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RESEARCH ARTICLE

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

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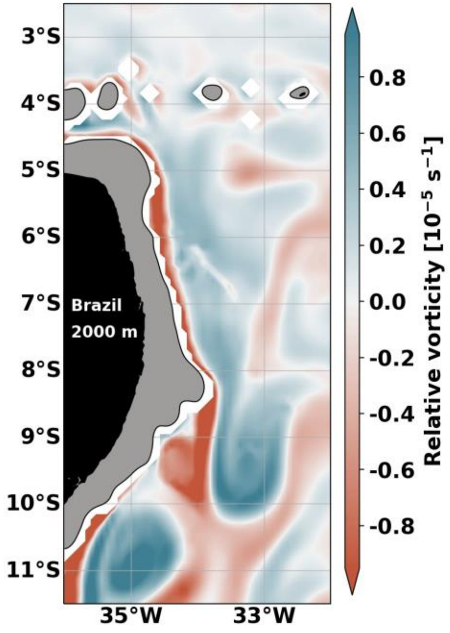
Key Points:

- Part of the Deep Western Boundary Current (DWBC) separates inertially off the continental slope while crossing the Pernambuco Plateau at 8°S
- The DWBC separation plays a crucial role in the formation of the DWBC deep anticyclonic eddies
- Barotropic instability significantly contributes to the growth of the deep anticyclonic eddies



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INTRODUCTION: The AMOC and the Deep Western Boundary Current

- The Deep Western Boundary Current (DWBC) transports the lower limb of the Atlantic Meridional Overturning Circulation (AMOC; Rintoul, 1991; Gordon, 1991).
  - The DWBC carries the North Atlantic Deep Water (NADW) across the whole Atlantic basin, feeding the Antarctic Circumpolar Current (Talley et al., 2011; Tomczak & Godfrey, 1994).

- The DWBC exports NADW to the Atlantic interior in regions of leakiness as observed:
  - south of the Newfoundland Basin (~42°N; Bower et al., 2009; Solodoch et al. 2020);
  - at the Vitoria-Trindade Ridge (~20°S; van Sebille et al. 2012; Garzoli et al., 2015).

- Dengler et al. (2004) reported that the DWBC breaks up into deep southward-propagating anticyclones at 8°S.
  - Upon reaching the Vitória-Trindade Ridge (~20°S), a portion of the DWBC deflects eastward (van Seville et al., 2012);
  - The main portion continues flowing southward as it reorganizes itself as a boundary current (Garzoli et al., 2015).

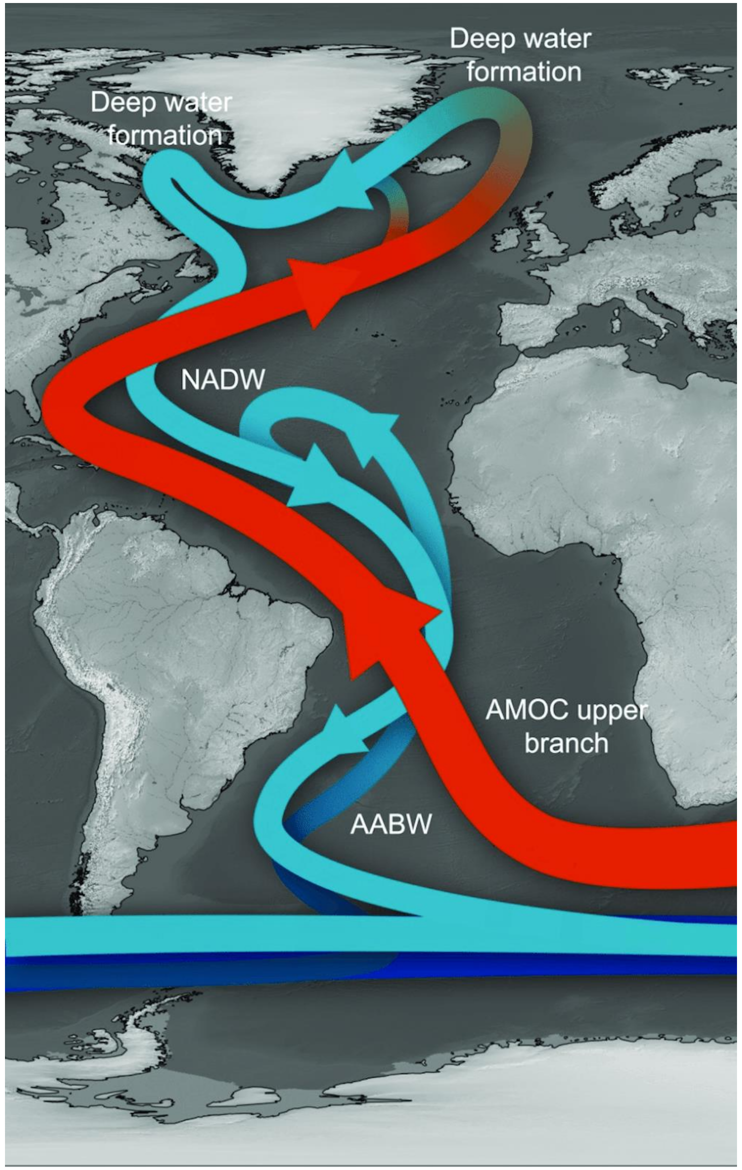


Figure extracted from Stefano Crivellari PhD thesis

INTRODUCTION: The anticyclones of the Deep Western Boundary Current at 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.

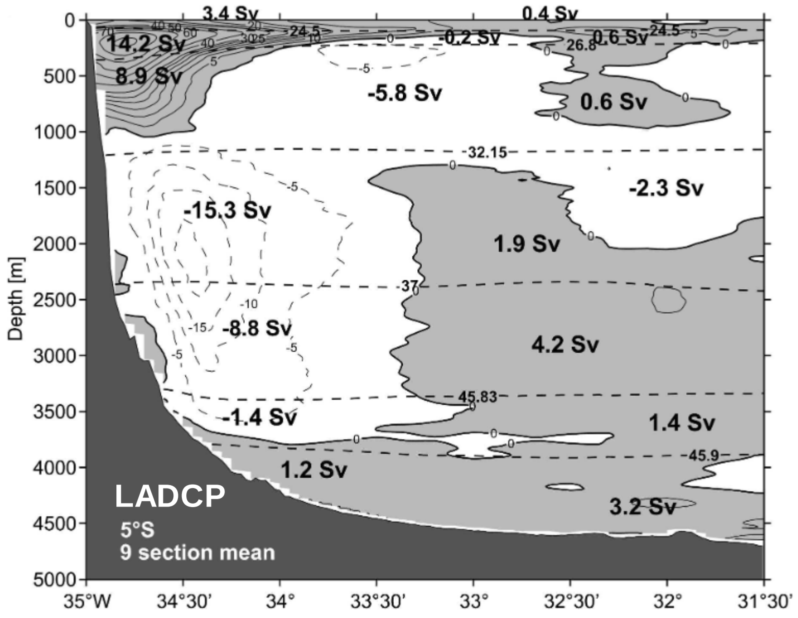
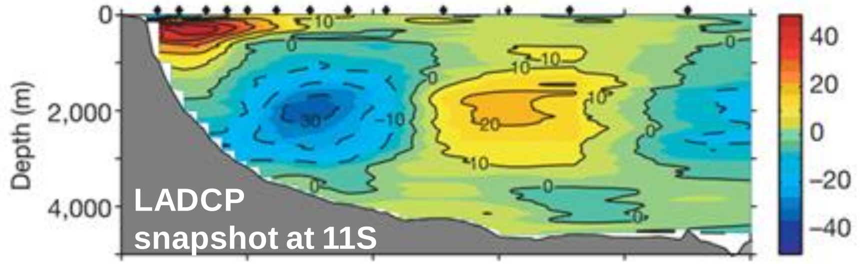
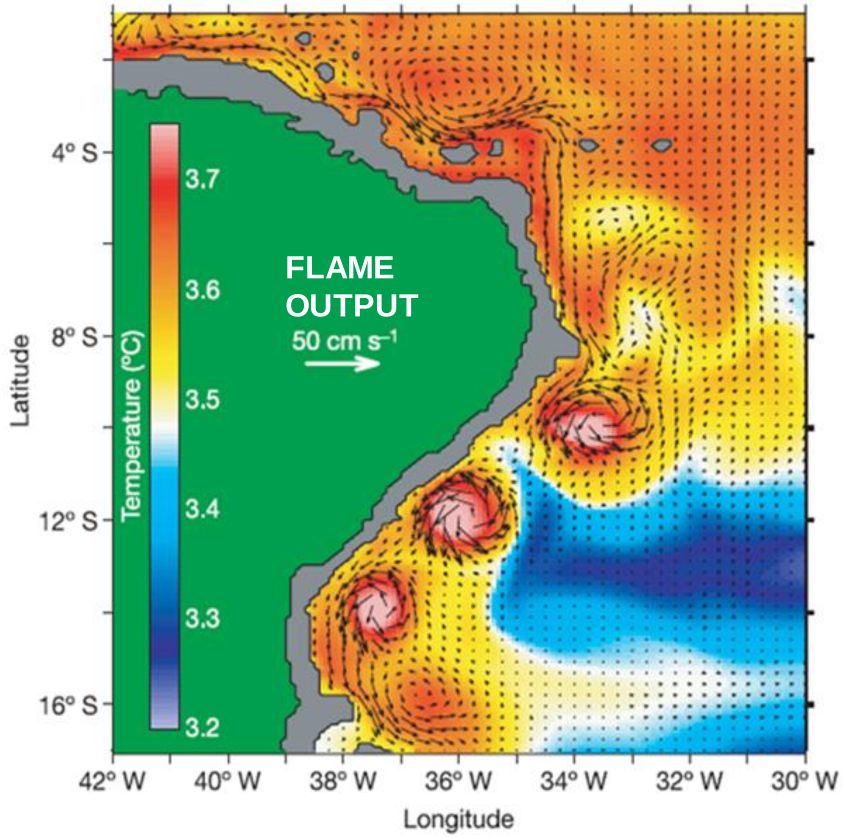


