JGR Oceans

RESEARCH ARTICLE

AGU ADVANCING EARTH AND SPACE SCIENCE

On the Deep Western Boundary Current Separation and Anticyclone Genesis off Northeast Brazil

A separação da Corrente de Contorno Oeste Profunda e formação de anticiclones no nordeste do Brasil

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d) UMass Dartmouth

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2. Dados hidrográficos
3. Saídas de modelo global
4. Conclusões

Corrente de Contorno Oeste Profunda e AMOC

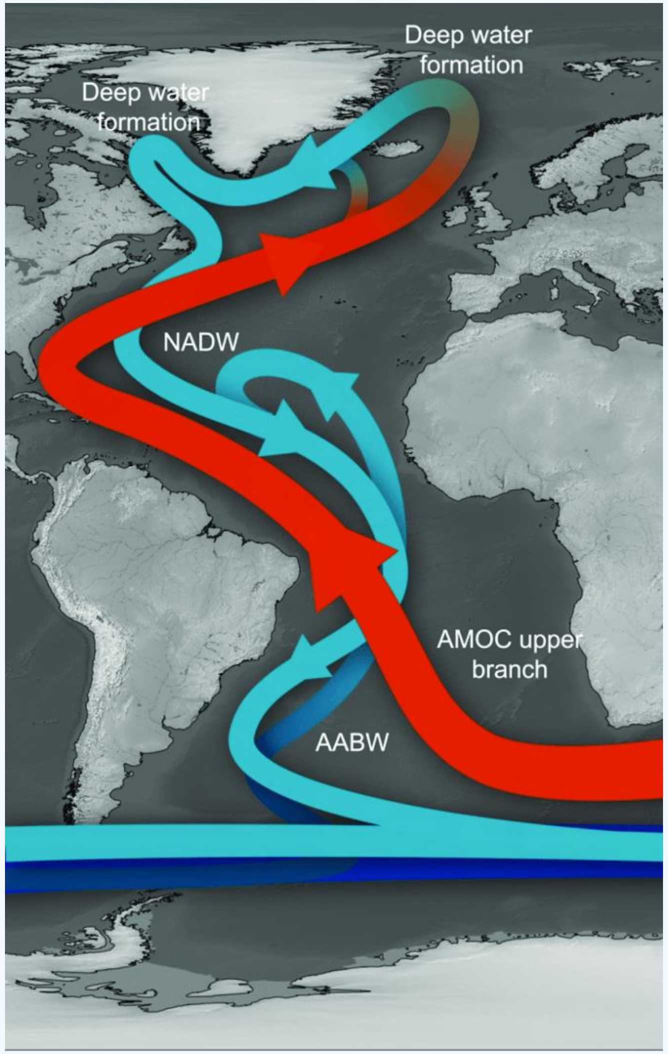

Figura extraída da tese de PhD de Stefano Crivellari (IGC, USP).

I. A Corrente de Contorno Oeste Profunda (CCOP ou DWBC) transporta o ramo inferior da Célula de Revolvimento Meridional do Atlantico (AMOC; Rintoul, 1991 e Gordon, 1991).
   - A CCOP transporta a **Água Profunda do Atlantico Norte** (APAN) do Hemisfério Norte para o Hemisfério Sul (Talley et al., 2011).

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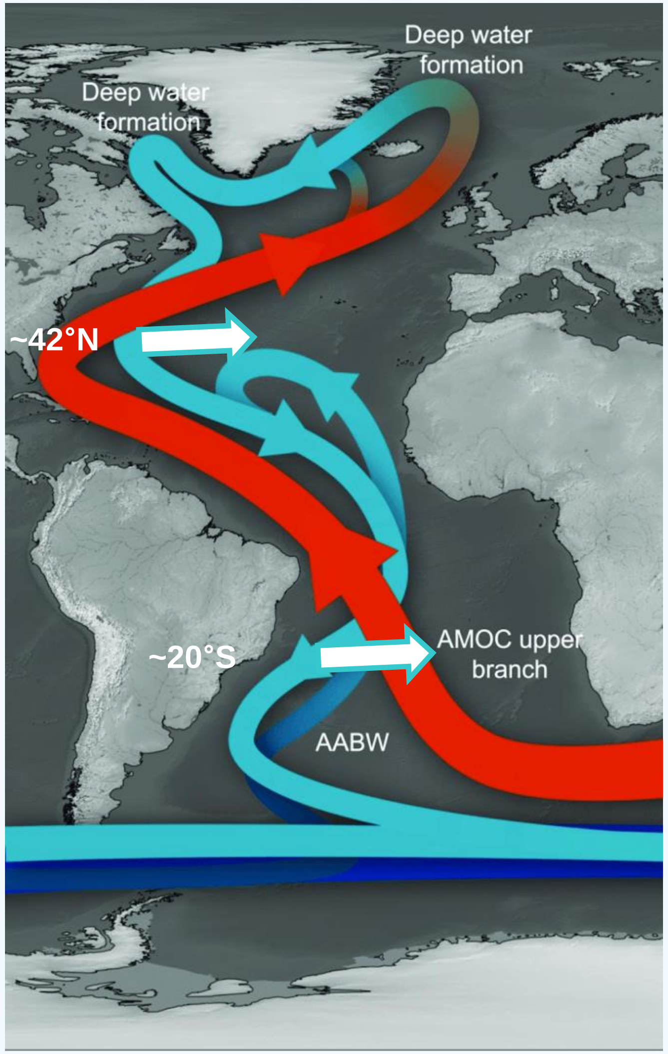

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II. A CCOP exporta a APAN para o interior do Atlântico em **regiões de "vazamento"** como observado:
   - ao sul da *Newfoundland Basin* (~42°N; Bower et al., 2009; Solodoch et al. 2020);
   - na cadeia de montes submarinos Vitoria-Trindade (~20°S; van Sebille et al. 2012; Garzoli et al., 2015).

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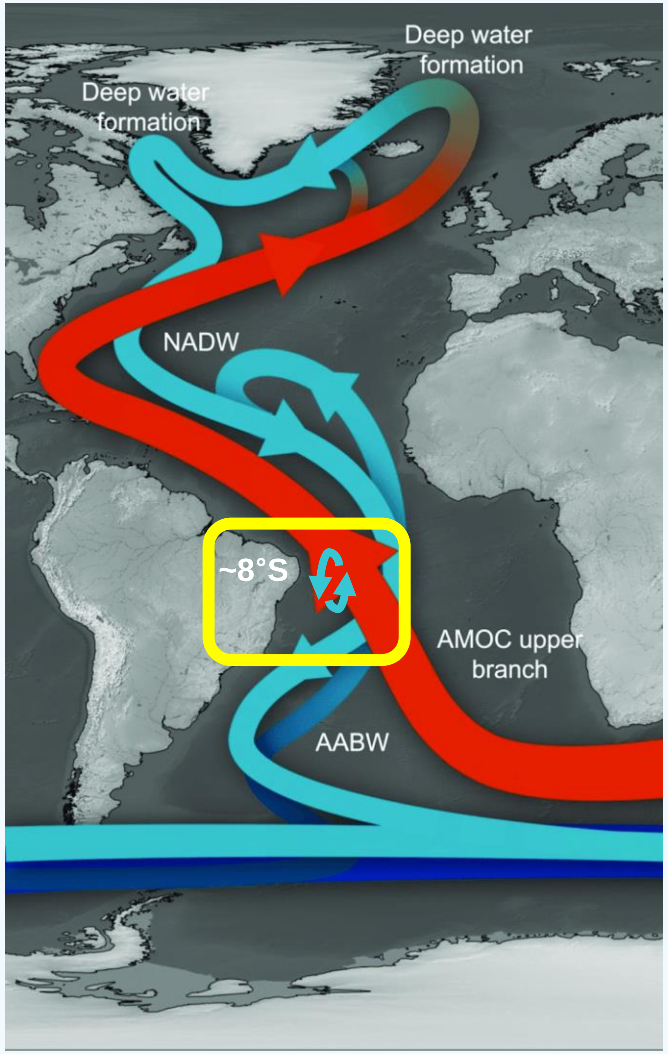

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III. Dengler et al. (2004) reportaram que a CCOP “se quebra”, na latitude de 8°S, em **anticiclones que migram para sudoeste**.
   - Parte da CCOP deflete para leste ao contornar a cadeia Vitoria-Trindade em ~20°S (van Sebille et al. 2012);
   - Outra parte da CCOP, ~78% do transporte, se reorganiza como corrente de contorno oeste ao cruzar os montes submarinos em 20°S (Garzoli et al., 2015)

Os anticiclones da CCOP em 8°S

- Near the Equator, Garzoli et al. (2015) estimated a NADW volume transport of **~14 Sv**;
- At 5°S, the DWBC flows as a continuous jet, with maximum mean velocities of **0.20 m s^{-1}** spanning from **1,200 to 4,000 m depths** (Schott et al., 2005);
- Further south, Dengler et al. (2004) identified **anticyclones at ~2,000 m** with **~100 km radii** using lowered-ADCP data and a mooring array **at 11°S**.

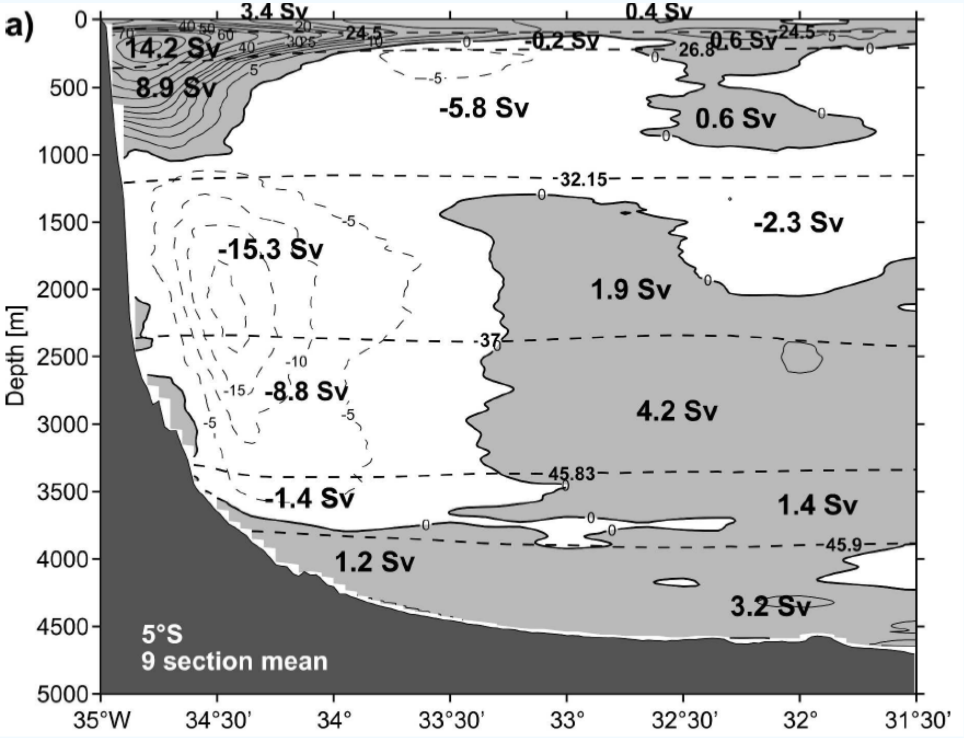
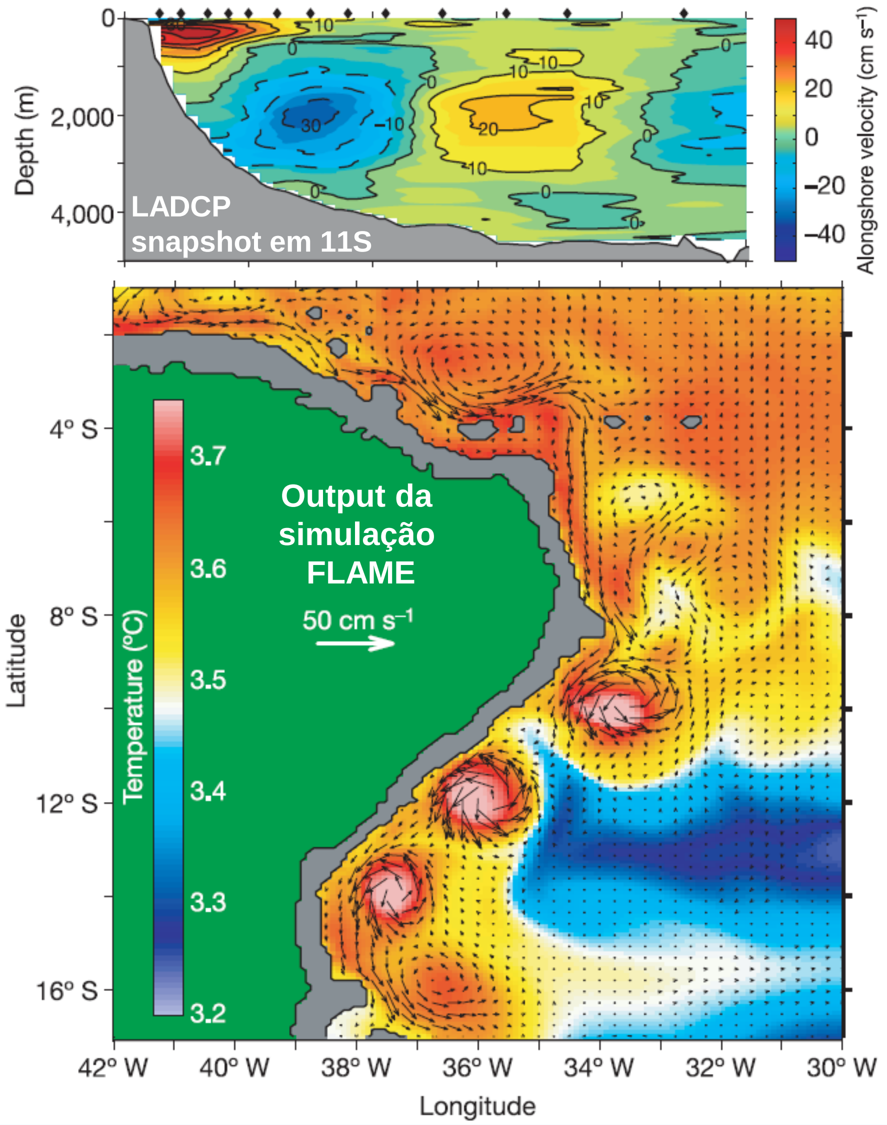


