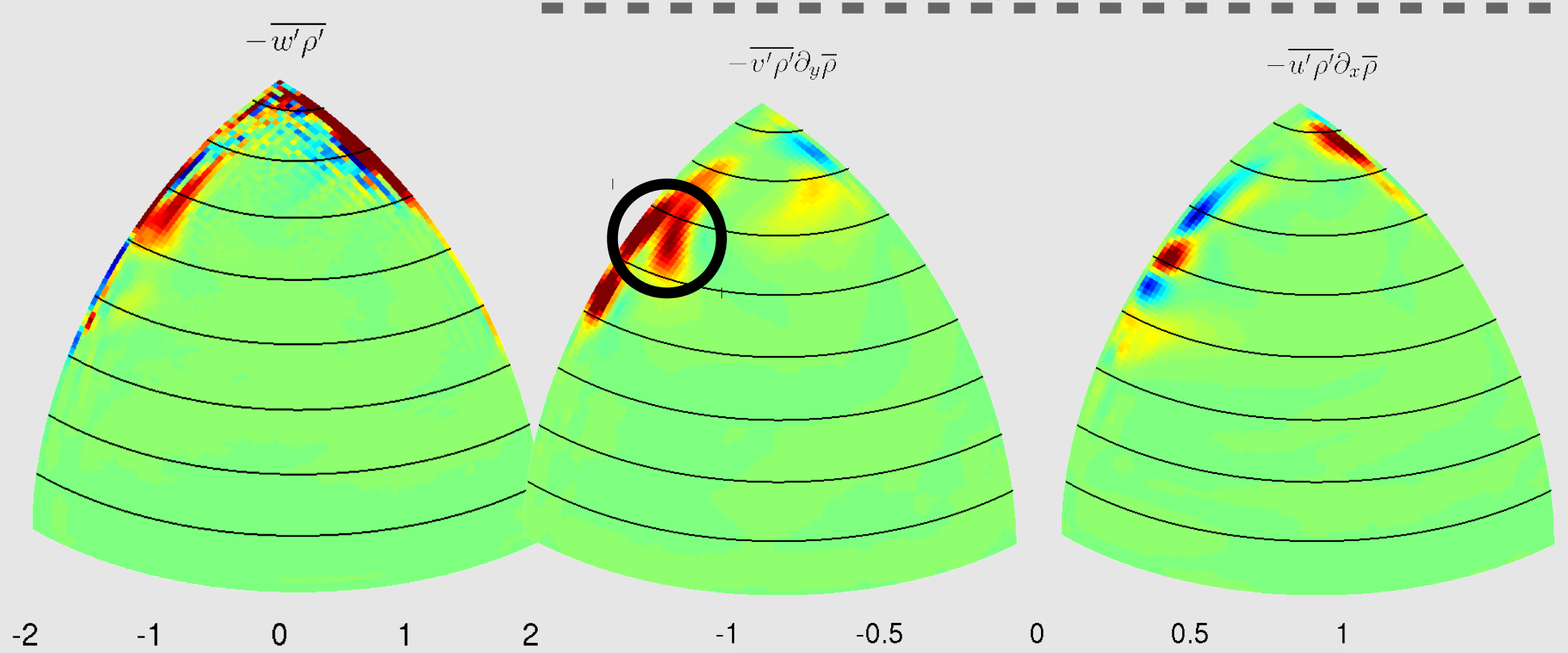
MITgcm[7] coupled configuration at 1° with an idealized flat bottom ocean geometry[8]

Double Drake[8] configuration at 1°:

→ 30-40 yr 'A'MOC variability associated with large scale Rossby waves[9,10].