Figure extracted from Scott et al. (2005; JPO)



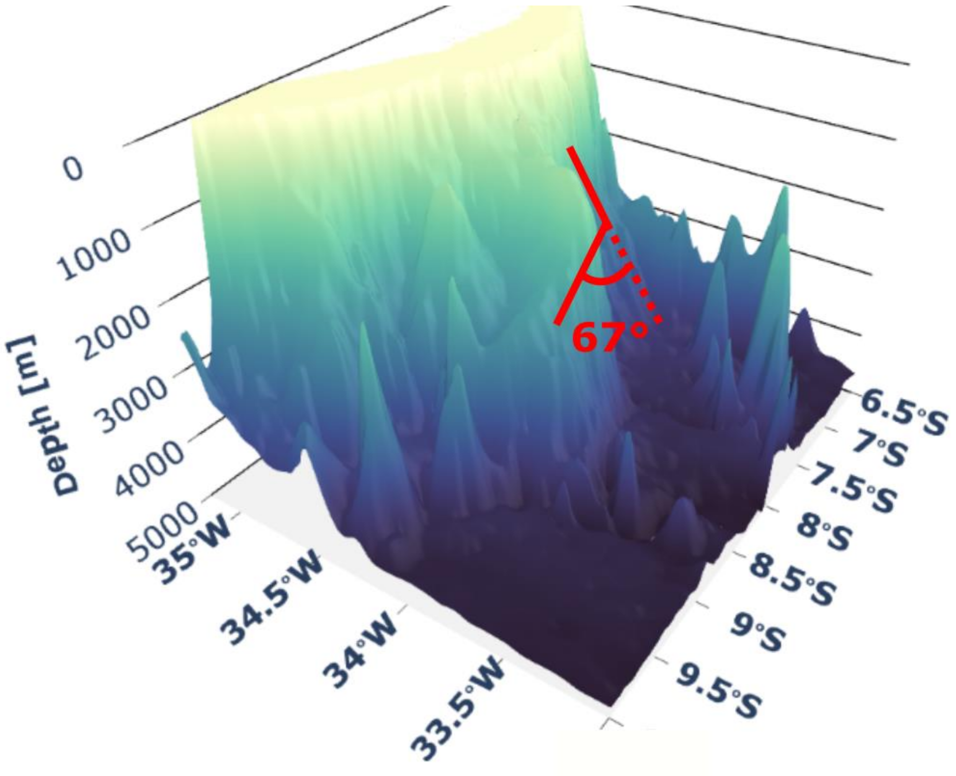


Figures extracted from Dengler et al. (2004; Nature)

The Pernambuco Plateau

- 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°).

- 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;



The Pernambuco Plateau and *Oceano Nordeste* oceanographic expedition

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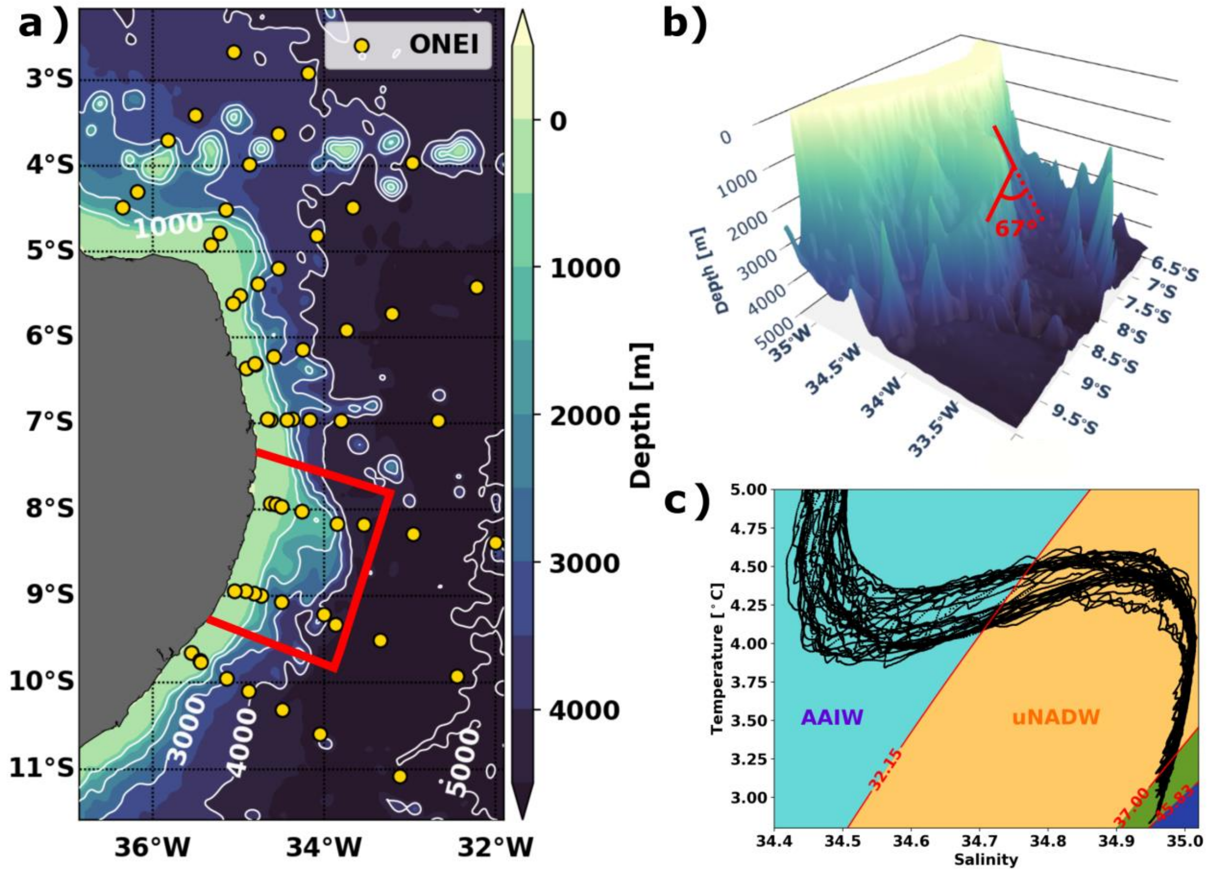
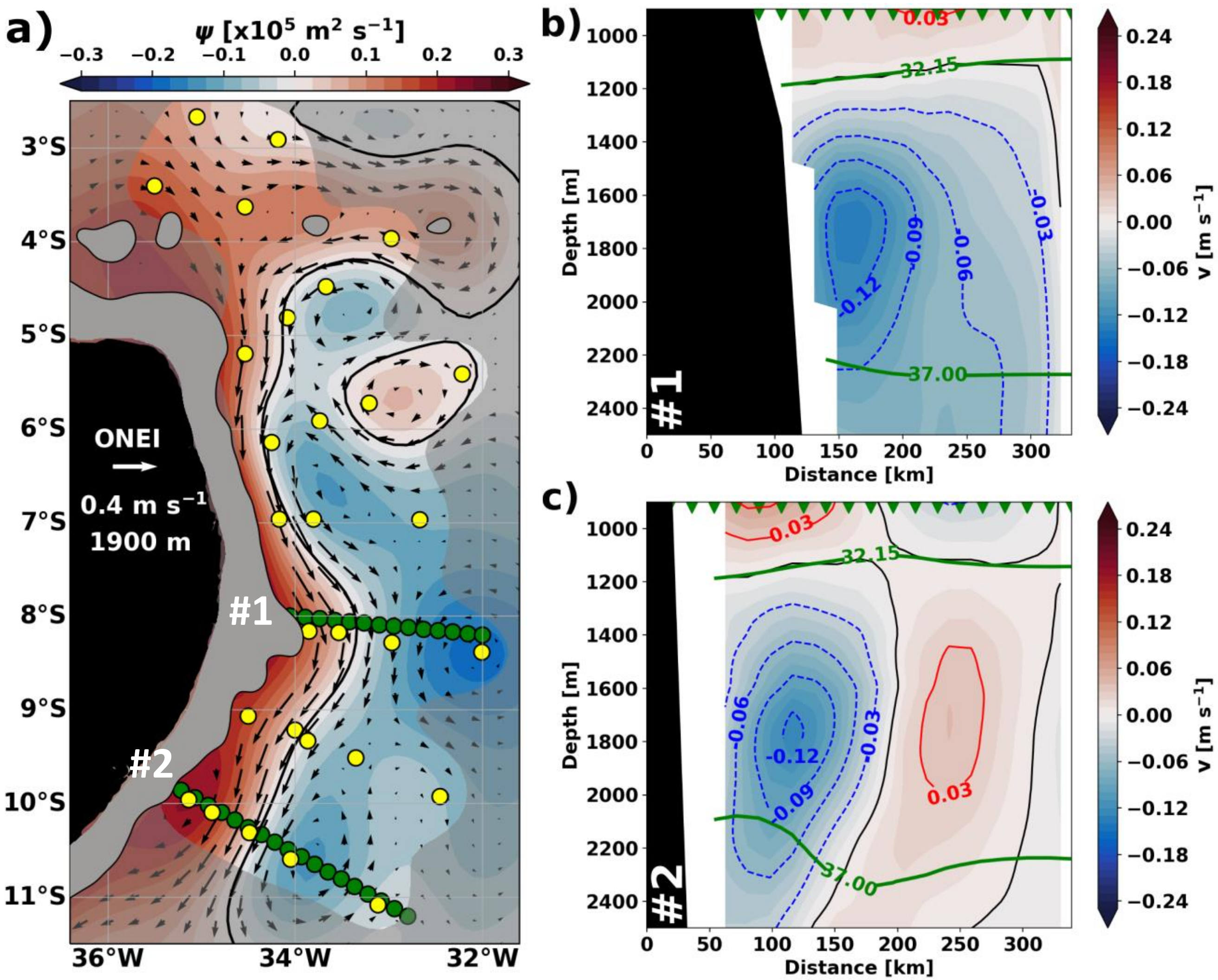


- *Oceano Nordeste*:
  - historical hydrographic data set carried out by the Brazilian Navy between 26 Feb and 21 Mar 2002;
  - **8 transects (57 stations) off northeast Brazil**;

- 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 isobaric level of no motion** to obtain the geostrophic velocities.