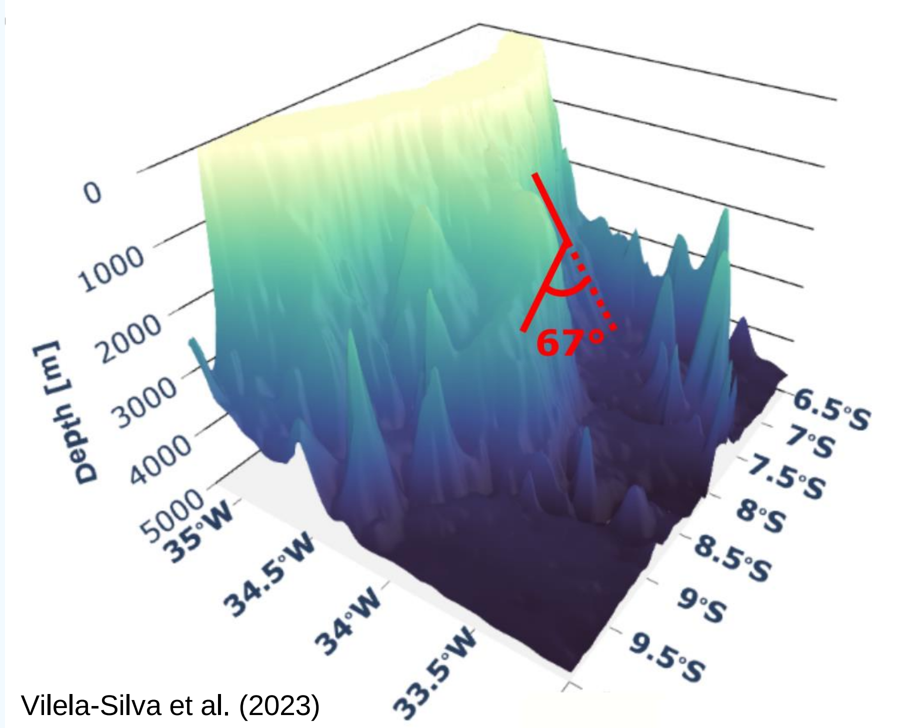
Figura extraída de Schott et al. (2005)



Figuras extraídas de Dengler et al. (2004)

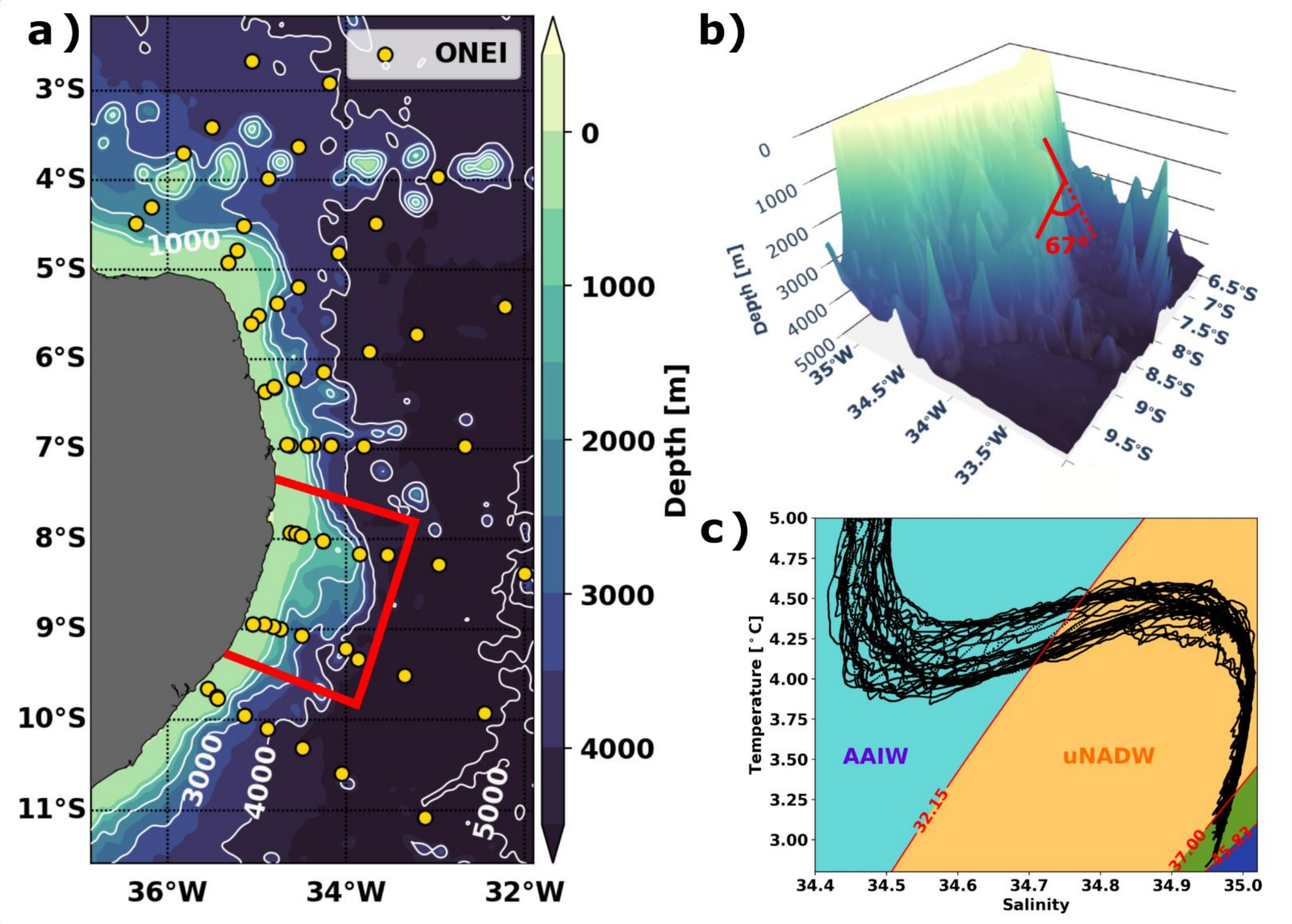
O Platô de Pernambuco

- Little is known about the observed DWBC structure and the eddy formation dynamics around 8°S.
  - The region delimits the location of the **Pernambuco Plateau** (PP; Kowsmann & Costa, 1976);
  - This feature marks a significant change in the continental slope orientation (67°).



O Platô de Pernambuco e a Operação Oceano Nordeste I

- We propose that the Pernambuco Plateau alters the DWBC flow resulting in eddy genesis. We explore this hypothesis with hydrographic observations, eddy-resolving numerical model outputs, and theory;

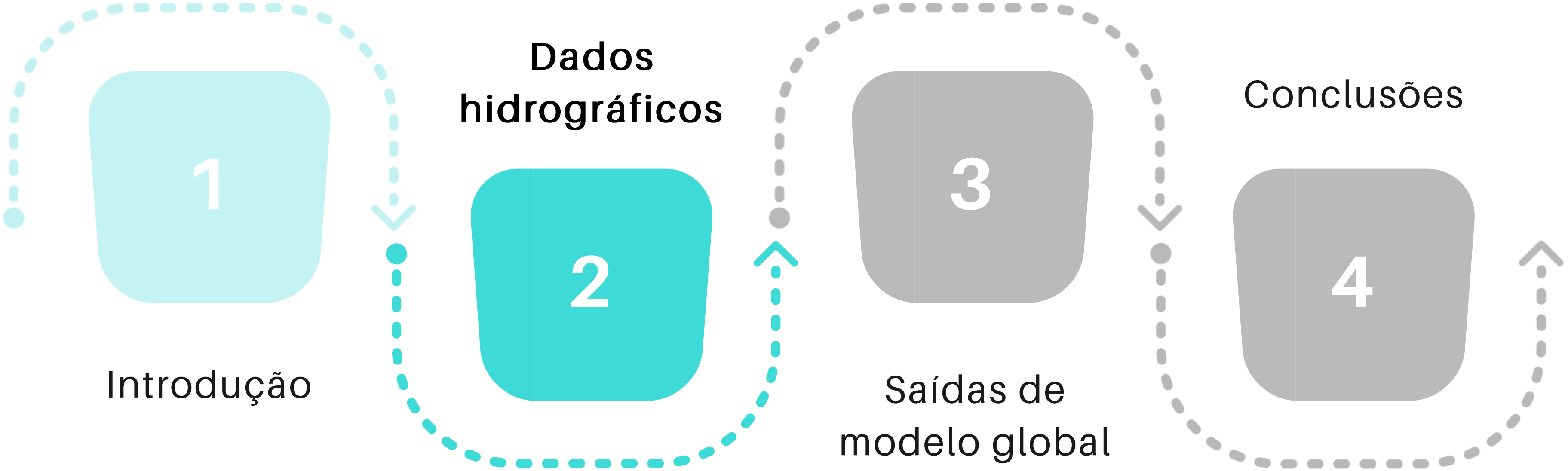


Vilela-Silva et al. (2023)

- *Oceano Nordeste*:
  - historical hydrographic data set carried out by the Brazilian Navy between 26 Feb and 21 Mar 2002;
  - **8 transects (57 stations) off northeast Brazil**;

- The $\sigma 1 = 32.15$ kg m−3 marks the boundary between the Antarctic Intermediate Water (AAIW) and the NADW (Rhein et al., 1995; Schott et al., 2002).
  - While the AAIW is transported equatorward, the DWBC transports the NADW poleward;
  - We set the **AAIW-NADW interface as the level of no-motion.**

OUTLINE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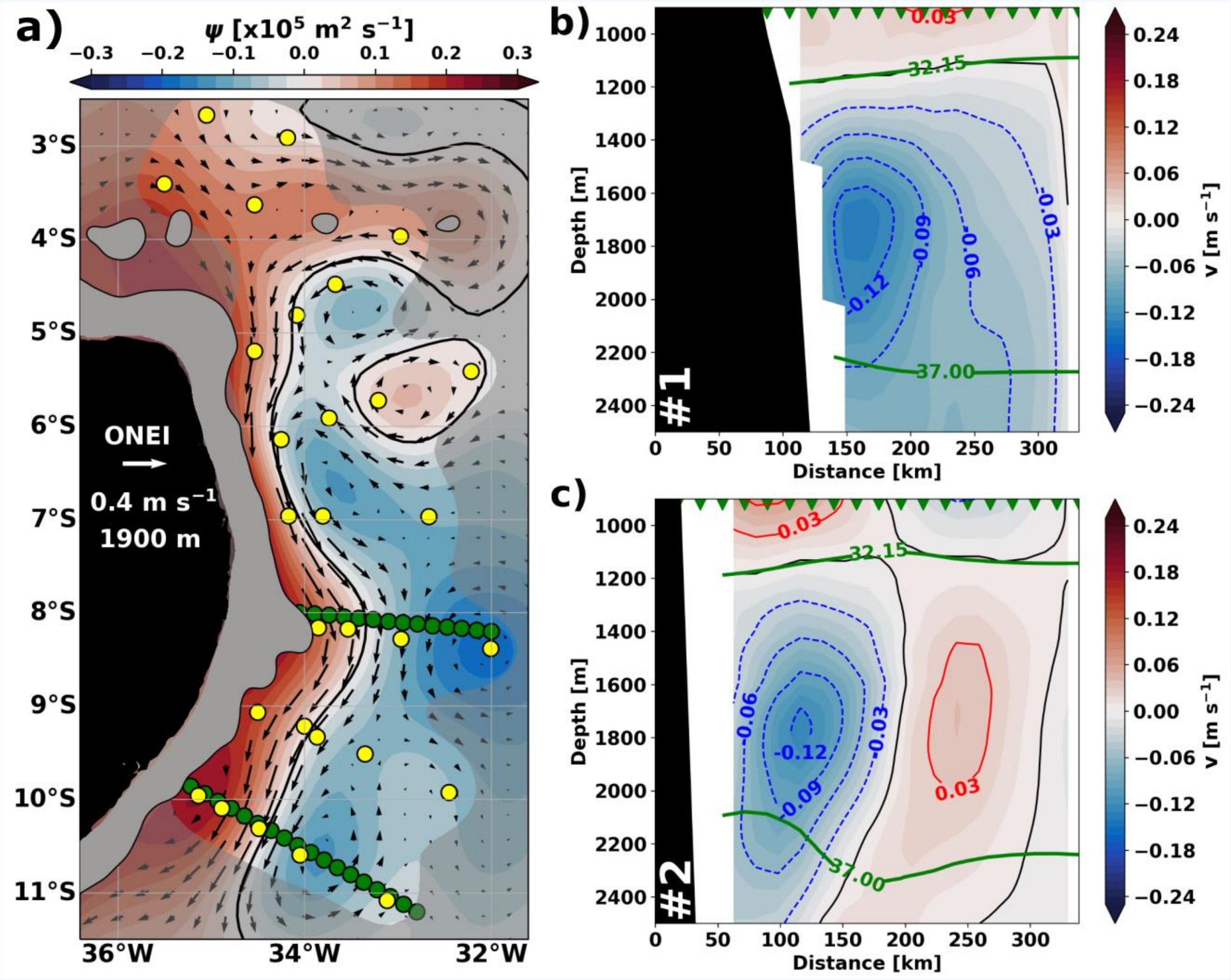
Campo quasi-sinóptico da circulação profunda no nordeste do Brasil



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- The *Oceano Nordeste* data presents the first horizontal scenario of the deep circulation off northeast Brazil;
  - The DWBC axis (ψ=0) separates the continental slope as it crosses the Pernambuco Plateau (Fig. a);
  - At 8°S, the DWBC occupies mainly the upper NADW with core velocity of ∼0.15 m s−1 (Fig b);
  - Further south (10.5°S), the observations capture the 100 km-radius and asymmetric anticyclone (Fig c);
- The snapshot suggests a possible separation mechanism acting on the DWBC at 8°S, with consequences for the flow downstream.

