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Supporting Information for Influence of the Gulf of Guinea islands on the Atlantic Equatorial Undercurrent circulation

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Contents of this file

Introduction

This supporting information is divided in three sections. Section S1 provides the cruise data from the French PIRATA cruises S-ADCP database used in the study. Section S2 provides information of (and access to) the animated potential vorticity maps. Section S3 provides the derivation and assumptions used in our potential vorticity analysis.

S1. ADCP cruises

The cruise data from the French PIRATA cruises S-ADCP database (https://www.seanoe.org/data/00335/44635/) used in the study is shown in Figure S1. Although this dataset presents only a few meridional sections upstream of São Tomé (Fig. S1a) and some overlap occur in the seasons in which the cruises happened, the different sections (Fig S1b-f) capture the variability of the EUC in terms of strength, core depth, and latitudinal migration.

S2. PV animations

This section provides the animated potential vorticity maps averaged within the EUC layer (1025.3–1026.4 $\mathrm{kg\,m^{-3}}$) for 10 years of our NEMO simulation for the With Island (WI; S2.1) and No Island (NI; S2.2) configurations. The files can be obtained at https://jmp.sh/QOM2NF2.

S2.1 Additional Supporting Information (Files uploaded separately)

- Animation S2.1: PV vertically averaged within the EUC layer for 10 years of the NEMO WI simulation. For details see Figure 4a to c in the paper;
- Animation S2.2: PV vertically averaged within the EUC layer for 10 years of the NEMO NI simulation. For details see Figure 4d to f in the paper.

S3. The evolution of PV

The potential vorticity (PV) evolution equation is a combination of advection, friction, and diapycnal mixing terms (Müller, 2006, see also, e.g., Thomas et al, 2005; Gula et al., 2019). Using the "rescaled" form of the PV (Morel et al., 2019), this equation is, in its Eulerian form,

$$\partial_t Q = -\,\mathrm{div}\Big(\underbrace{\mathbf{u}\,Q}_{\text{ADVEC.}} + \underbrace{\boldsymbol{\nabla} G_\rho \times \mathbf{F}}_{\text{FRICTION}} - \underbrace{(\boldsymbol{\zeta}+\mathbf{f})\frac{dG_\rho}{dt}}_{\text{DIAP. MIXING}}\Big)\,, \qquad (1)$$

where the rescaled PV is

$$Q = (\boldsymbol{\zeta}+\mathbf{f})\cdot\boldsymbol{\nabla} G_\rho\,. \qquad (2)$$

In (2), $\boldsymbol{\zeta}$ and $\mathbf{f}$ are the relative vorticity and the Coriolis force, respectively, and G_ρ is the PV-rescaling function (e.g., Morel et al., 2019; Assene et al., 2020) based on a reference density profile $\rho(z)$. In (1), $\mathbf{u}= (u, v, w)$ is the velocity and $\mathbf{F}$ represents friction and other nonconservative forces (e.g., Thomas, 2005; Gula et al., 2019).

In the PV analysis of the present study, we must put forth a few assumptions which allow a qualitative estimate of the processes that play a major role in changing the PV within the Gulf of Guinea. The approach, assumptions, approximations, and their implications are detailed below.

S3.1 Streamtubes

The mean circulation that flows in and out of the Gulf of Guinea follows "streamtubes" (Fig. S3), bounded on the sides by streamlines (mean currents) and on the vertical by isopycnals (the EUC layer). Using this streamtube approach, we can analyse the northern and southern hemisphere circulations independently. Taking ∂V as the surface of the streamtube and integrating (1), the PV budget in the tube is

$$\partial_t \iiint_V Q = - \oiint_{\partial V} \left(\mathbf{u}\, Q + \boldsymbol{\nabla} G_\rho \times \mathbf{F} - (\boldsymbol{\zeta} + \mathbf{f}) \frac{dG_\rho}{dt} \right) \cdot \mathbf{n}\, \mathrm{dS}\,. \tag{3}$$

The DIAP. MIXING term, the last on the right-hand side of (3), is zero across isopycnal surfaces and only (weak) frictional and diabatic terms can change the PV budget (the impermeability theorem, Haynes & McIntyre, 1987). Basically, we neglect DIAP. MIXING on all lateral boundaries. Therefore, there is no effect of diapycnal mixing on the integrated amount of PV. However, as shown below, diapycnal mixing affects the average PV, creating *PV anomalies* that are important for the circulation and dynamics within the isopycnal layer.