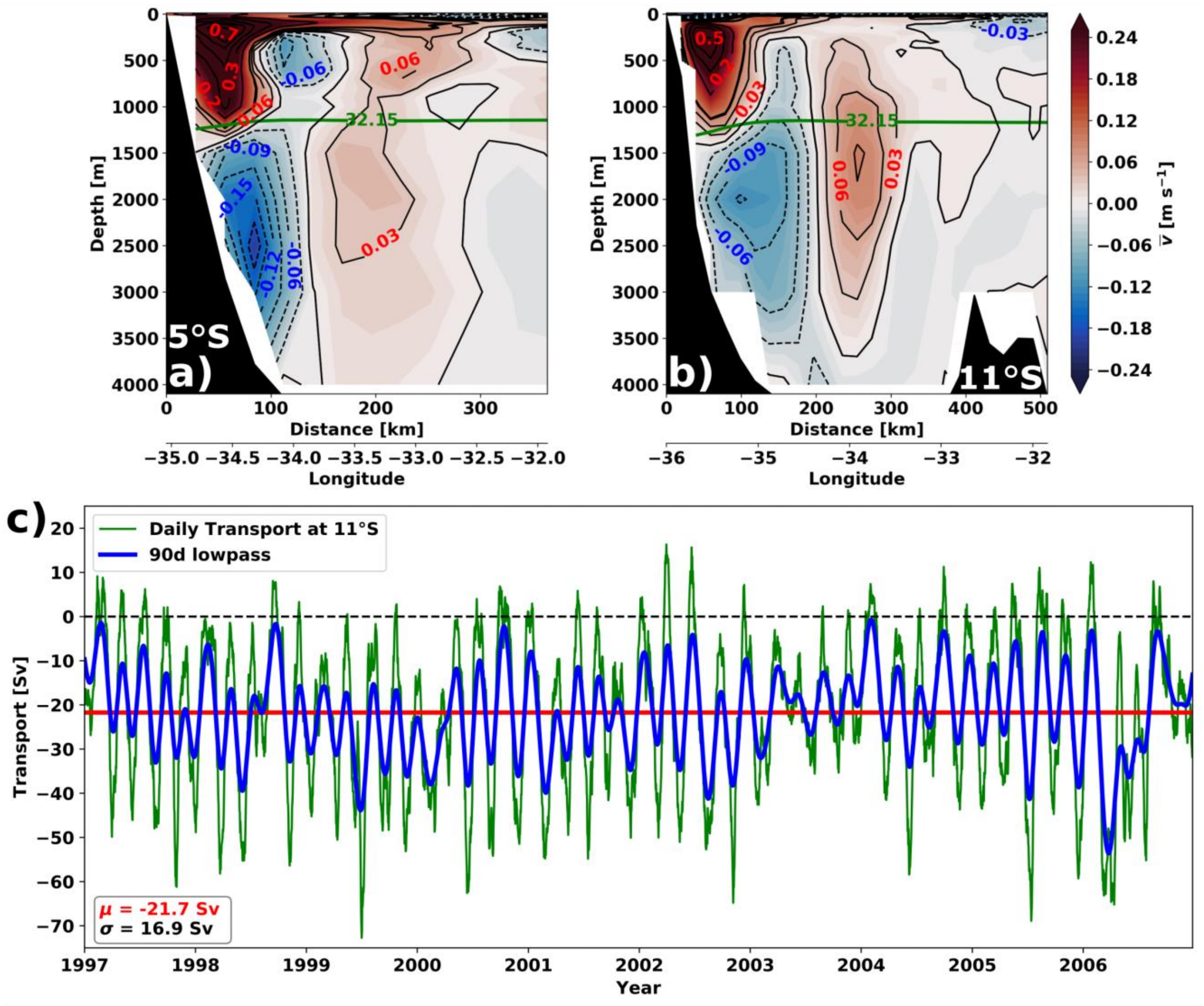
A quasi-synoptic view of the deep circulation off northeast Brazil



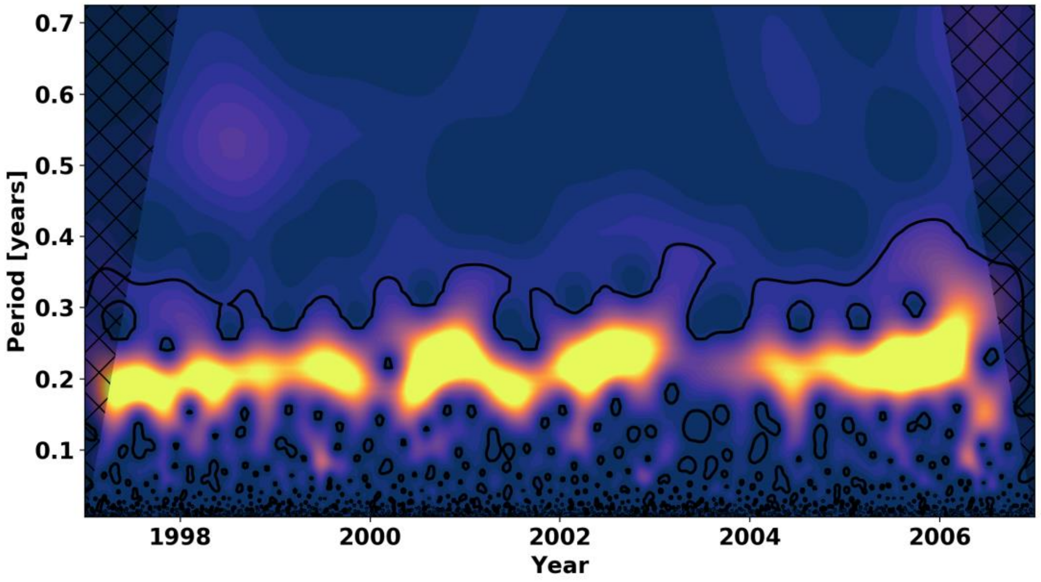
- The *Oceano Nordeste* data presents the **first horizontal scenario of the deep circulation off northeast Brazil**;
  - The DWBC axis (ψ = 0) separates the continental slope as it crosses the PP (Fig. a);
  - At 8°S, the DWBC occupies mainly the upper NADW with core velocity of ~0.15 m s^{-1} (Fig 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.

The HYbrid Coordinate Ocean Model (HYCOM) #19.1

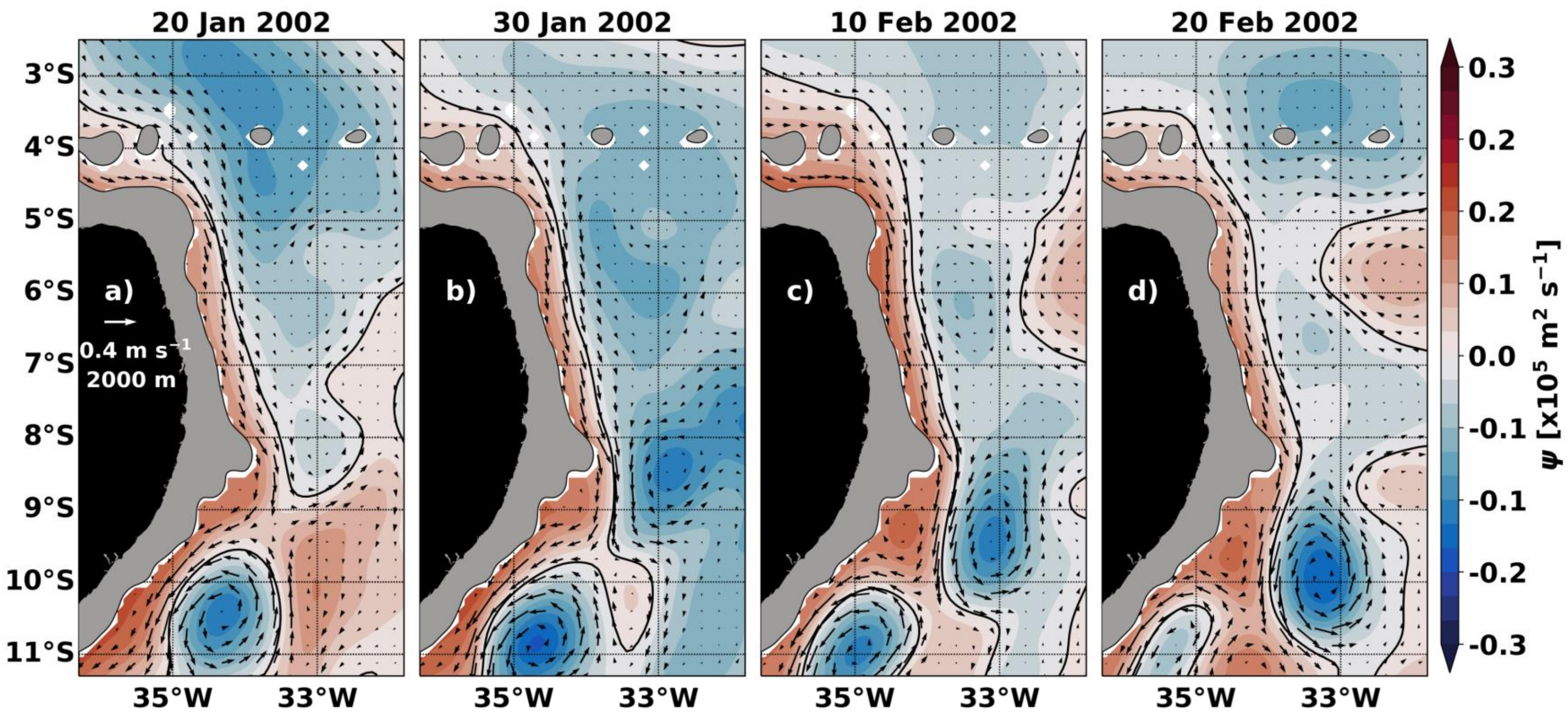


- To explore the **separation hypothesis**, we use a 10year time series of a reanalysis (HYCOM model) with **10 km resolution in 40 vertical levels**;
- Both the upper current (North Brazil Undercurrent) and DWBC from the model present the morphometric aspects as in previous observations;
- The modelled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