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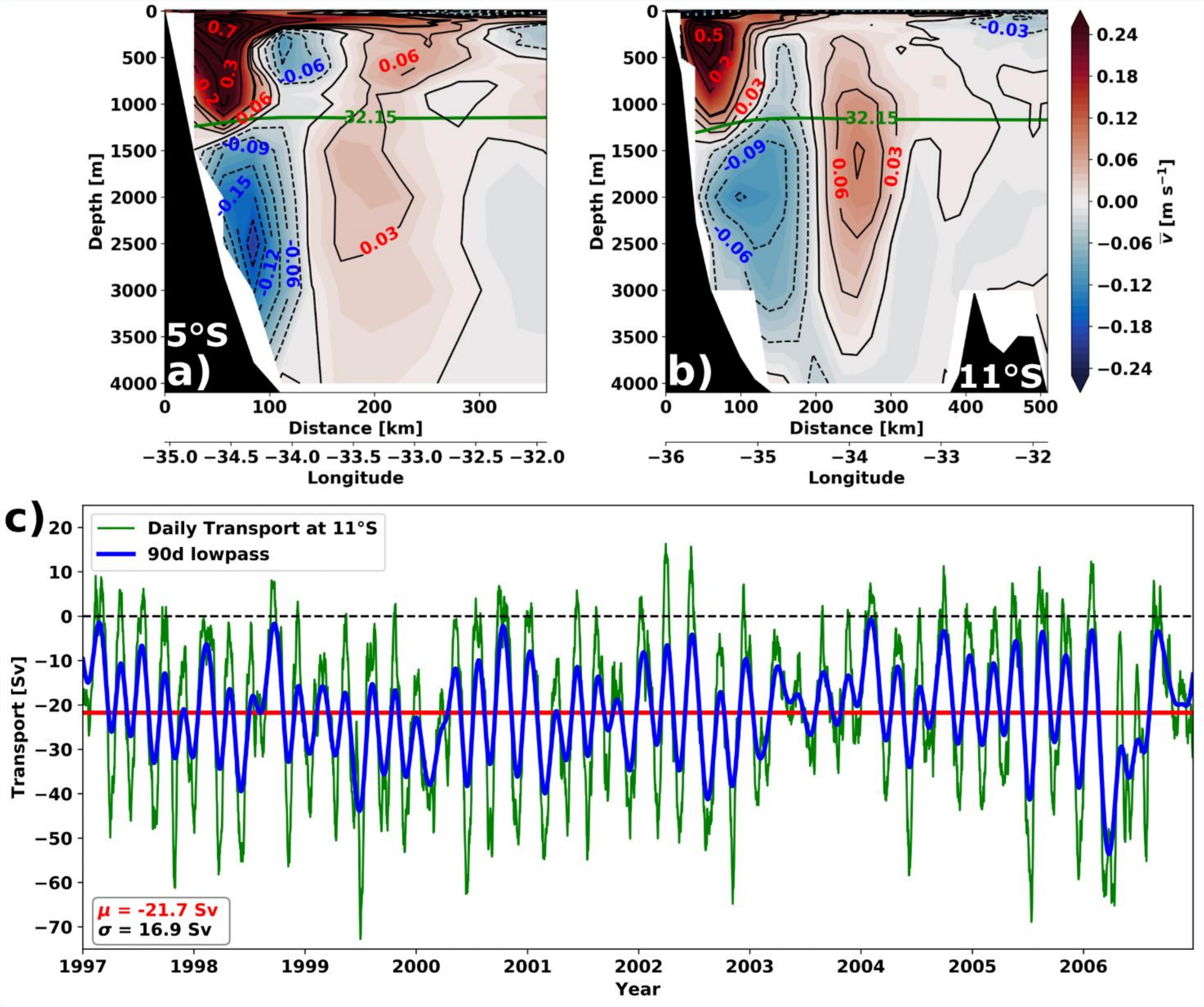
HYbrid Coordinate Ocean Model (HYCOM) #19.1



Vilela-Silva et al. (2023)

- To explore the separation hypothesis, we use a **10year time series** of a **daily reanalysis** (HYCOM model) with **10 km resolution** in 40 vertical levels;
- Both the upper current (North Brazil Undercurrent) and DWBC from the model present the morphometric aspects as in previous observations;
- The modelled **DWBC transport variability** (−21.7 ± 16.9 Sv) lies within the expected range (−19.1 ± 14.0 Sv; Schott et al., 2005);

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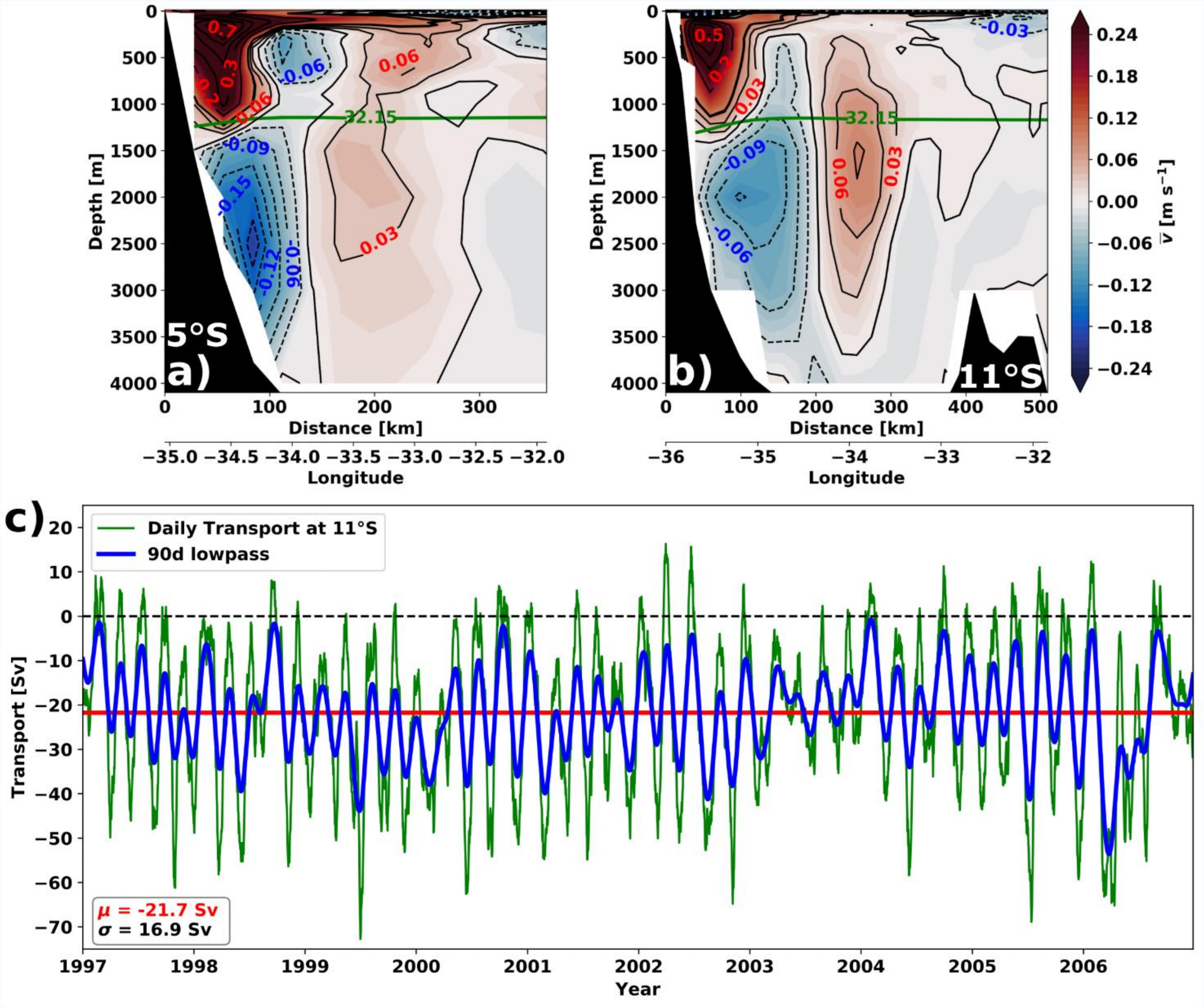

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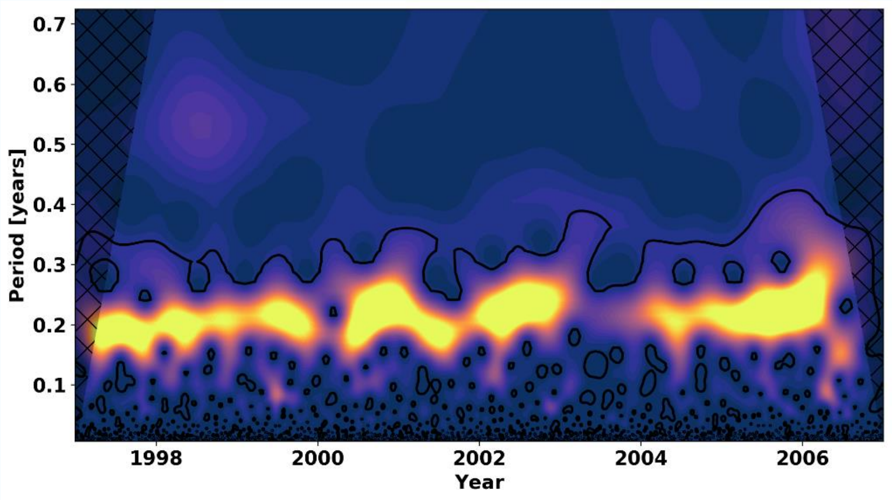
- The **periods of energy peaks** of the transport time series show the largest variability of **71 ± 3 days**, which is consistent with previous observations (Dengler et al., 2004)

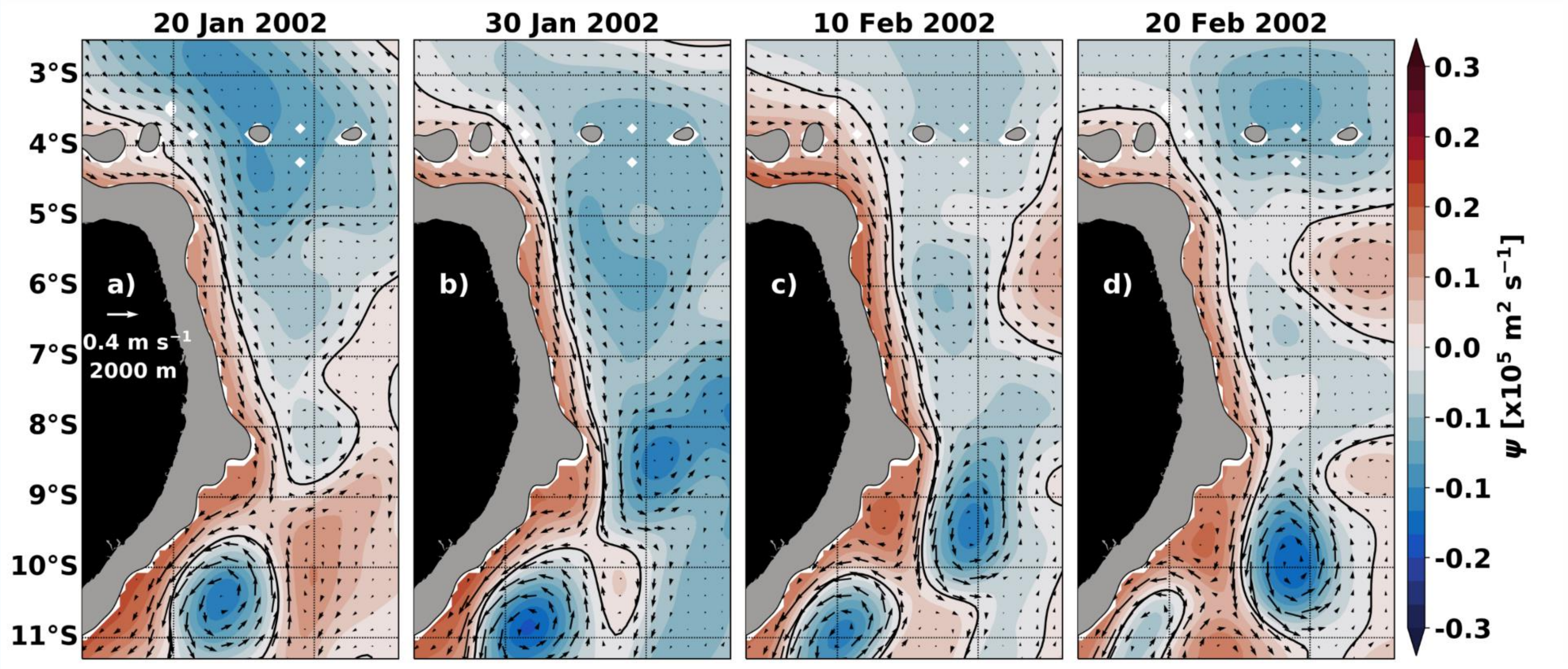


Vilela-Silva et al. (2023)

A CCOP no Platô de Pernambuco

- For the model outputs, we computed the stream function (ψ) through a Helmholtz velocity decomposition algorithm based on Li et al. (2006);

- Timeline:
  - On 20 Jan 2002, the DWBC flows adjacent to the continental slope (Fig a);
  - Ten days later, the **main axis of the DWBC moves away from the slope** (Fig b and as in our observations);
  - On 10 Feb 2002, the **DWBC backflips into an anticyclone** (Fig c);
  - Finally, the anticyclone sheds on 20 Feb 2002, briefly interrupting the DWBC flow at the lee of the Pernambuco Plateau.



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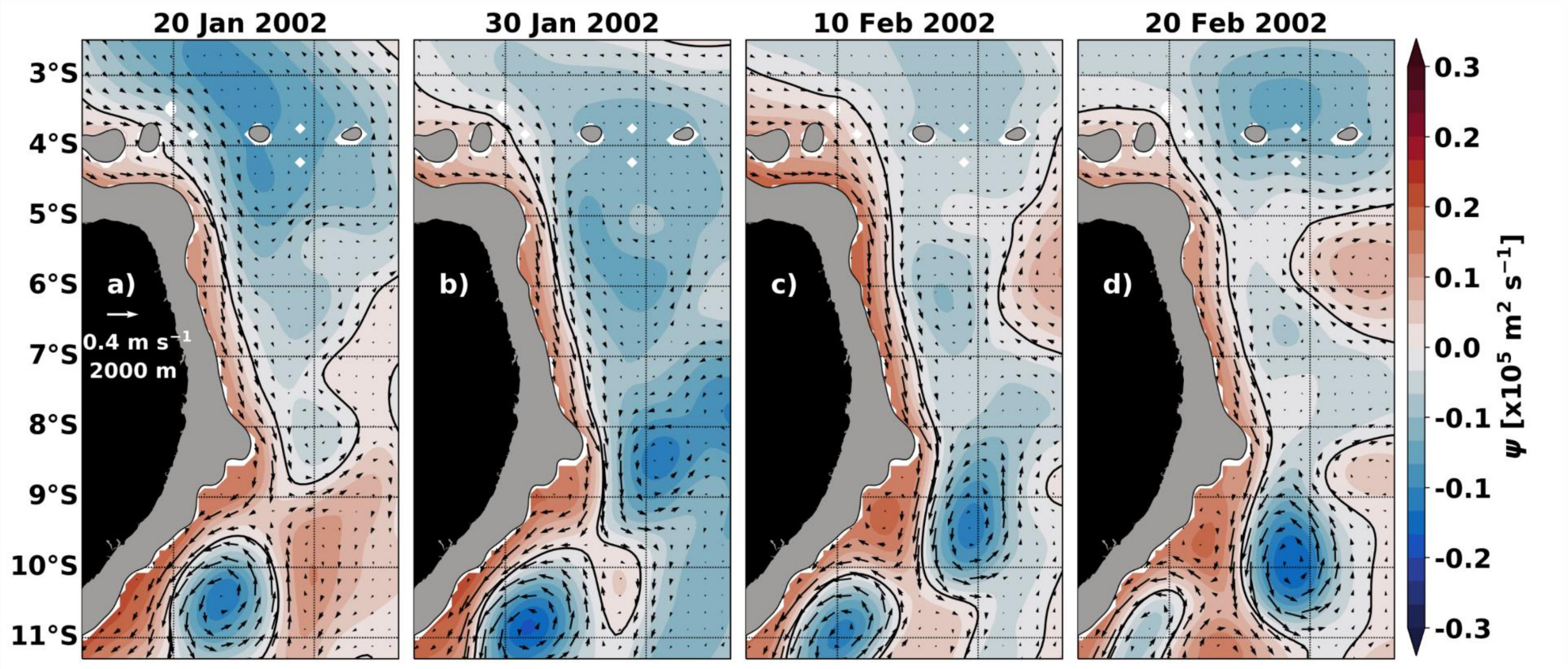