→ **Where and how these large scale waves are generated?**

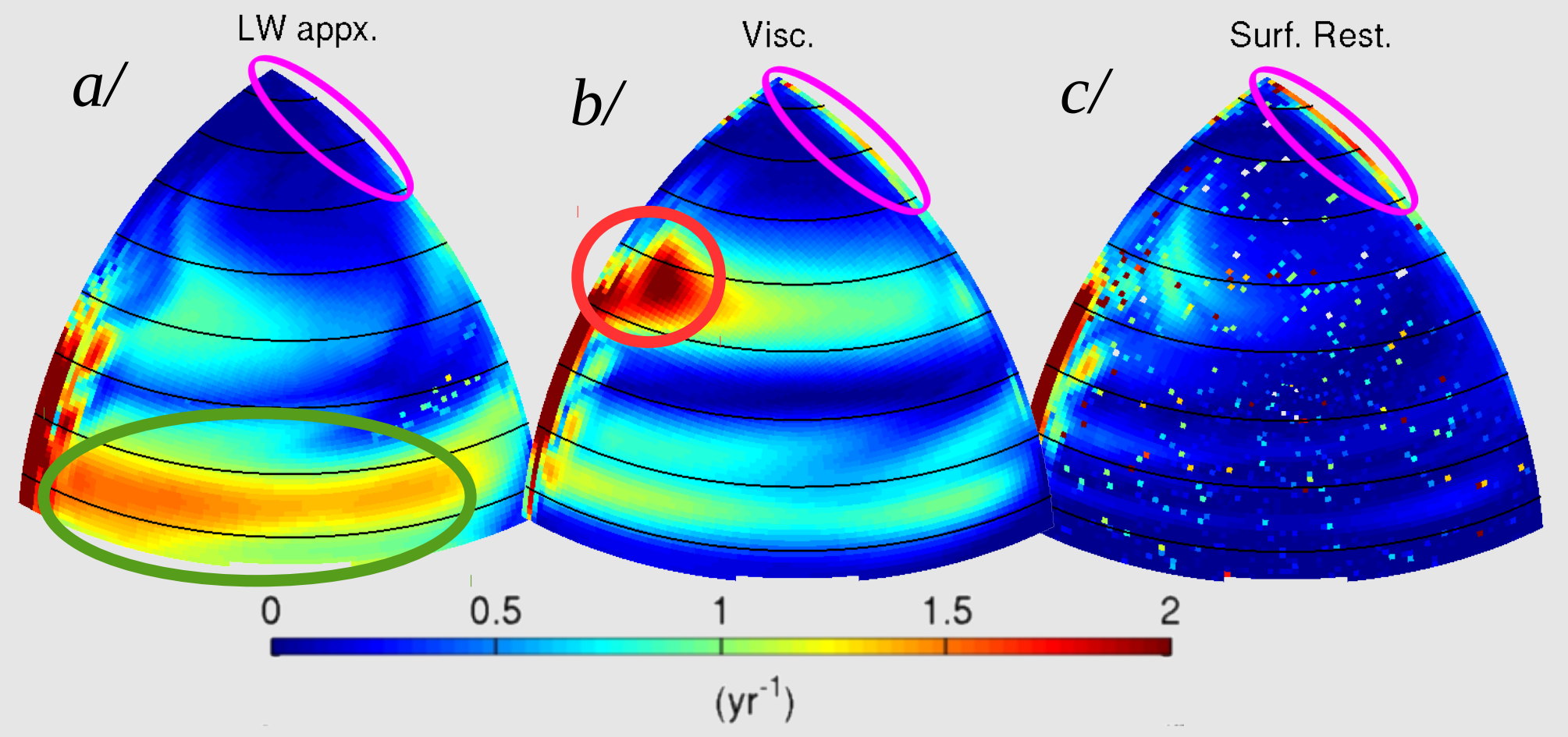
A/ Diagnosing baroclinic energy conversion regions



Vertical eddy fluxes $-\overline{w'\rho'}$ (left) and zonal (middle) and meridional (right) contributions of the downgradient eddy density fluxes $-\overline{\boldsymbol{u}'\rho'}\nabla\overline{\rho}$

- 2 active regions at high latitudes:
  - → Western boundary: $(\partial_y\overline{\rho}\propto\overline{u_g})$ instability of the **zonal current**
  - → Eastern boundary: $(\partial_x\overline{\rho}\propto\overline{v_g})$ instability of the **meridional current**
- **Local instability** of the oceanic mean state?

B/ Local linear QG stability analyses of the oceanic mean state



*Growth rate ω_i of most unstable modes within the Atlantic-like basin for 3 stability analyses, i.e. a/ under the LW appx. (eq. **(2)**), b/ with KEV only in eq. **(3)** and **A_h= 4 10^4 m^2 s^{-1}**, and c/ with an additional surface restoring (eq. **(3)**)*

- Most unstable modes found at **low latitudes** under the **LW approximation**
  - → Weak coherence with the NL model solution
- Mid- and low-latitudes unstable modes damped by surface restoring

→ **Eastern boundary current unstable for a wide range of length-scale**

	A/ Diagnostic approach	**B/ Prognostic approach**
Low-latitudes ○	✗ No large scale waves	✔ Most unstable regions under the LW appx.
Mid-latitudes ○	✗ No large scale waves	✔ Most unstable region in adiabatic and viscous conditions, but damped by surface restoring
Western boundary (>50°N) ○	✔ Baroclinic energy conversion	✗ Weakly unstable
Eastern boundary (>60°N) ○	✔ **Baroclinic energy conversion**	✔ **Unstable for a wide range of length-scale**

CONCLUSIONS

Growth of large scale Rossby waves in the North Atlantic does not satisfy the LW approximation[3], but is rather controlled by diabatic processes

**Proposed mechanism for the Double Drake:
Radiative baroclinic instability of the eastern boundary current[11]**

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