The DWBC crossing of the Pernambuco Plateau

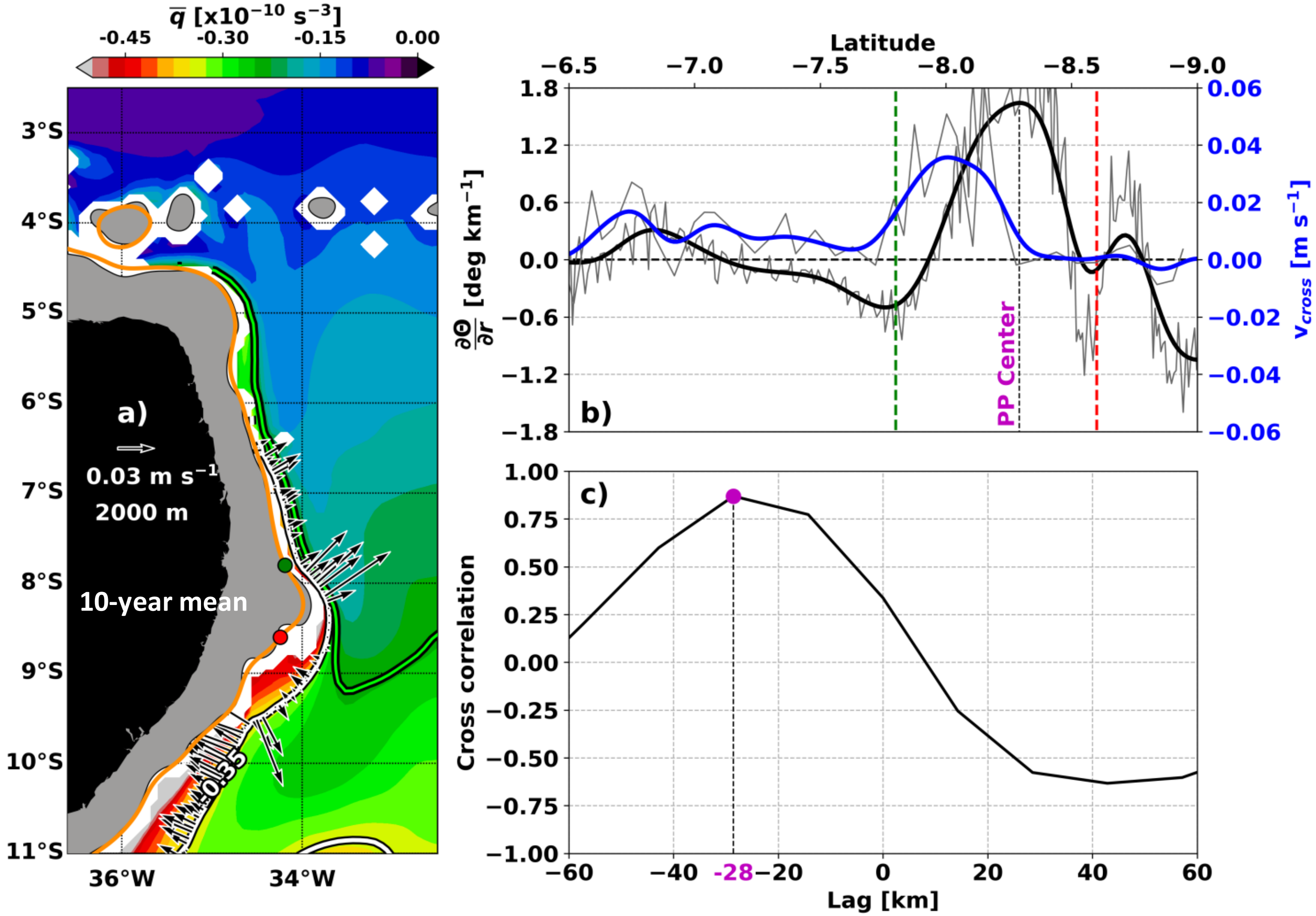
- For the model outputs, we computed the stream function ψ through a Helmholtz velocity decomposition algorithm based on Li et al. (2006);
- Timeline:
  - On 20 Jan 2002, the DWBC flows adjacent to the continental slope (Fig a);
  - Ten days later, **the main axis of the DWBC moves away from the slope** (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.



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

Figure extracted from
Stern & Whitehead (1990; JFM)

Diagnostics for the DWBC separation



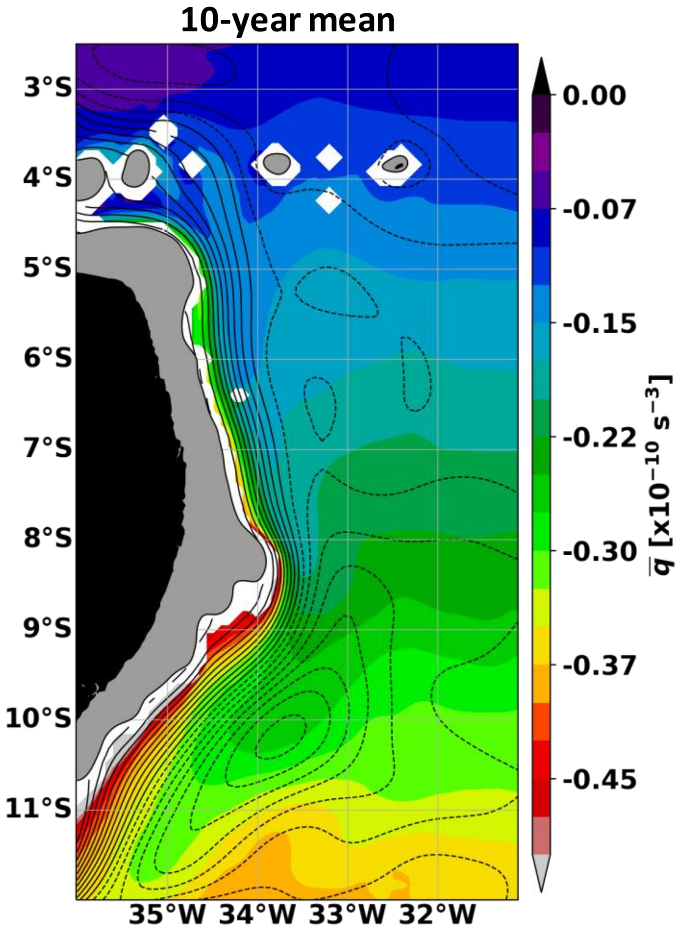
Here, we use Ertel's PV definition for large and mesoscale flows (Pedlosky, 1987),

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

- ✓ The distortion of the PV field near capes hints at inertial separation of the mean streamlines (Pickart and Huang, 1995);
- ✓ The cross-stream velocities along the westernmost and continuous PV contour (white line in a) increase immediately upstream the Pernambuco Plateau;
- ✓ 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.