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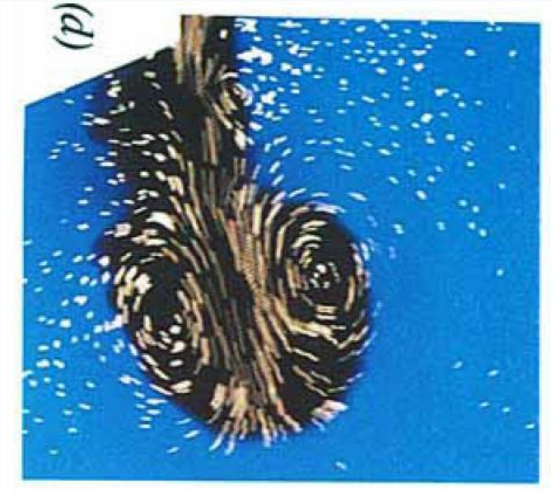
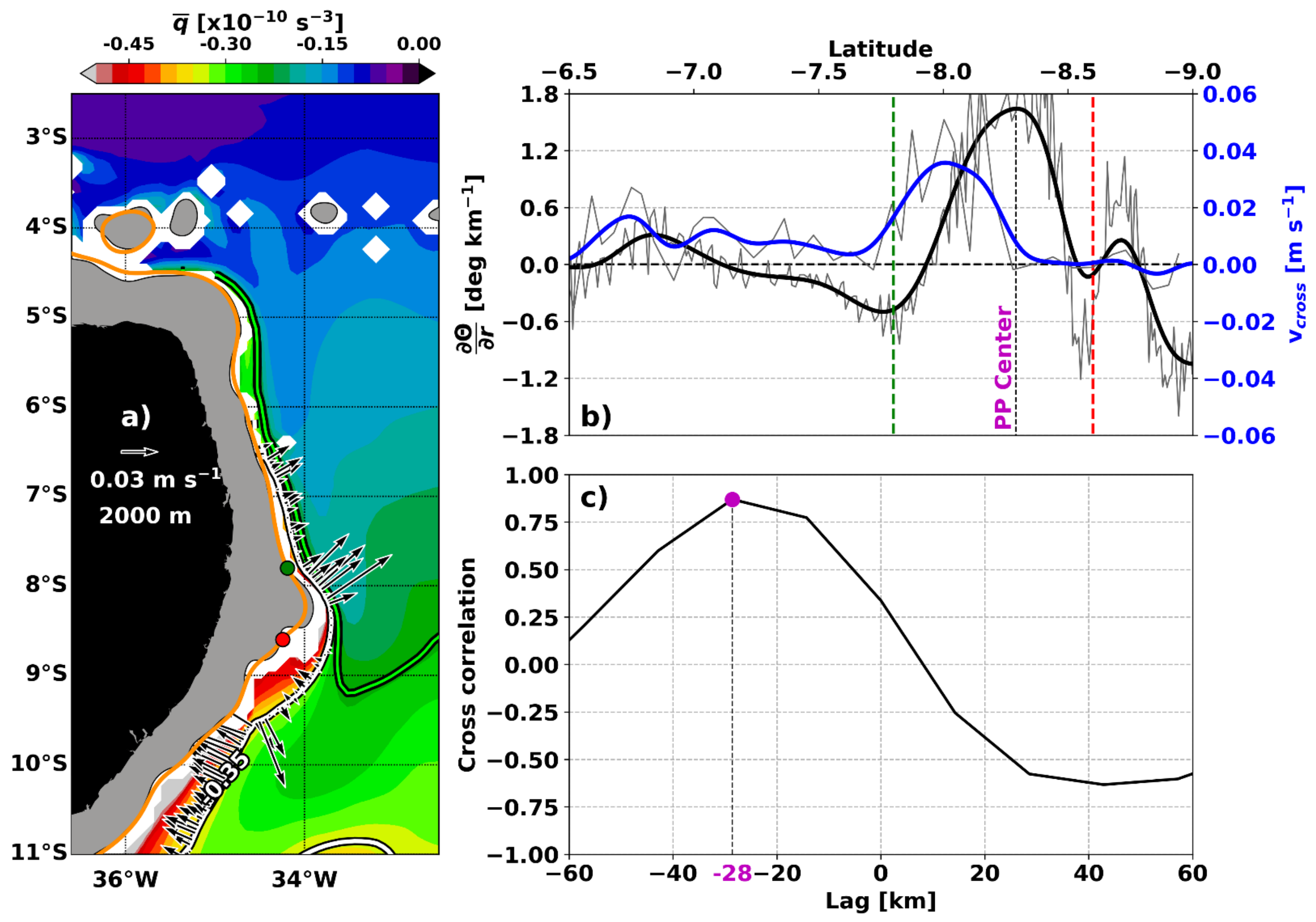
- The DWBC separation in the observations and model outputs is **like rotating tanks experiments** and theories for separating boundary currents (Stern & Whitehead, 1990)



Stern and Whitehead (1990)

Diagnósticos da separação da CCOP em 8°S



Vilela-Silva et al. (2023)

✓ The distortion of the PV field near capes hints at inertial separation of the mean streamlines (Pickart and Huang, 1995);

❖ Here, we use Ertel's PV definition for large and mesoscale flows (Pedlosky, 1987),

$$q = (\zeta + f)\, b_z$$

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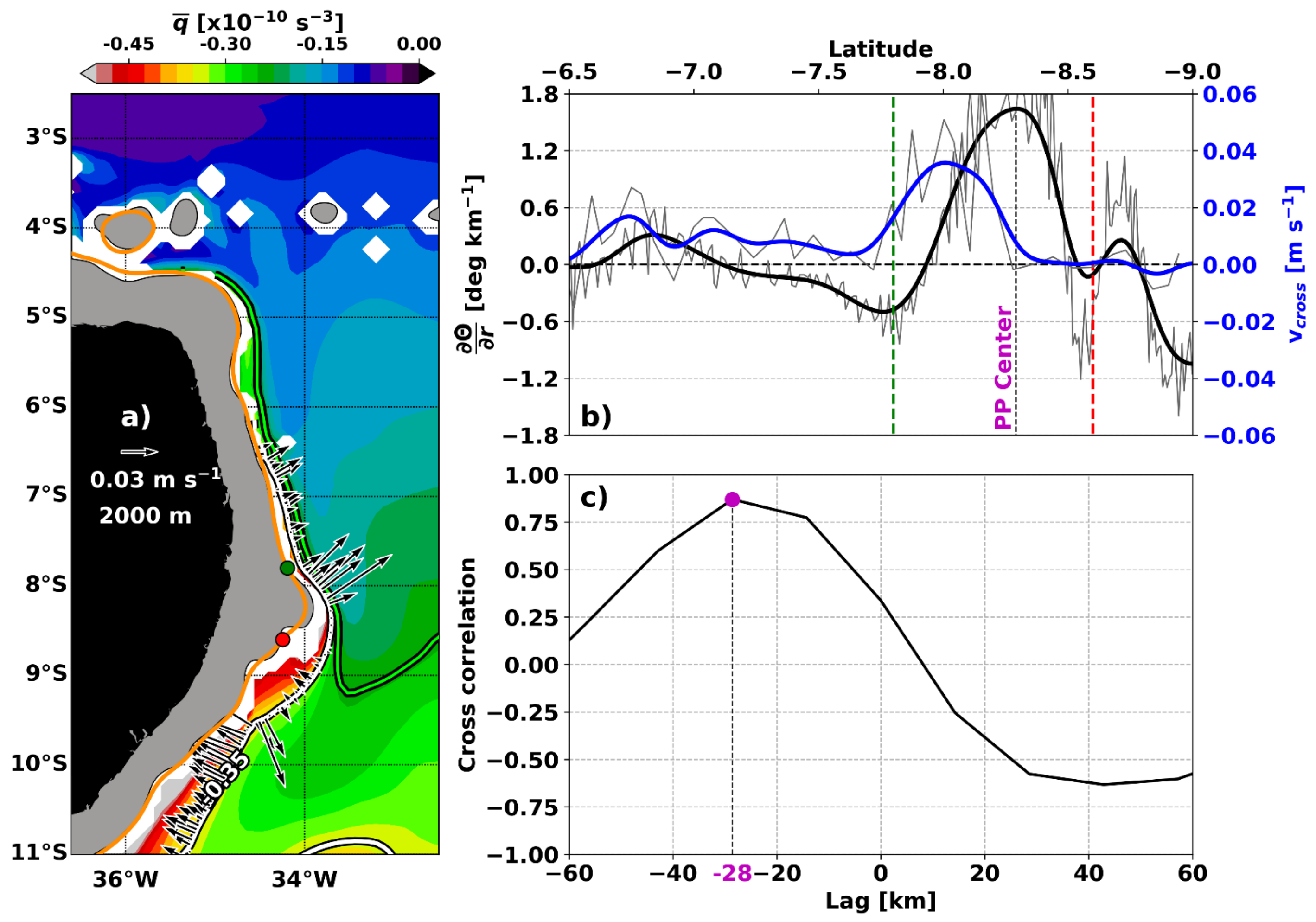

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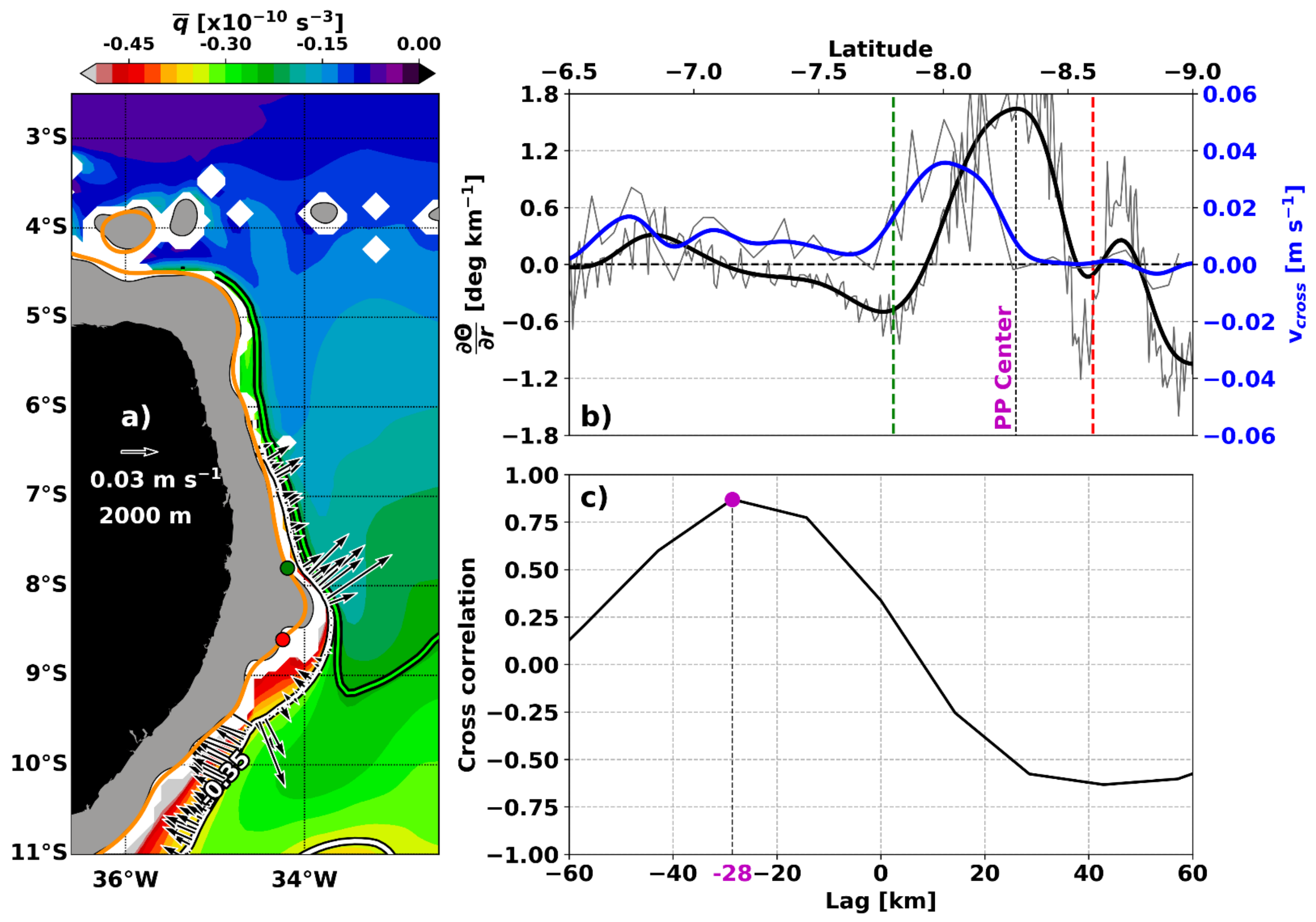

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- ✓ The lead lag correlation between the cross-stream velocities and the plateau's curvature shows the highest correlation at ~30km upstream the PP centre;

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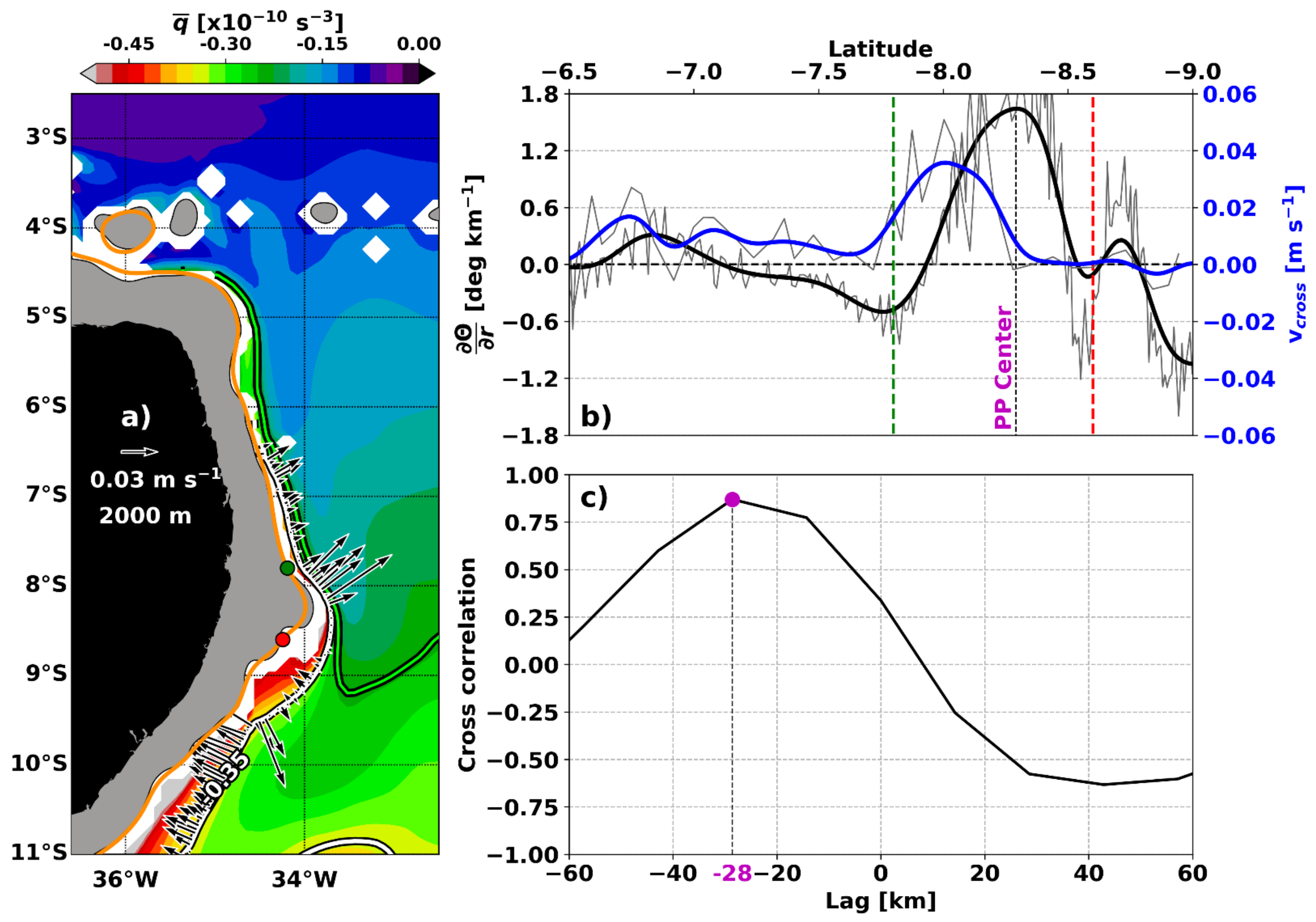

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- ✓ The lead lag correlation between the cross-stream velocities and the plateau's curvature shows the highest correlation at ~30km upstream the PP centre;
- ➢ These patterns are characteristic of flow separation. However, the PV tongue (green contour) could indicate a meandering of the flow.