S3.2 Quasi-steady circulation

Assuming a quasi-steady circulation within the streamtubes,

$$\overline{\partial_t \iiint_V Q} \approx 0\,, \tag{4}$$

where the overbar denotes a time mean over 10 years of simulation. Time-averaging (3) and using (4) for the sections *in* and *out* of the streamtube, and recalling that DIAP. MIXING is neglected in those sections, the *flux of PV* at the exit of the streamtube is

$$\overline{\iint uQ|_{out}}\, dydz = \overline{\iint uQ|_{in}}\, dydz + \overline{\mathrm{FRICTION}} + \overline{\mathrm{SIDE}}\,, \tag{5}$$

where $\overline{uQ}$ is the flux of PV evaluated at the exit and initial vertical sections.

When integrating the friction term of (3) over a layer, the net result is associated with lateral fluxes where isopycnic surfaces intersect land (Haynes & McIntyre, 1987). Thus FRICTION with land (e.g. bottom friction or lateral viscous boundaries) likely dominate. The SIDE term includes PV flux anomalies $\overline{\mathbf{u}'Q'}$ associated with isopycnal mixing at the boundaries. Since our model does not present the diagnostics to distinguish between

PV changes due to friction and lateral boundary fluxes, we defined the term $\overline{\text{OTHER}} = \overline{\text{FRICTION}} + \overline{\text{SIDE}}$.

S3.3 The role of Q_{in}

We define the mean PV values at the exit and entrance of the streamtube:

$$\overline{Q_{out}} = \frac{\overline{\iint uQ|_{out}\,\mathrm{dydz}}}{\overline{\Phi_{out}}} \quad \text{and} \quad \overline{Q_{in}} = \frac{\overline{\iint uQ|_{in}\,\mathrm{dydz}}}{\overline{\Phi_{in}}}\,, \tag{6}$$

where $\Phi = \iint u\,dydz$ is the volume flux across the sections. Here, we assume that the $\overline{Q_{in}}$ of particles entering the domain through the EUC section of the streamtube (see Fig. S3) is representative of the initial PV for the entire volume. Using (6), (5) can be written as

$$\overline{\Phi_{out}}\,\overline{Q_{out}} = \overline{\Phi_{in}}\,\overline{Q_{in}} + \overline{\text{OTHER}}\,. \tag{7}$$

With $Q_{out} = Q_{in} + \delta Q$ and $\Phi_{out} = \Phi_{in} + \delta\Phi$, the PV variations is

$$\overline{\delta Q} = -\overline{Q_{in}}\frac{\overline{\delta\Phi}}{\overline{\Phi_{out}}} + \frac{\overline{\text{OTHER}}}{\overline{\Phi_{out}}}\,.$$

Therefore, the effect of diapycnal mixing at any point of the trajectory connecting these two sections can be rearranged as

$$\overline{\delta Q}_{mix} = -\overline{Q}_{in}\frac{\overline{\delta\Phi}}{\overline{\Phi}_{out}}\,, \tag{8}$$

and the residual change accounting for friction and isopycnal mixing is

$$\overline{\delta Q}_{other} = \overline{Q}_{out} - \overline{Q}_{in} - \overline{\delta Q}_{mix}\,. \tag{9}$$

S3.4 Calculation of the mean diapycnal flux $\overline{\delta\Phi}$

The mean flux at the exit of the domain and in each hemisphere ($\overline{\Phi_{out}}$) as well as the total (north + south) EUC flux at the entrance ($\overline{\Phi_{in}}$) are readily estimated from the model outputs. To evaluate the impact of mixing and other terms on PV variations in each hemisphere (Eq. 8 and 9) we have to split $\overline{\Phi_{in}}$ into parts contributing to the northern and southern regions. Since our goal is to get an order of magnitude of these terms, we simply assume that the incoming EUC transport to each hemisphere follows the same ratio σ as the split between hemispheres at the exit,

$$\overline{\Phi}_{in} = \begin{cases} \sigma \, \overline{\Phi}_{in} & \text{for the Northern Hemisphere, and} \\ (1-\sigma) \, \overline{\Phi}_{in} & \text{for the Southern Hemisphere,} \end{cases} \quad (10)$$

where σ is obtained for each simulation from Equation 3 of the main manuscript, but applied to the volume flux instead of salinity. This is a rough approximation to obtain $\overline{\delta\Phi} = \overline{\Phi_{out}} - \overline{\Phi_{in}}$, but sufficient to get an order of magnitude for the effect of diapycnal mixing on the PV budget.