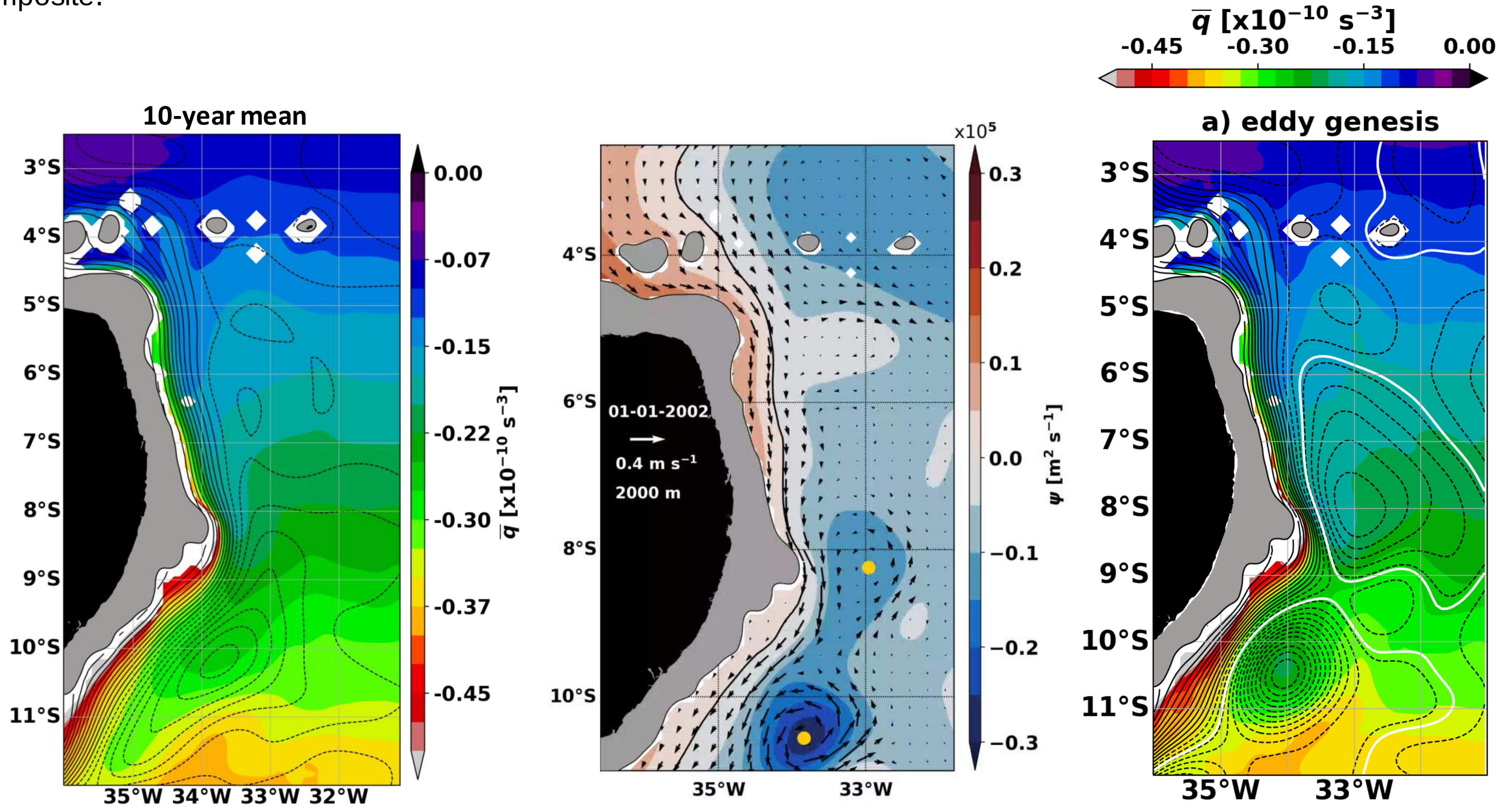
The DWBC mean pathway

- 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;



The DWBC mean pathway and composites

- 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;
- 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.



The DWBC inertial separation

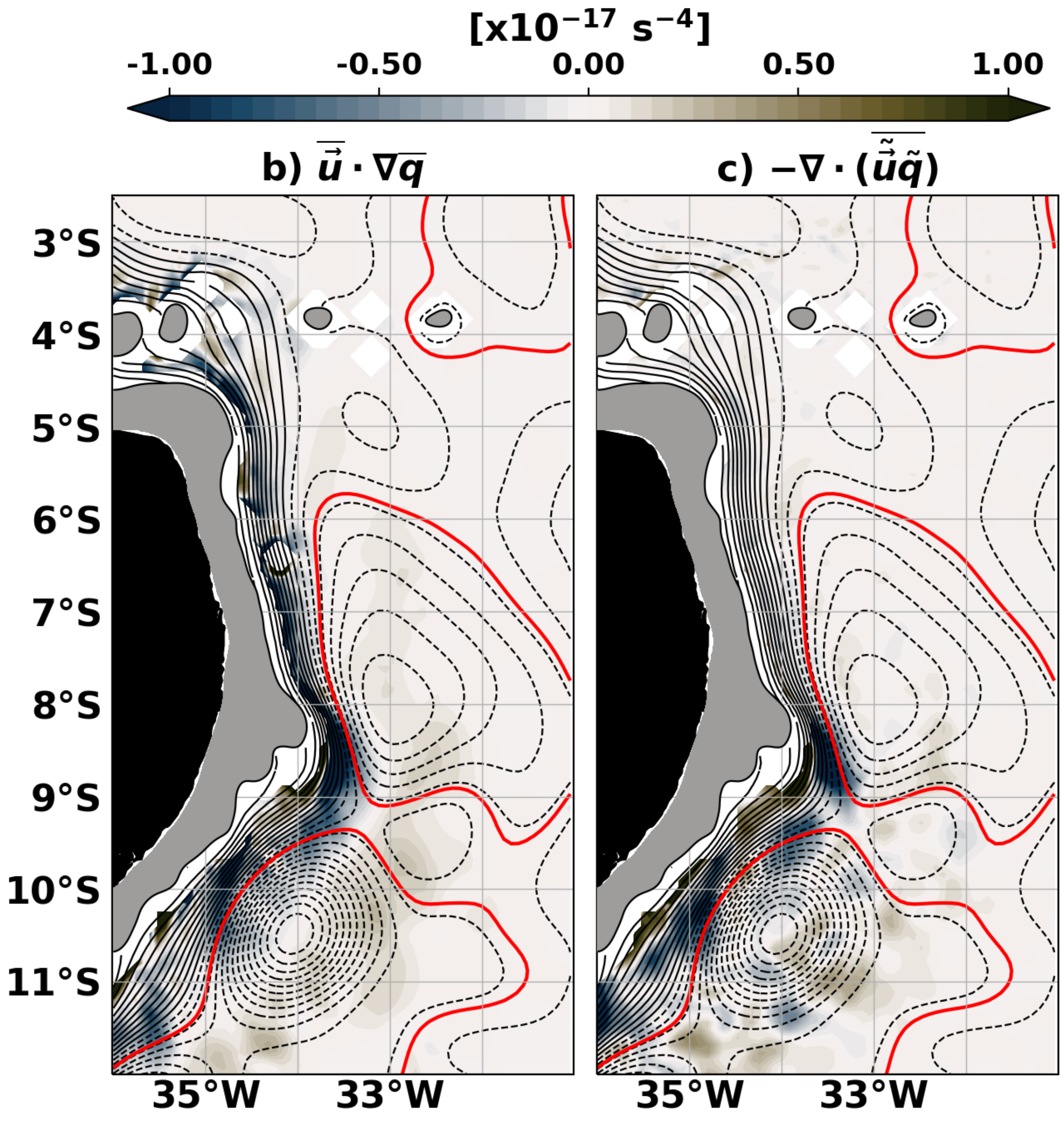
- To test the inertial processes, we evaluate the Turbulent Sverdrup Balance (Rhines & Holland, 1979),

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

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

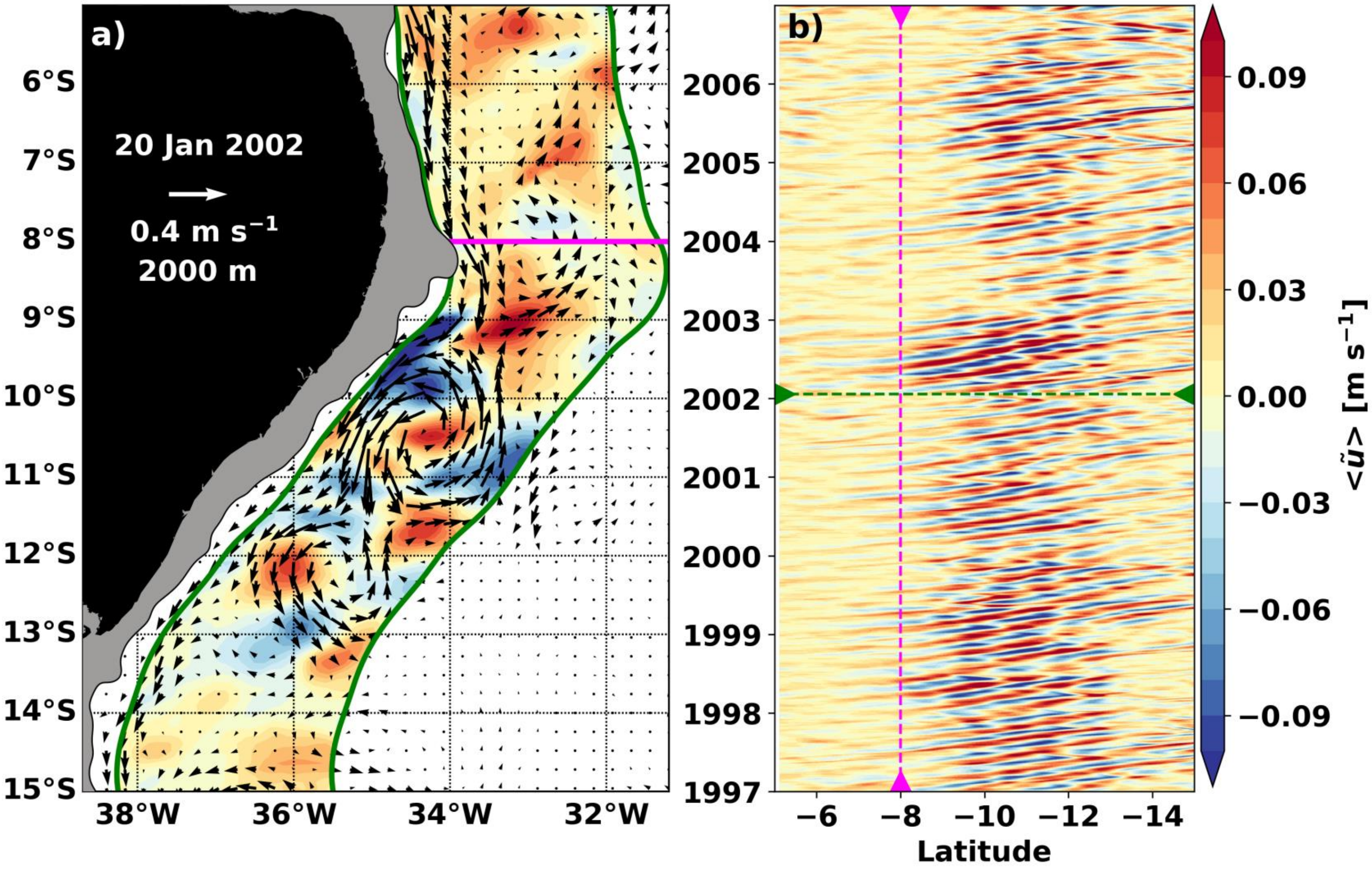
- The Turbulent Sverdrup Balance is valid at the DWBC core from 8°S to 11°S similarly to model representations of the DWBC in other locations (van Sebille et al., 2012; Solodoch et al., 2020; Biló et al., 2021);
  - Downstream the separation of the boundary, both terms in the equation decrease up to 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.