❖ Here, we use Ertel's PV definition for large and mesoscale flows (Pedlosky, 1987),

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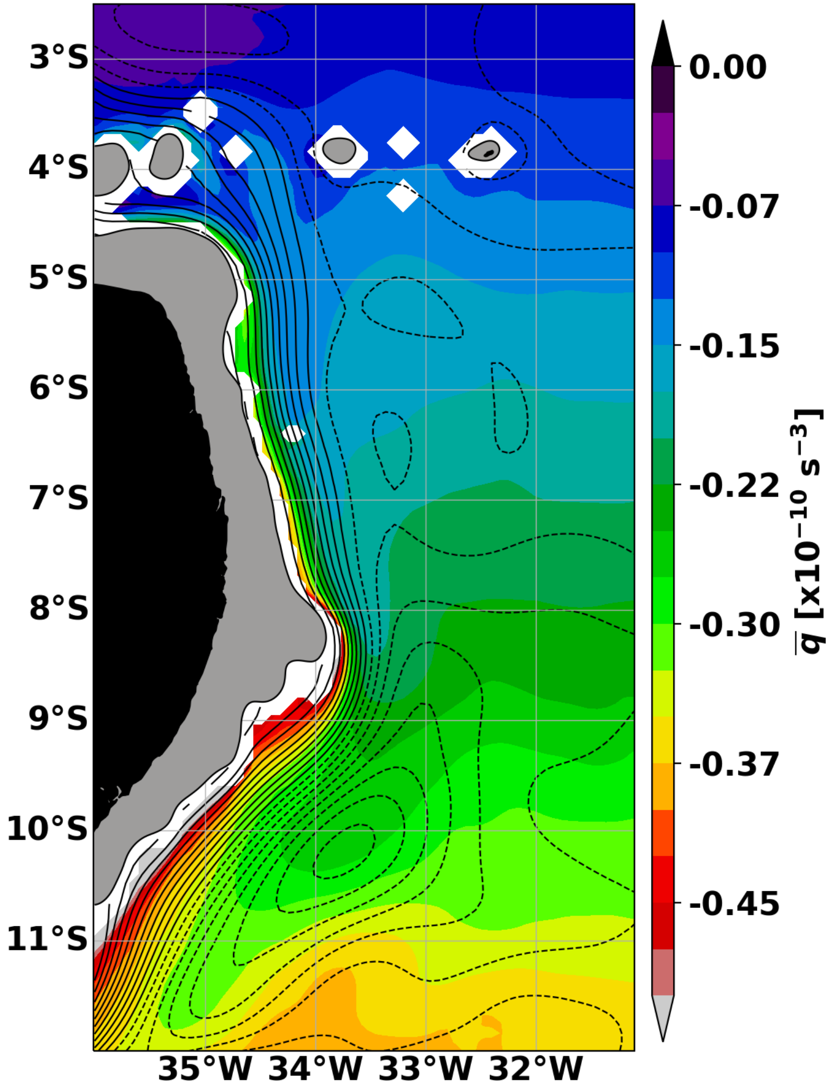
O campo de circulação médio da CCOP



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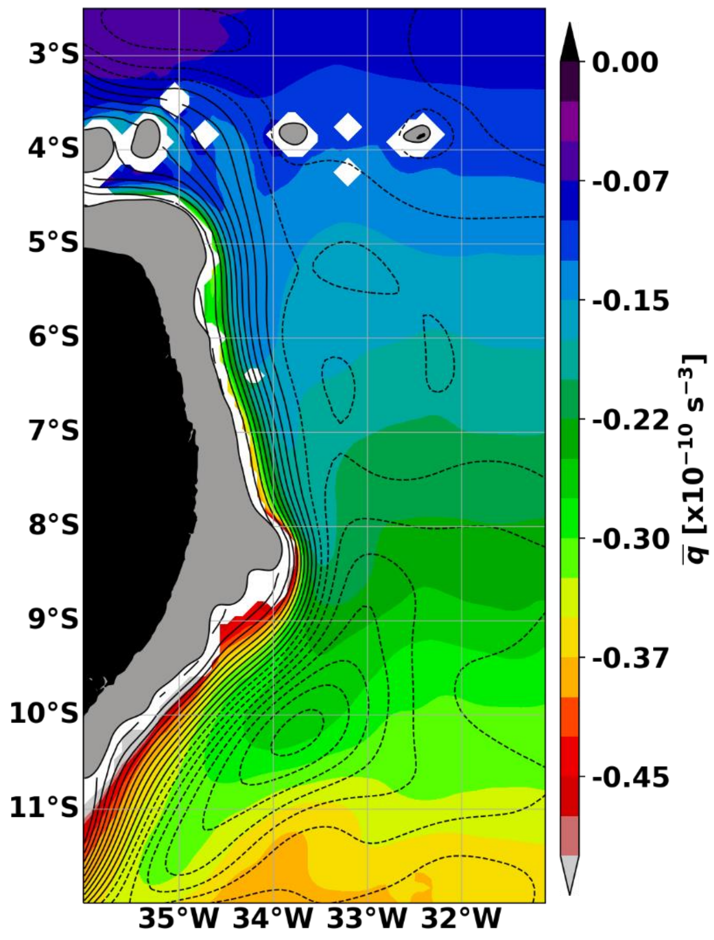
- In a 10-year mean, the **separating streamlines tend to be smeared and averaged out** due to the anticyclones' southwestward propagation south of the Pernambuco Plateau;

O cenário composto de formação de anticiclones

- Thus, we propose to assess the PV during the DWBC **eddy genesis events**.
  - The separating streamlines follow the veered PV contours eastward once they leave the western boundary in the eddy genesis composite.



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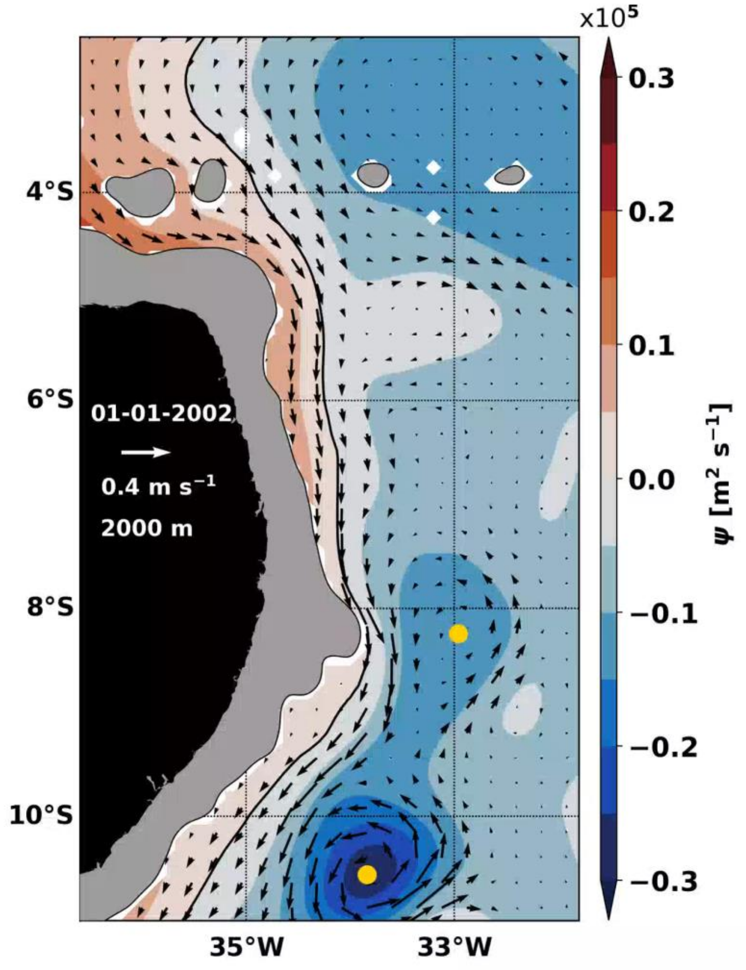
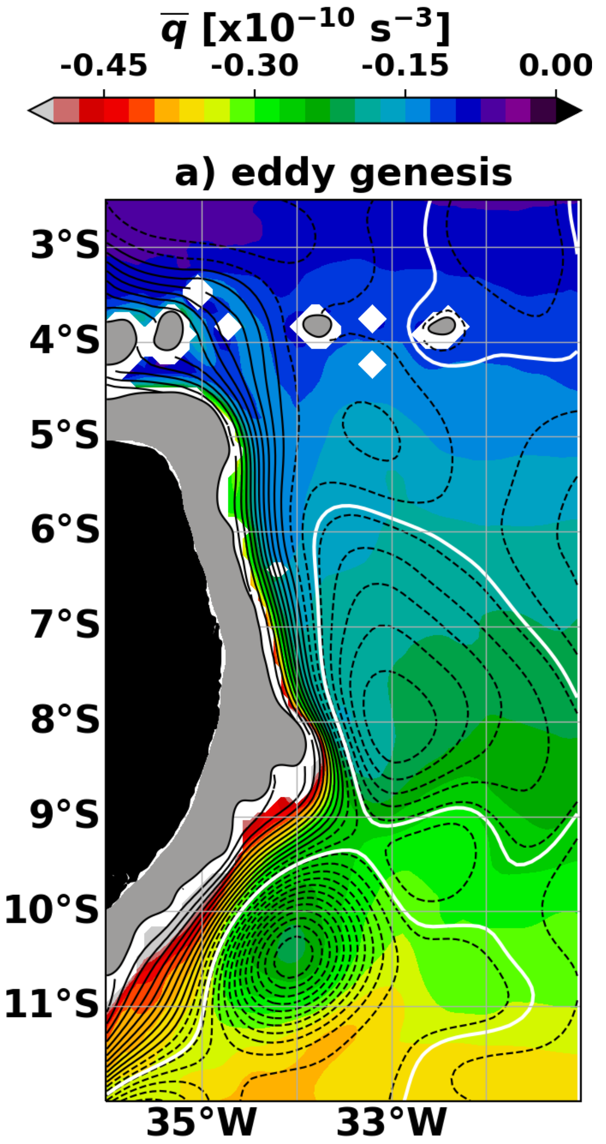




A separação inercial da CCOP

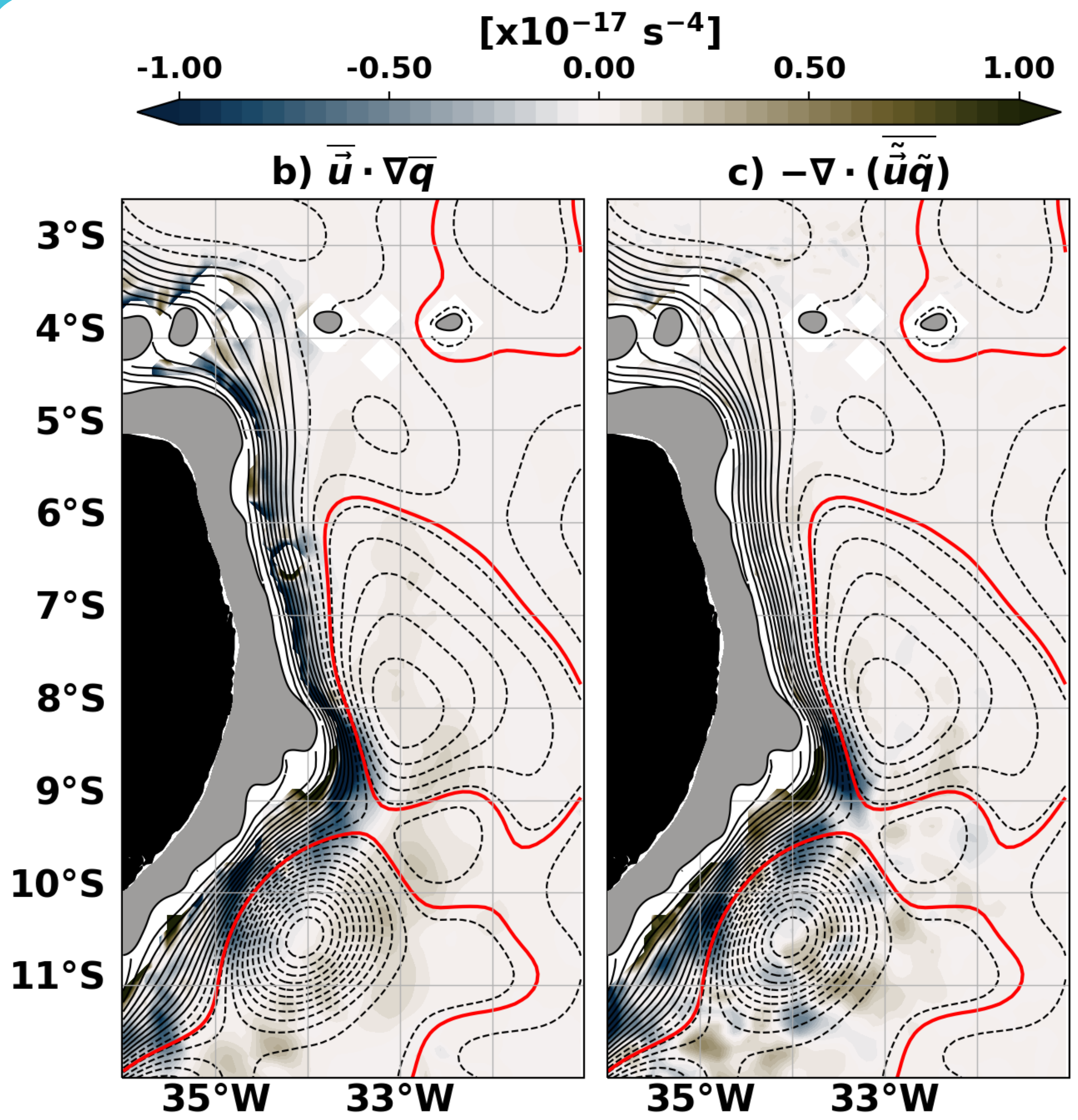
- ✓ To test the inertial processes, we evaluate the Turbulent Sverdrup Balance (Rhines & Holland, 1979),

$$\bar{\mathbf{u}} \cdot \nabla \bar{q} = -\nabla \cdot \left(\overline{\tilde{\mathbf{u}} \tilde{q}} \right)$$

as the balance between the mean PV advection (LHS) and convergence of eddy-PV fluxes (RHS) (e.g., Solodoch et al., 2020).