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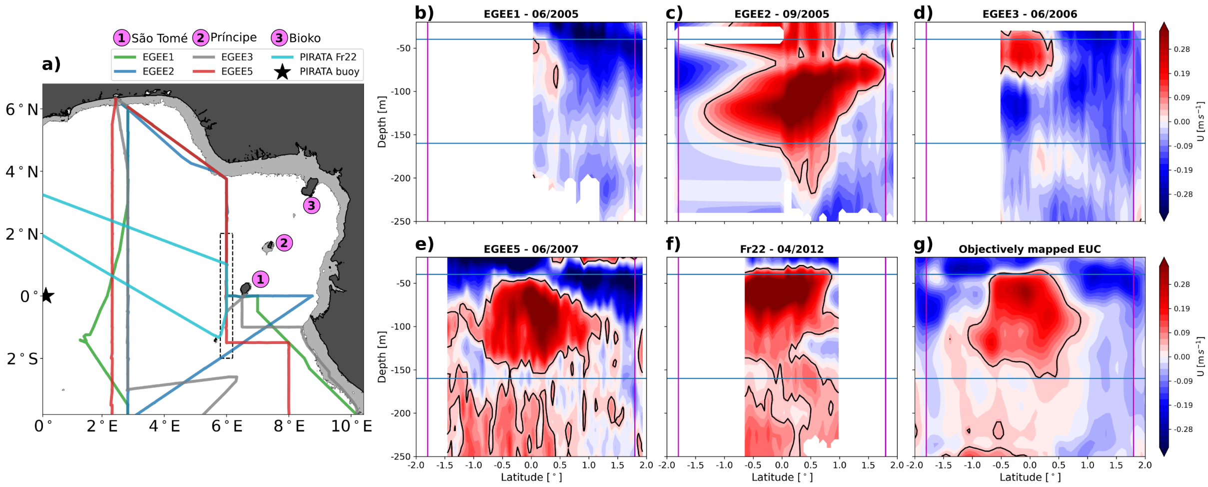

Figure S1. PIRATA/EGEE shipboard ADCP cruises used in the study. The cruise sections were linearly interpolated in a regular grid prior to the objective analysis. (a) map of the study region with the cruises tracks. (b) EGEE1 - 06/2005; (c) EGEE2 - 09/2005; (d) EGEE3 - 06/2006; (e) EGEE5 - 06/2007; (f) PIRATA Fr22 - 04/2012; (g) Objective analysis mean section.

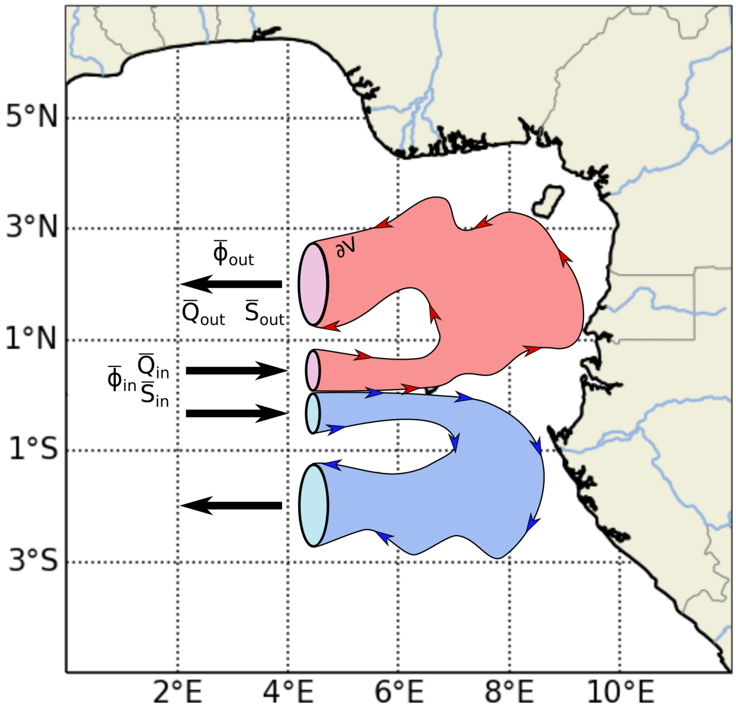

Figure S3. Schematics of the streamtube approximation for estimating the processes transforming the EUC PV. The northern (southern) hemisphere streamtube is represented in red (blue). ∂V is the volume of the tube and $\overline{\Phi}$, $\overline{Q}$, and $\overline{S}$ are the mean volume flux, potential vorticity, and salinity in and out of the streamtube.