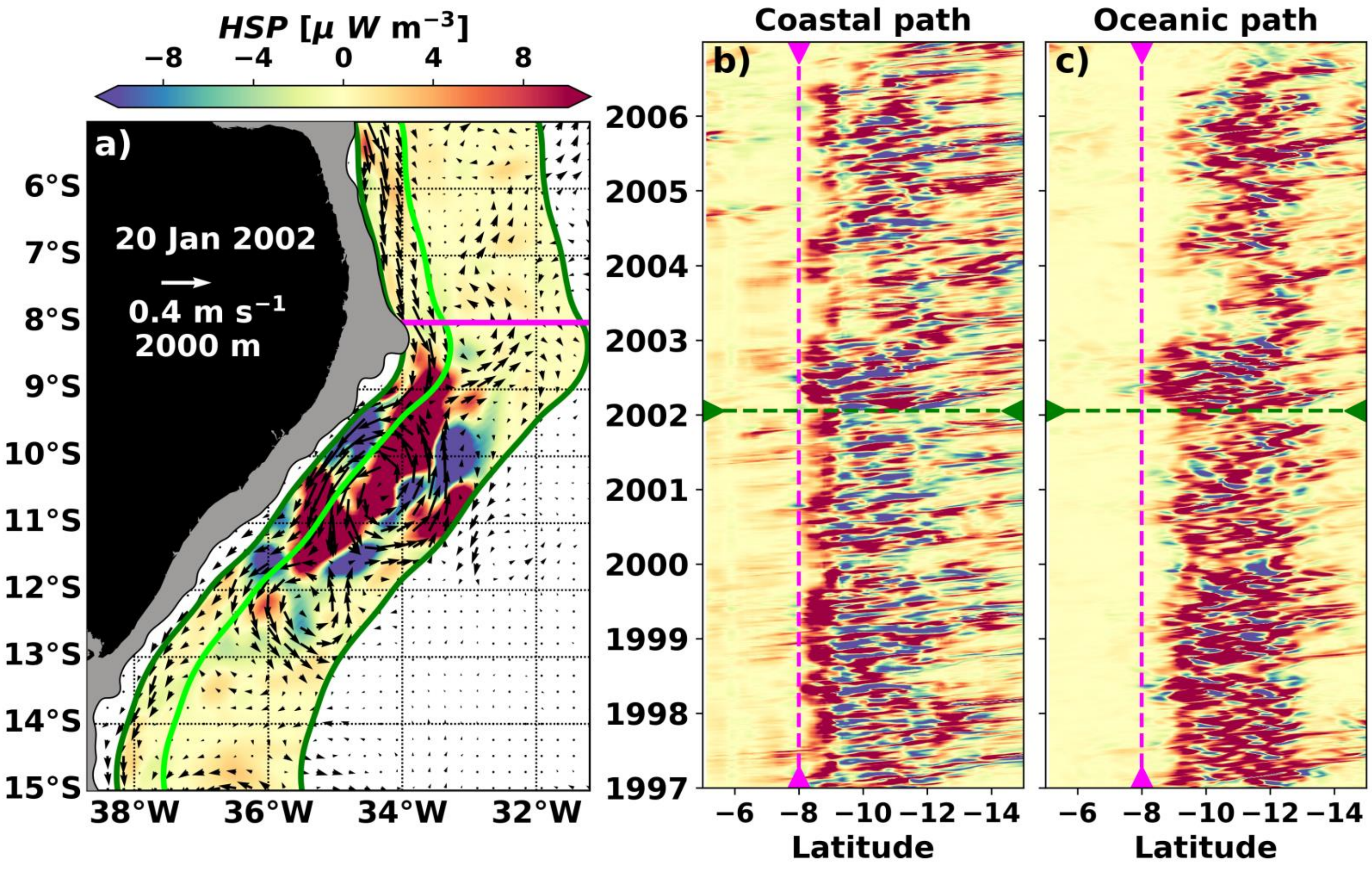
What happens downstream the separation?

- 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 PP is responsible for the DWBC anticyclone genesis downstream the separation;
    - Perturbations may amplify due to instability processes (Philander, 1990).



The growth mechanism for the anticyclones

- Eddies can be a product of energy conversions and instability processes (Phillips & Rintoul, 2000; 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);



$$HSP = -\rho_1 \left[\overline{(\tilde{v}^2 - \tilde{u}^2)} \psi_{xy} + \overline{\tilde{v}\tilde{u}} (\psi_{xx} - \psi_{yy}) \right]$$

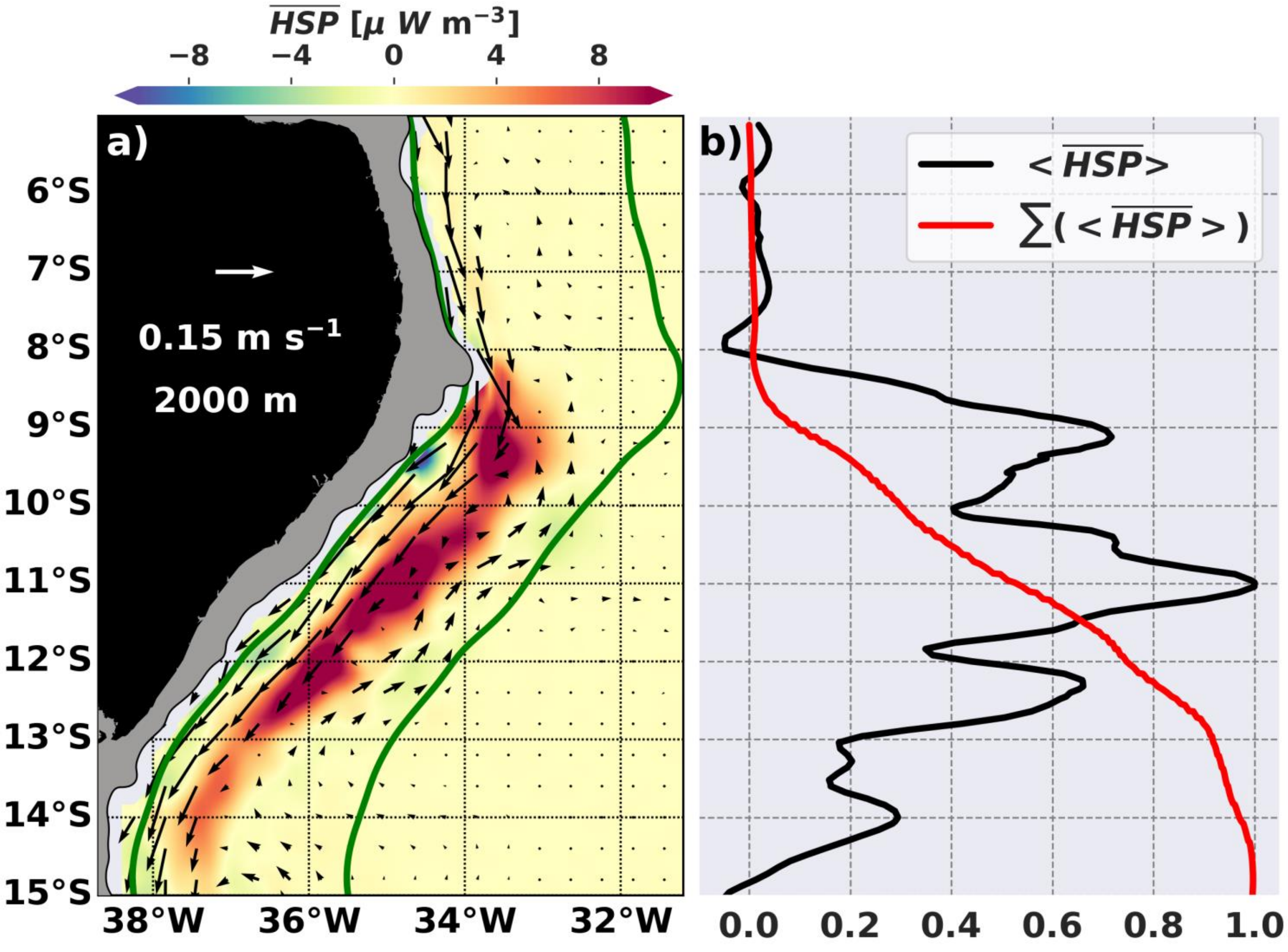
HSP = Horizontal Shear Production
We obtained the anomalies using a 60-day low-pass filter

- 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.

The DWBC Anticyclones' Net HSP

- The time-mean HSP overlaid by the time-mean velocity field links the DWBC separation at the PP to the anticyclones' initial growth at 8°S;
  - Note the strong velocity pointing offshore at the corner of the plateau;
  - Downstream of the separation, the cumulative net HSP (red line) increases exponentially from 8°S to 13°S.