- ✓ The Turbulent Sverdrup Balance is valid at the DWBC core from 8°S to 11°S similarly to model representations of the DWBC in other locations (van Sebille et al., 2012; Solodoch et al., 2020; Biló et al., 2021);
    - Downstream the separation of the boundary, both terms in the equation decrease up to two orders of magnitude;
    - These patterns indicate that the flow mainly follows the PV contours as it separates the PP.

- ✓ Part of the DWBC flow separates the continental slope inertially during eddy genesis.



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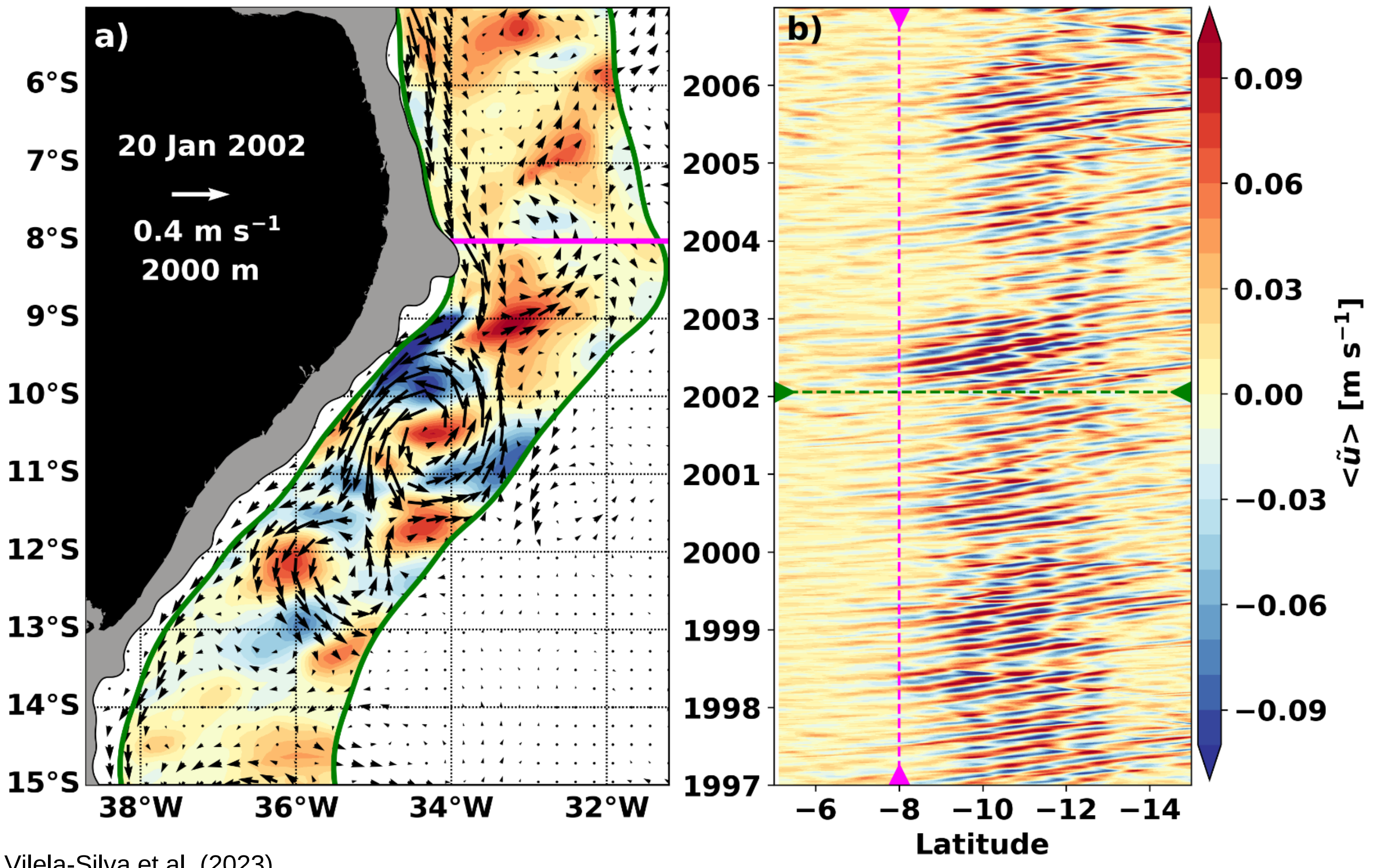
O que acontece depois da separação?

- Downstream of the plateau, the anticyclones can be identified by velocity anomalies (60-day low-pass filter);
  - The perturbations in the velocity field further indicates that the Penambuco Plateau is responsible for the DWBC anticyclone genesis downstream the separation;
  - Perturbations may amplify due to instability processes (Philander, 1990).



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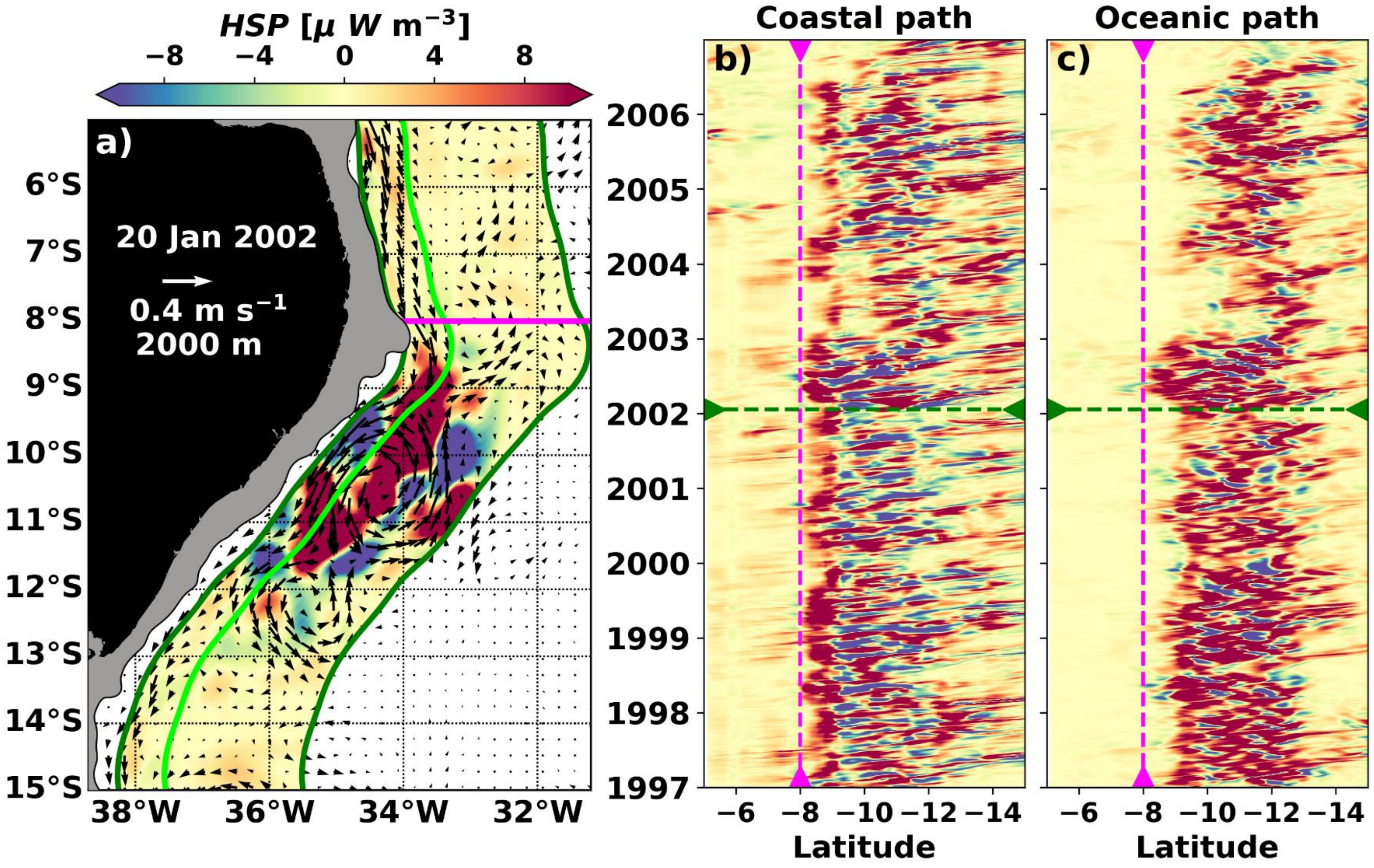
O crescimento dos vórtices

- Eddies can grow due to energy conversions and instability processes (Mata et al., 2006; Napolitano et al., 2019);
  - Barotropic instabilities have been shown to play a role in the DWBC regional dynamics (Schulzki et al., 2021; Brum et al., 2023);



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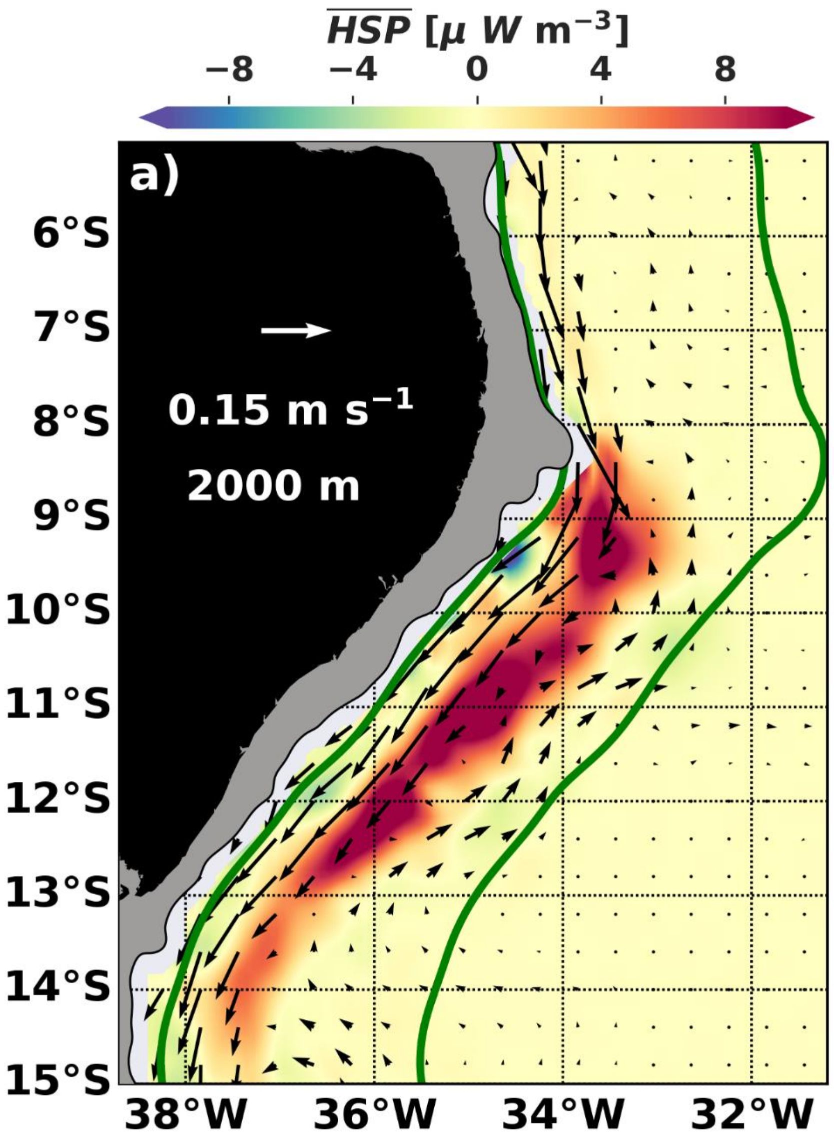
- Along the coastal path, the perturbations draw energy from the mean flow downstream the DWBC separation at 8°S (HSP > 0);
  - The MKE to EKE conversions attest to the growth of the DWBC anticyclones.
- On the oceanic path, the pinched-off eddies continue to grow south of 9°S by feeding off the mean flow.

O "saldo" de produção de shear lateral da CCOP



- The time-mean horizontal shear production overlaid by the time-mean velocity field links the DWBC (*CCOP*) separation at the Pernambuco Plateau to the anticyclones' initial growth at 8°S;

- Note the strong velocity pointing offshore at the corner of the plateau;

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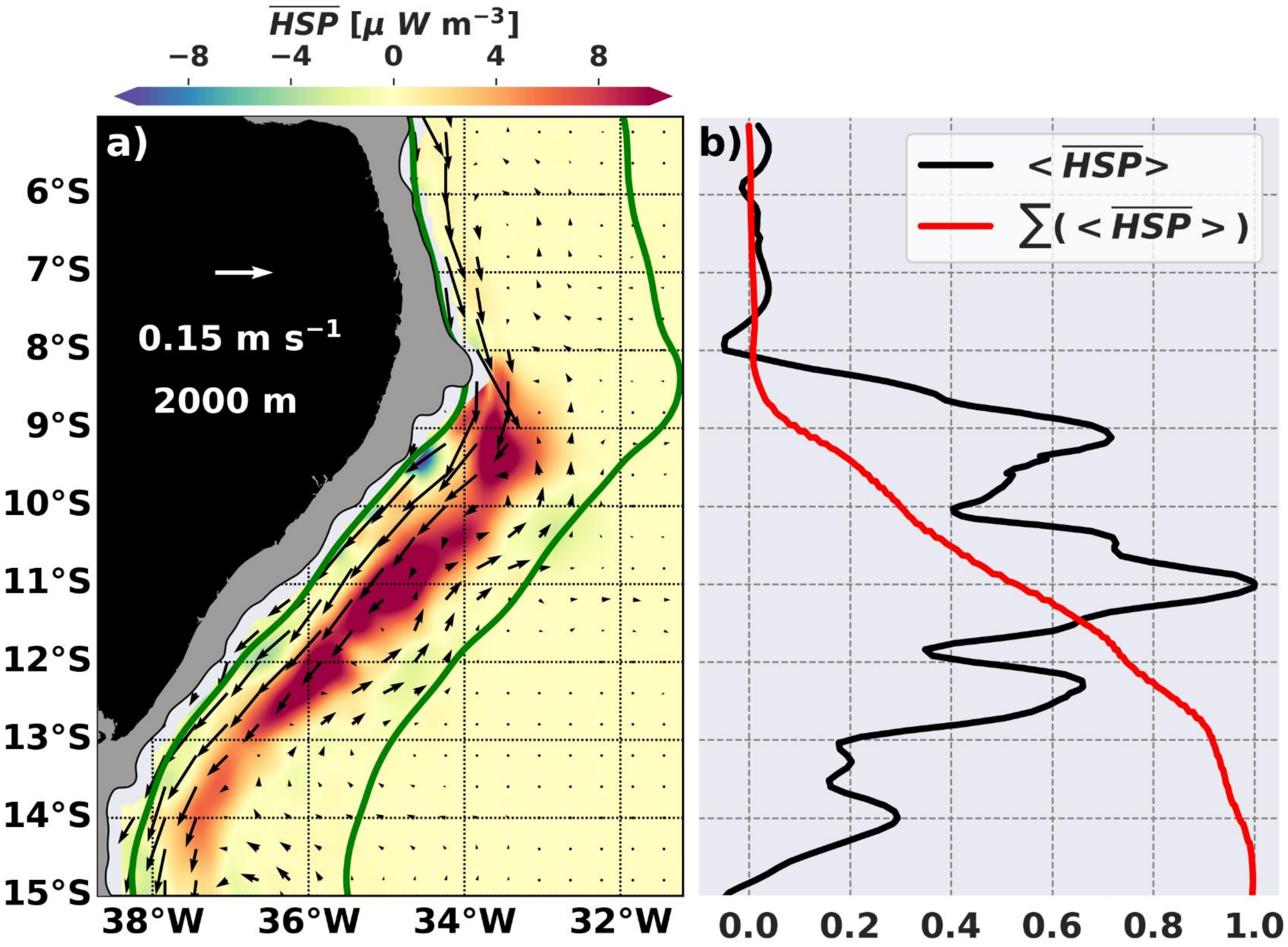
O “saldo” de produção de shear lateral da CCOP



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- Downstream of the separation, the cumulative net HSP (red line) increases from 8°S to 13°S.
- South of 14°S, the cumulative net HSP stabilizes;
  - barotropic conversions through HSP are weak or nonexistent from this latitude southward;

- To conserve energy, the regional EKE budget requires dissipation due to:
  - eddy decay and mixing (Kang & Curchitser, 2015; Spingys et al., 2021)?
  - advection by the mean flow out of the domain (Chen et al., 2014; Napolitano et al., 2019)?

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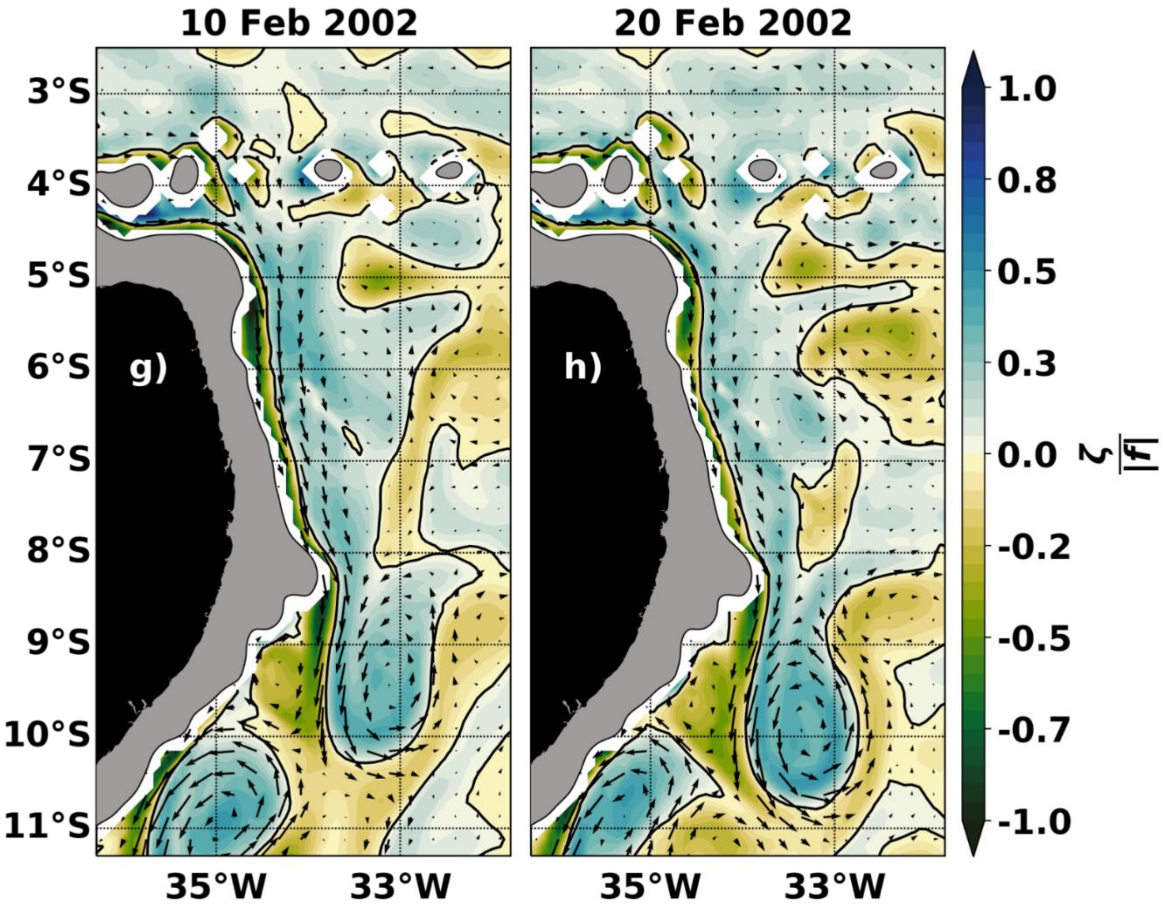
Conclusões

1

Oceano Nordeste expedition:

a) The cross-bathymetry transects at 8°S and 10°S confirms that the DWBC breakup occurs at 8°S;

b) The quasi-synoptic map of stream function presents patterns of flow separation downstream of the Pernambuco Plateau.



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2

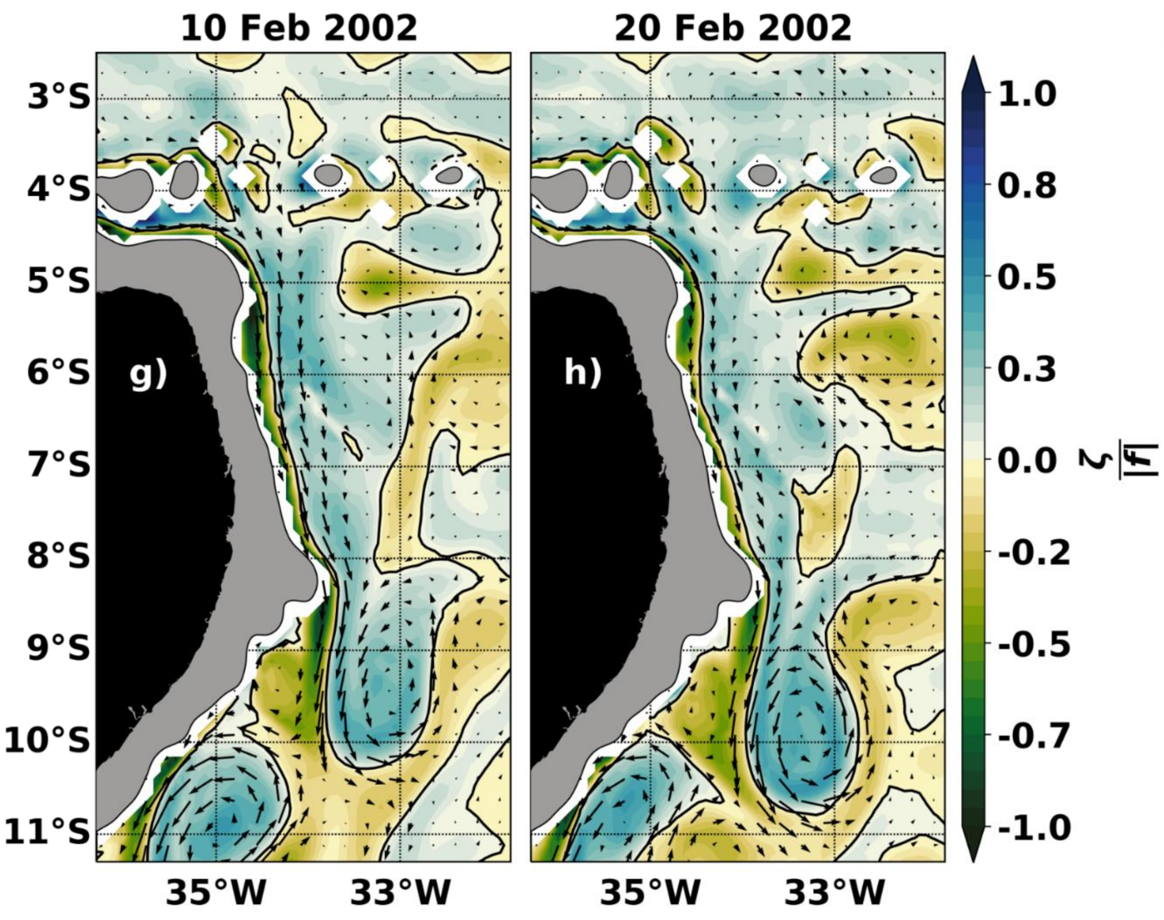
Model output (HYCOM):

a) We tested 3 separation theories (Røed, 1980; Stern & Whitehead, 1990; Solodoch et al., 2020);

b) The result of the tests converge to indicate that the DWBC undergoes a local, intermittent separation while contouring the Pernambuco Plateau;

c) Downstream of the separation, the DWBC offshore lobe, with positive relative vorticity, folds into anticyclones which travel southwestward;

d) Barotropic instability is a mechanism relevant to the DWBC eddies' growth.



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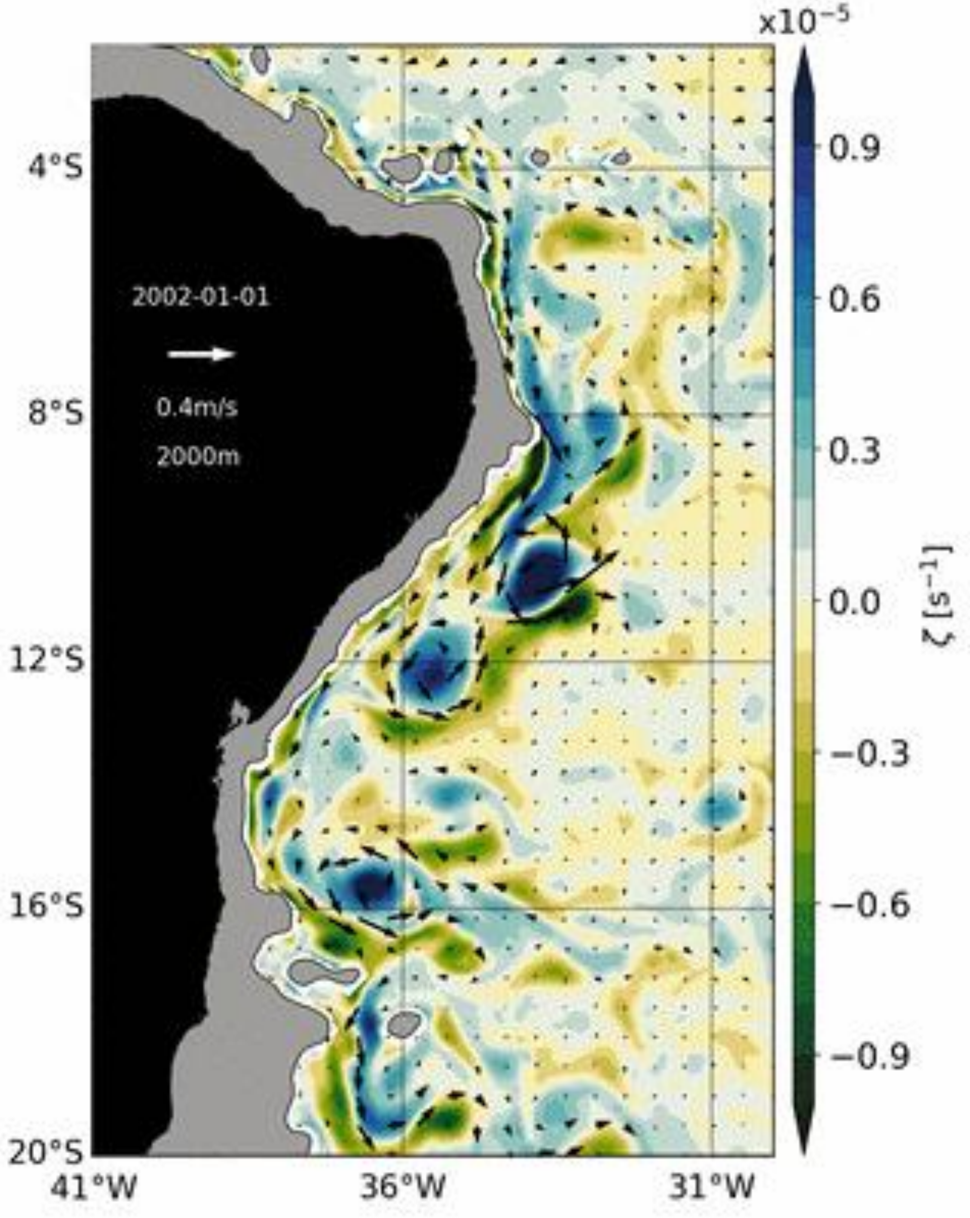
Considerações finais

- As the DWBC separates, leakiness of NADW water might occur.
    - If so, it modifies the pathways of the AMOC's lower limb;
    - These pathways are important to understand the basin-scale heat fluxes and deep ocean ventilation;
    - The DWBC eddies at 8°S might play a relevant role in the deep South Atlantic's heat storage and carbon residence time.