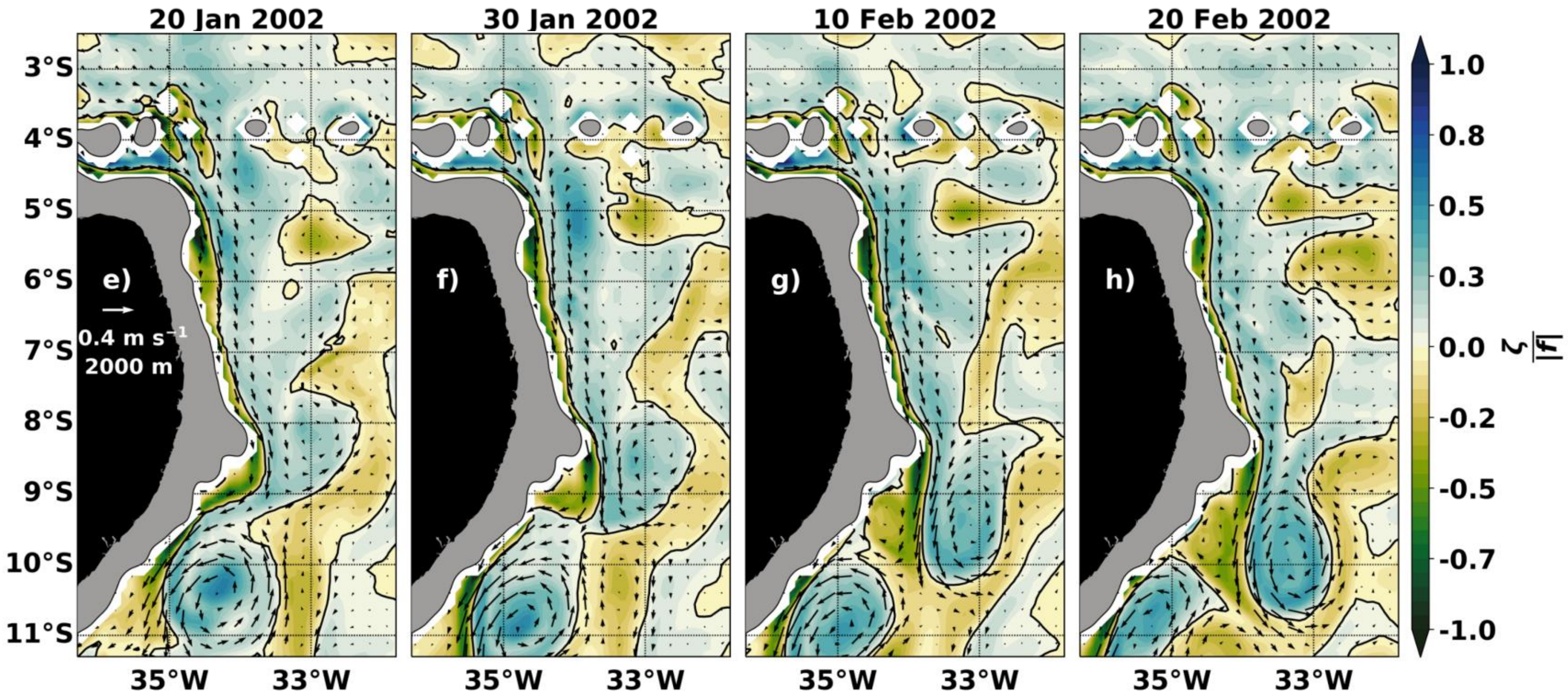


- South of 14°S, the cumulative net HSP stabilizes;
  - barotropic conversions through HSP are weak or nonexistent from this latitude southward;
- To conserve energy, the regional EKE budget requires dissipation due to:
  - lee waves generated by geostrophic motions (Nikurashin and Ferrari, 2013)?
  - 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)?

Final remarks

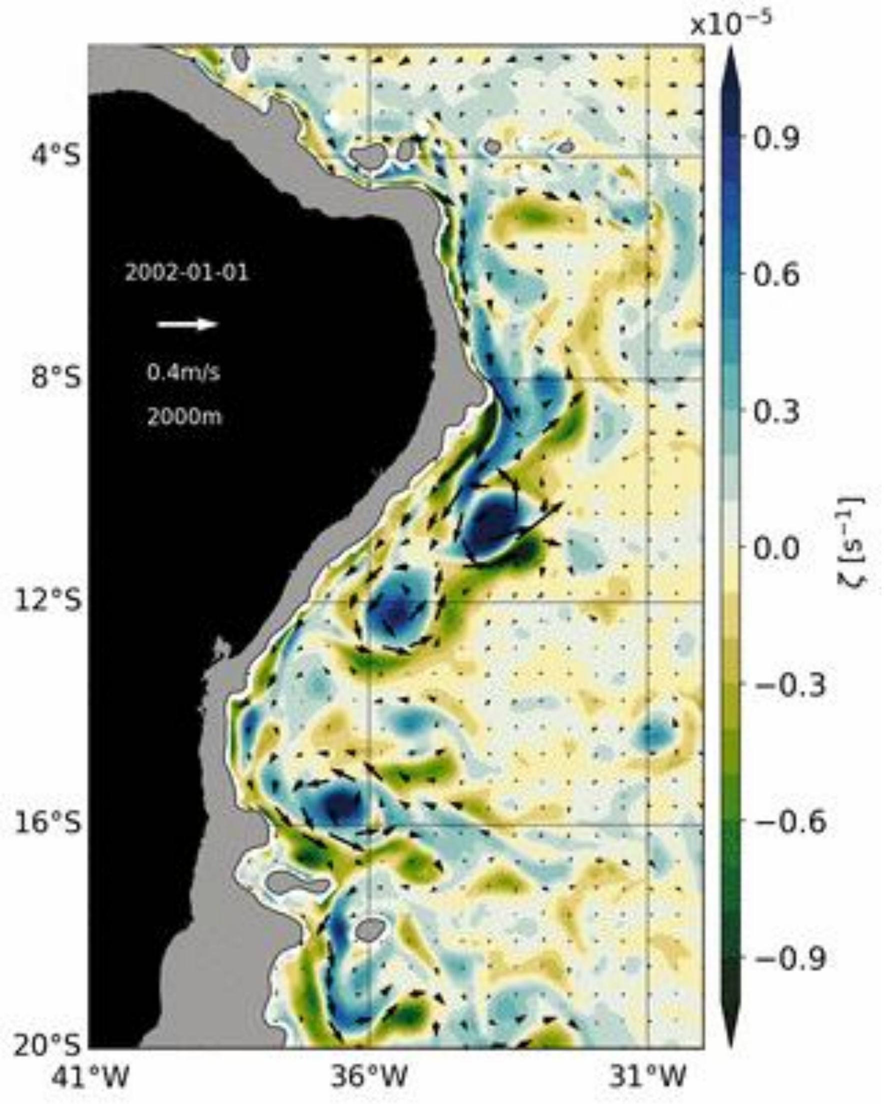
- The ONEI oceanographic expedition:
  - The cross-bathymetry transects at 8°S and 10°S confirms that the DWBC breakup occurs at 8°S;
  - The quasi-synoptic map of stream function presents patterns of flow separation downstream of the Pernambuco Plateau.

- Model outputs (HYCOM):
  - We tested 3 separation theories (Røed, 1980; Stern & Whitehead, 1990; Solodoch et al., 2020);
  - The result of the tests converge to indicate that the DWBC undergoes a local, intermittent separation while contouring the Pernambuco Plateau;
  - Downstream of the separation, the DWBC offshore lobe, with positive relative vorticity, folds into anticyclones which travel southwestward;
  - Barotropic instability is a mechanism relevant to the eddies' growth.

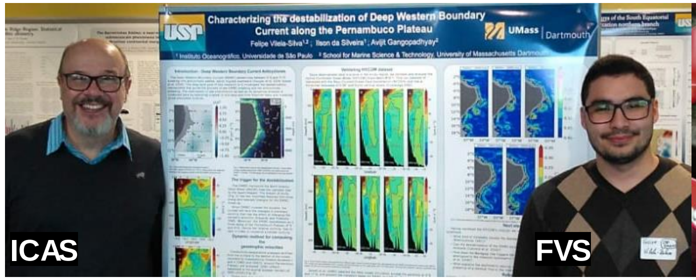


Final remarks

- 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.



Acknowledgements and thanks to



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Marinha do Brasil: Authors

HYCOM: Authors

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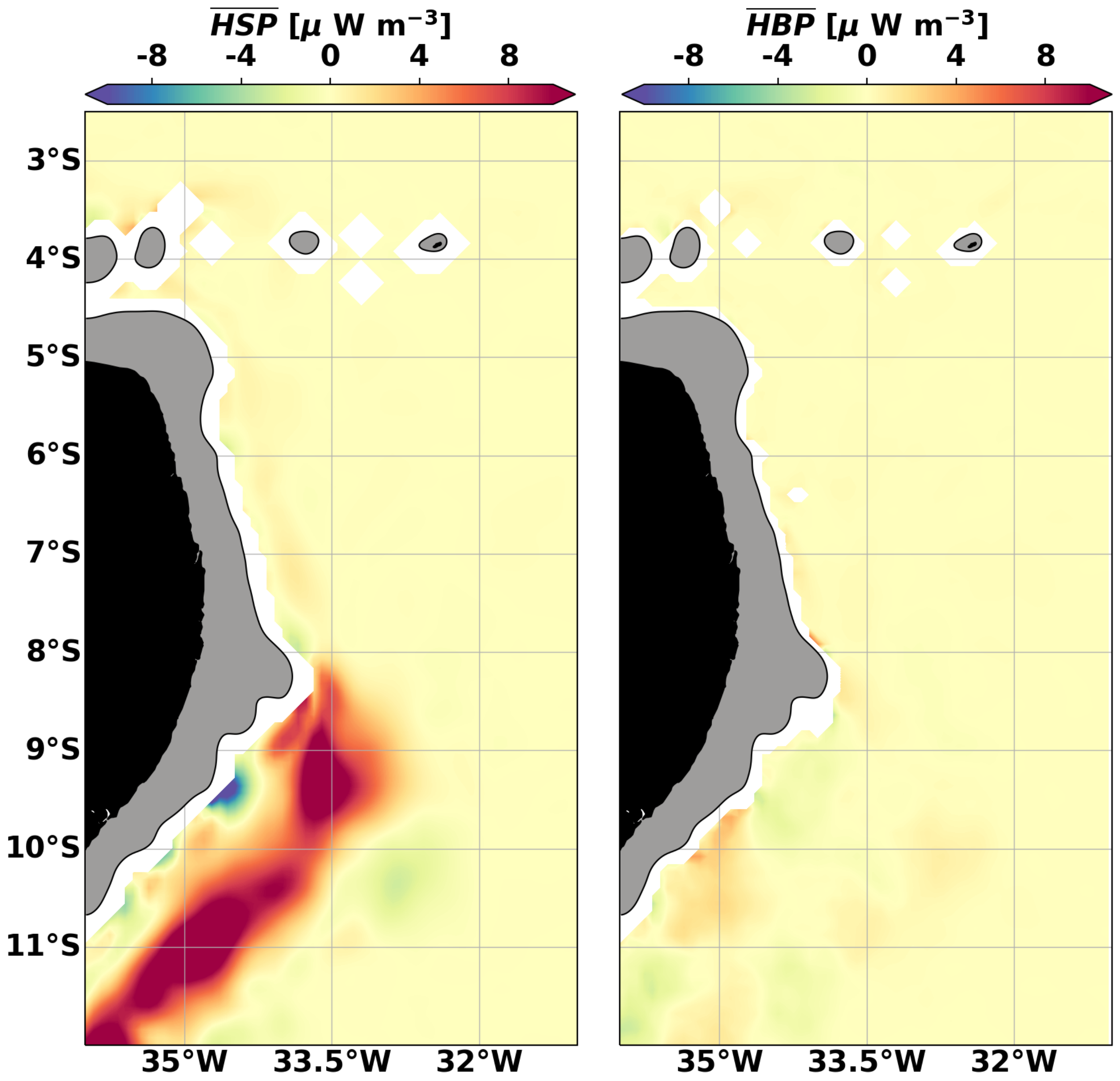
We dedicate this work to the memory of B.M. Castro.