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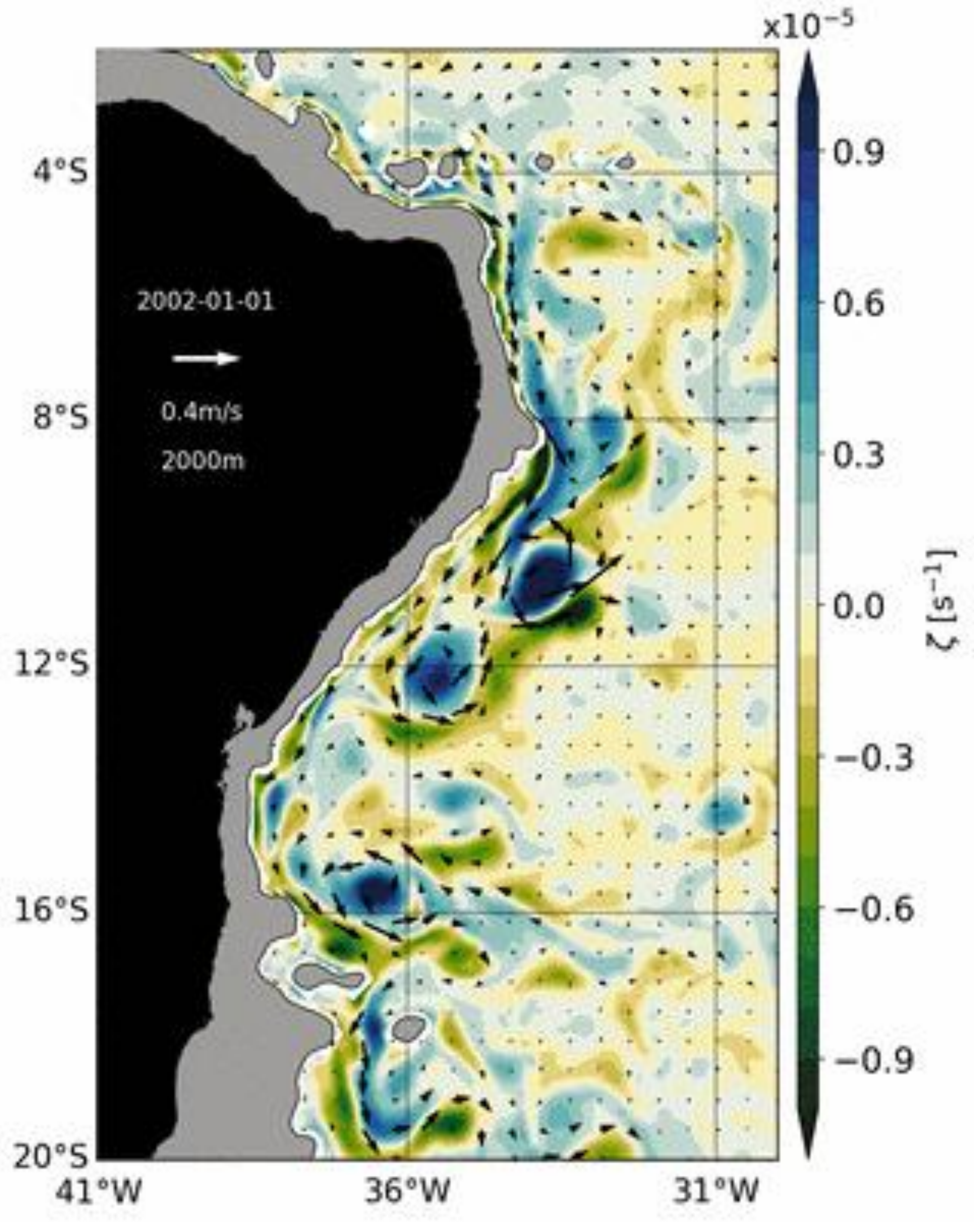
Pergunta em aberto

- Maragogi e Abrolhos são conhecidas como regiões com biodiversidade abundantes;

- Seria razoável considerarmos que, talvez, a CCOP transporte larvas adormecidas entre Maragogi e Abrolhos?

- A CCOP transporta a APAN com temperatura entre 3°C e 5°C.
  - Esse é um intervalo razoável para manter larvas em estado dormente no fundo do Atlântico tropical?



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Bora falar sobre redemoinhos?

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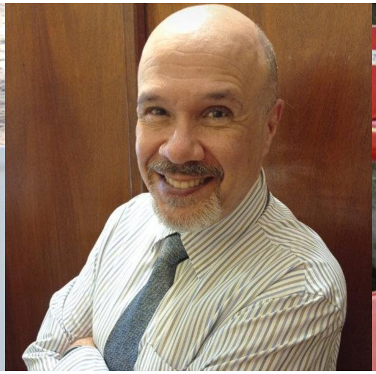
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We dedicate this work to the memory of **B.M. Castro**.

EXTRAS


1
Introduction
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Saídas de modelo global
Conclusões
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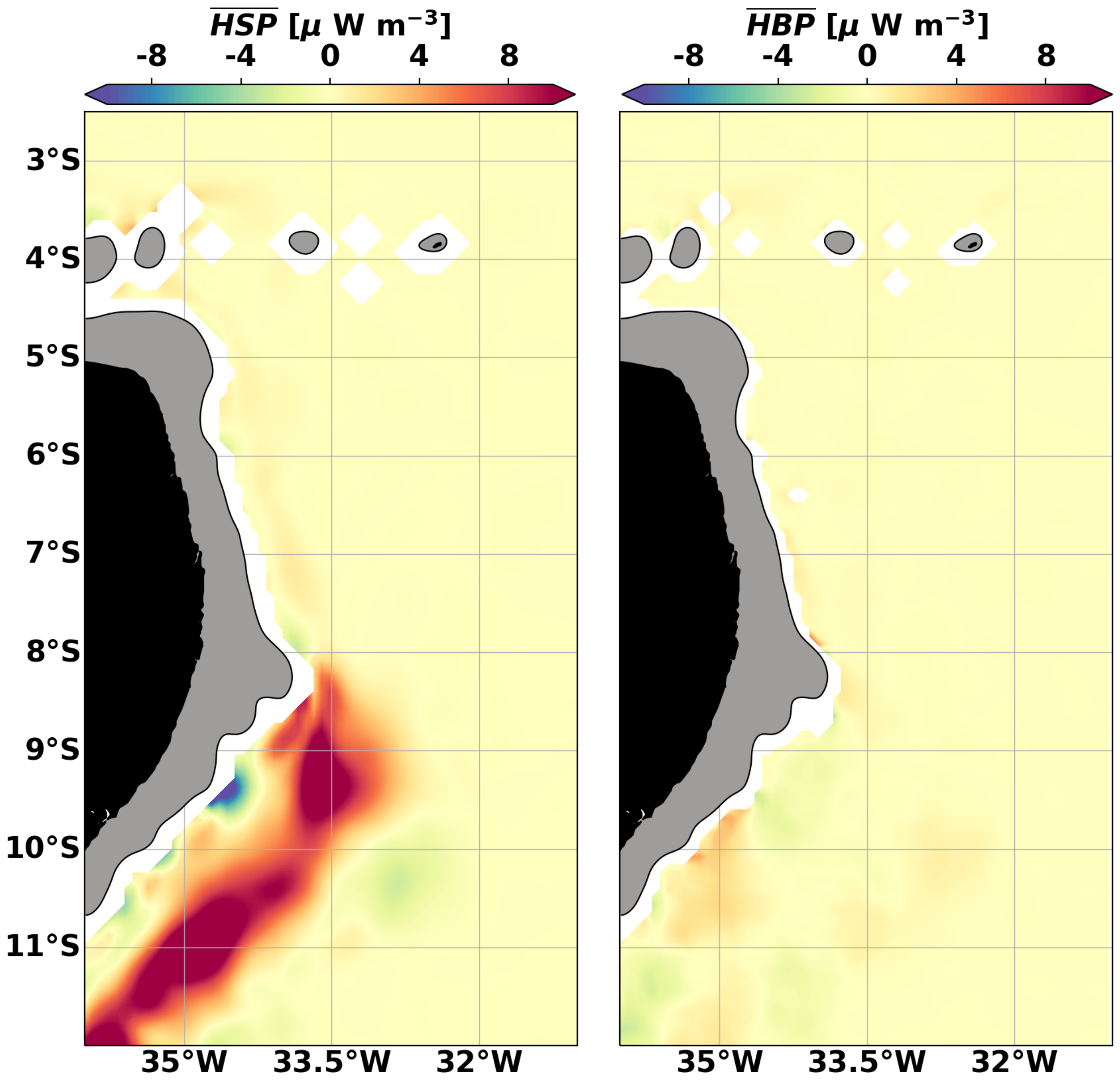
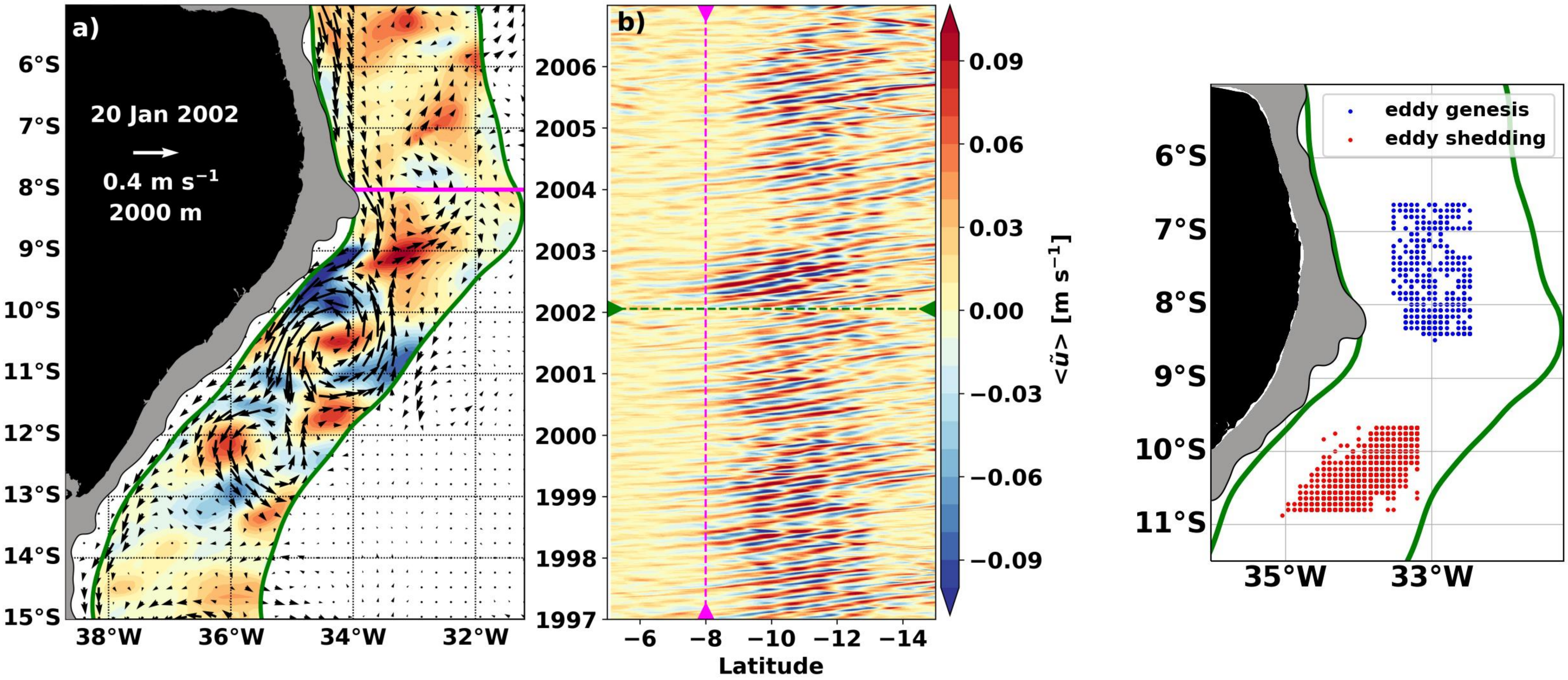
Extras

Extras: Horizontal Shear Production vs Horizontal Buoyancy Production



Extras: The Eddy Corridor From the Pernambuco Plateau to 15°S

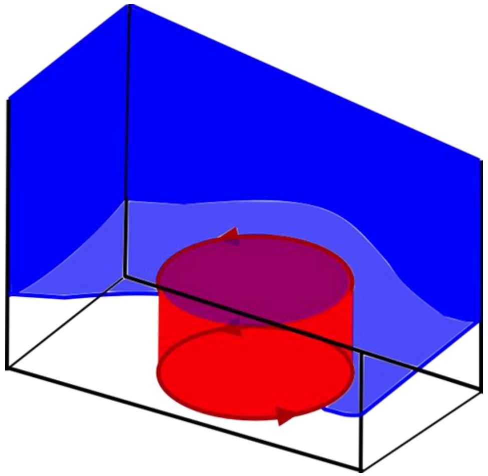
- Downstream of the plateau, the propagation of the anticyclones can be identified by **velocity anomalies** (60-day low-pass filter);
  - The perturbations in the velocity field further indicates that the **PP is responsible for the DWBC anticyclone genesis** downstream the separation;



The curvature effect of the Pernambuco Plateau

- Røed (1980) explored how the curvature of a cape influences the separation of a barotropic boundary current from an irregular wall based on a geographic parameter,

$$\hat{R} = \tanh\left(\frac{2R_d}{W_c}\right)$$



Courtesy from Filipe Pereira

- If we think of the DWBC dynamics as an upside-down equivalent-barotropic flow with a rigid lid dividing the upper (NBUC) and bottom (DWBC) layers, we obtain $R > 0.999$.
  - According to Røed (1980) and Pratt and Whitehead (2007), the flow separates under such conditions.

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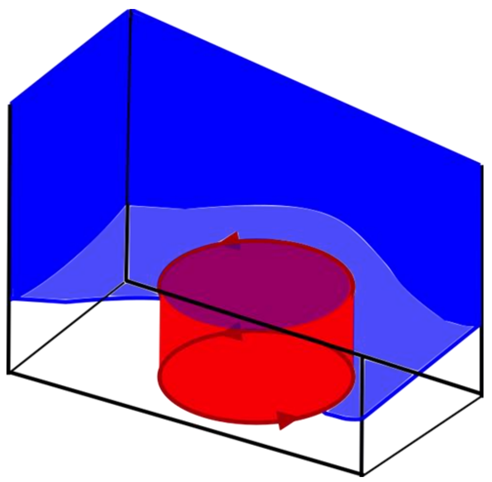

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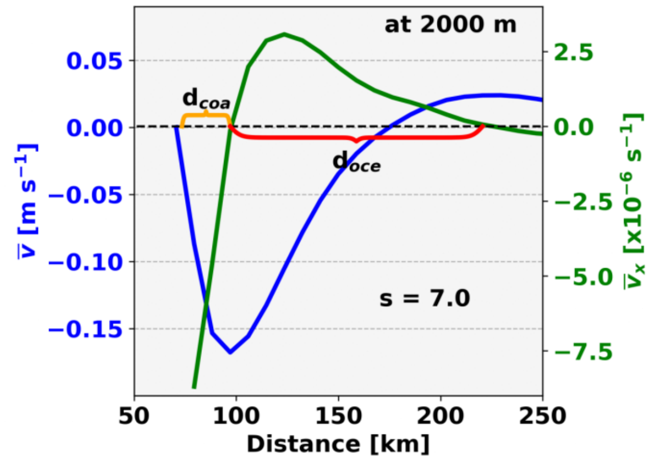
- Stern and Whitehead (1990) revealed that a barotropic jet sheds eddies as it crosses a corner.
  - The authors proposed two parameters to evaluate whether or not the jet separates from the adjacent wall:
  - the angle θ and the ratio *s*,

$$s = \frac{d_{\mathrm{oce}}}{d_{\mathrm{coa}}}$$



  - If θ > 45° and *s* > 1 →
    - The current separates and sheds eddies;
    - The Pernambuco Plateau angle is 67°;
    - The DWBC-like jet returns s = 7.0.