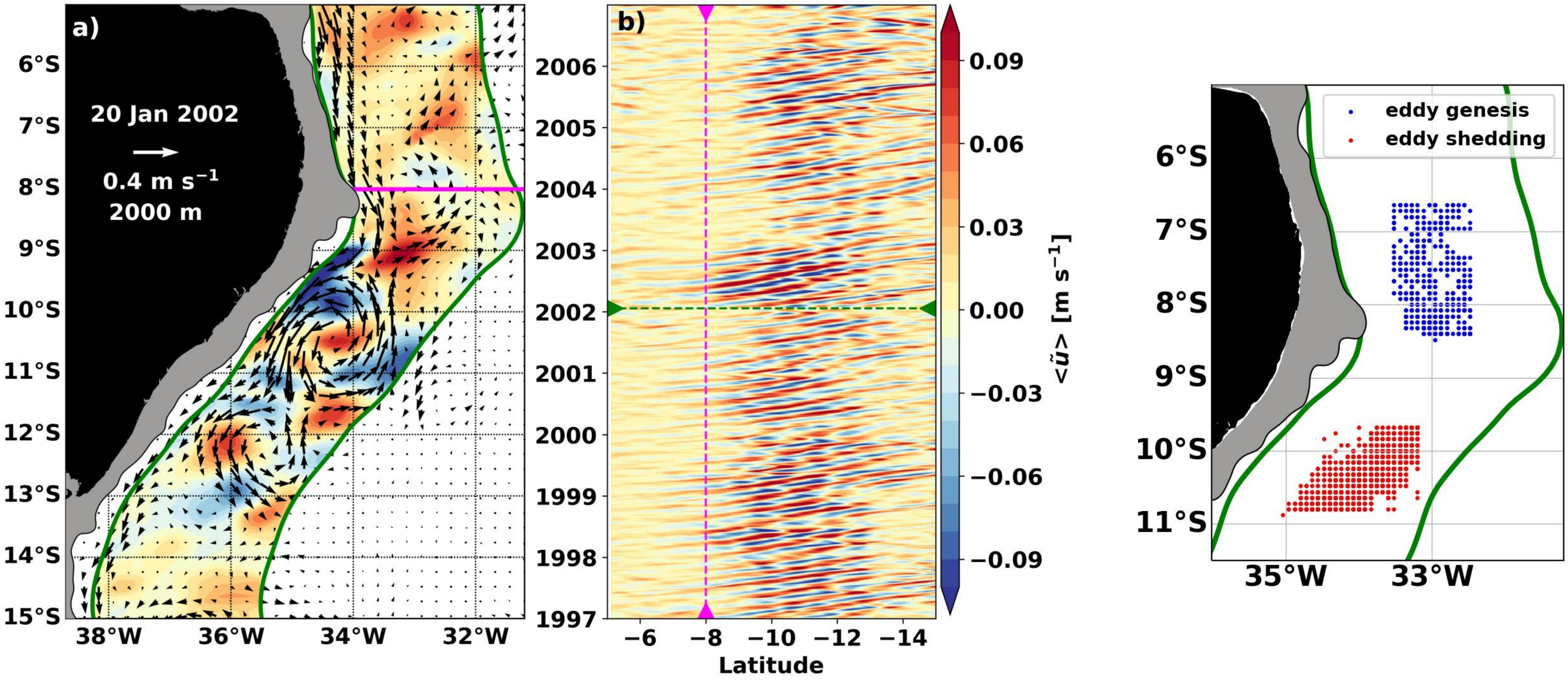
The authors acknowledge the sampling efforts by the crew and scientists in the Brazilian Navy R/V Antares during the Oceano Nordeste expedition.

Extras: Horizontal Shear Production vs Horizontal Buoyancy Production



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

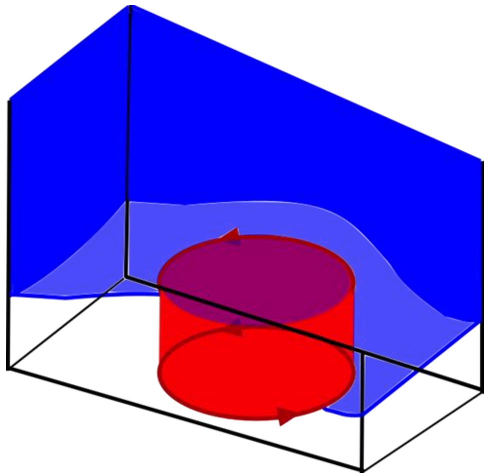
- Downstream of the plateau, the propagation of the anticyclones can be identified by **velocity anomalies** (60-day low-pass filter);
  - The perturbations in the velocity field further indicates that the **PP is responsible for the DWBC anticyclone genesis** downstream the separation;



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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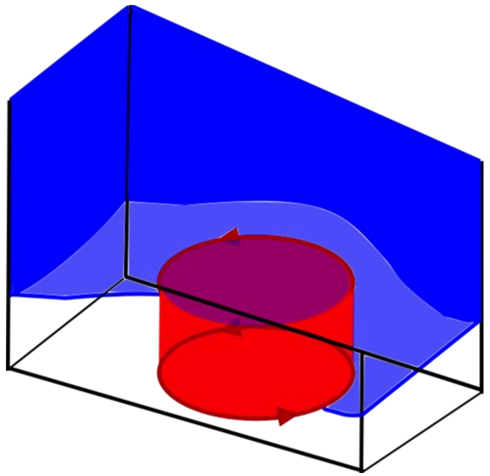

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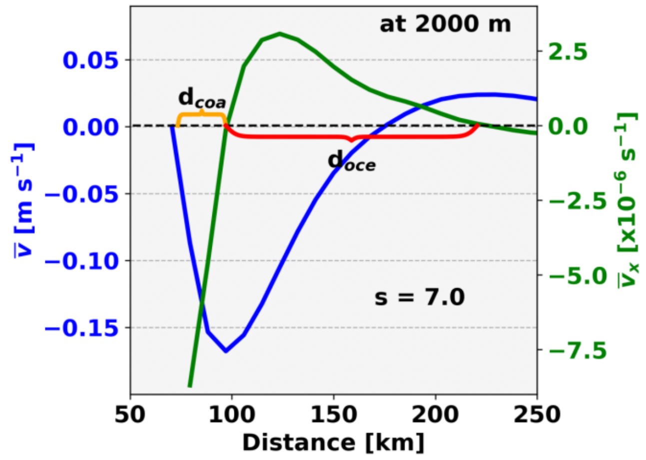
- Stern and Whitehead (1990) revealed that a barotropic jet sheds eddies as it crosses a corner.
  - The authors proposed two parameters to evaluate whether or not the jet separates from the adjacent wall:
  - the angle θ and the ratio *s*,

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



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

The DWBC inertial separation

➢ In addition, following Solodoch et al. (2020), inertial separation takes place when $\Delta U < 0$:

$$\Delta U \approx U\frac{W}{R_c} - fW\frac{dh}{h} = -0.26 \text{ m s}^{-1}$$

$U\frac{W}{R_c}$ → -0.50 m s^{-1}

$fW\frac{dh}{h}$ → 0.24 m s^{-1}

✓ The values of the scaling analysis suggest that the DWBC along the Pernambuco Plateau undergoes an inertial separation during the eddy genesis.

A quasi-synoptic view of the deep circulation off northeast Brazil

- We interpolated the hydrographic data onto a regular grid using the Fast Marching Method (FMM) and Objective Analysis (Agarwal & Lermusiaux, 2011).
  - The FMM finds the shortest sea distance between two coordinates and improves the interpolation grid of the standard Objective Analysis in regions of irregular bathymetry;
  - The method was first used for the Indonesian Throughflow region (Agarwal & Lermusiaux, 2011).

- With the 3D density structure, we computed the **geostrophic stream function**,

$$\psi = \frac{\Delta\Phi}{f_0}, \quad \Delta\Phi \stackrel{\text{def}}{=} -\int_{p_0}^{p} \delta\, dp$$

$$(u, v) \stackrel{\text{def}}{=} (-\psi_y, \psi_x)$$