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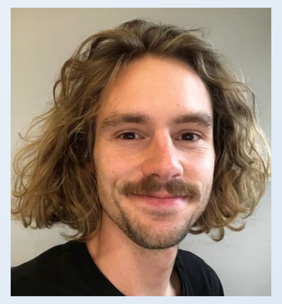

The Impact of **Stratification** on Surface-Intensified **Eastward Jets** in **Turbulent Gyres**

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Eastward Oceanic Jets

Eastward jets in the ocean are detached extensions of western boundary currents which retain their coherence in the presence of mesoscale turbulence. Such jets are present in the North Atlantic (Gulf Stream), the North Pacific (Kuroshio) and the Southern Indic (Agulhas), but no such jets exist in the Southern Atlantic or the Southern Pacific. Here, we revisit the long-standing question of what conditions the existence of such jets (Thompson, 1971) by studying the role of stratification in a two-layer quasi-geostrophic model of the wind-driven circulation (Miller, 2025).

Stratification in 2-Layer Quasi-Geostrophic Gyres

The simplest model that can qualitatively model turbulent eastward jets is the two-layer quasi-geostrophic model.

$$\frac{\partial q_1}{\partial t} + \mathbf{u}_1 \cdot \nabla q_1 = \frac{\nabla \times \tau}{H_1} + \nu \nabla^4 \psi_1$$

$$\frac{\partial q_2}{\partial t} + \mathbf{u}_2 \cdot \nabla q_2 = \nu \nabla^4 \psi_2$$

$$q_1 = \nabla^2 \psi_1 + \frac{1-\delta}{L_d^2}(\psi_2 - \psi_1) + \beta y$$

$$q_2 = \nabla^2 \psi_2 + \frac{\delta}{L_d^2}(\psi_1 - \psi_2) + \beta y$$

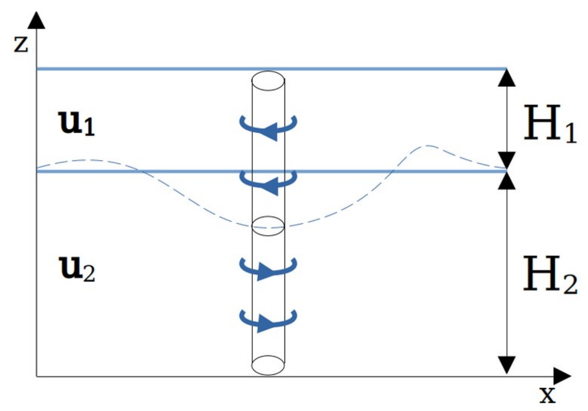

Figure 2: Schematic of the two-layer quasi-geostrophic model.

Here, q_i is the potential vorticity, $\mathbf{u}_i$ the fluid velocity and ψ_i the streamfunction. We solve this system on a square domain of length L and apply no-slip boundary conditions. The forcing is set to a double-gyre wind forcing $\tau_x = \tau_0 \cos(2\pi y/L)$. H_i are the layer thicknesses. Western-intensified Gyres (see Figure 2A for a schematic) appear when the planetary vorticity gradient β is important, and they become turbulent when the viscosity ν is small. The non-dimensional numbers that describe the effects of stratification are then

$$\boxed{\delta = \frac{H_1}{H_1 + H_2}, \quad \xi = \frac{\delta_I^2}{L_d^2}}$$

The **relative thickness of the upper layer δ** measures the surface-intensification of stratification, and the **flow criticality ξ** measure the density difference between the two layers. It is written here as the ratio of the (inertial) width of the western boundary current $\delta_I = \sqrt{8\pi\tau_0/(H_1\beta^2 L^3)}$ and the deformation radius L_d. We study turbulent gyres at different values of ξ and δ in order to explore their role for the organization of mesoscale turbulence and the formation of eastward jets.

Linear Stability Analysis: Dividing the Parameter Space

To see which stratification is favorable for jet formation, we start by dissecting the parameter space spanned by δ and ξ into three regimes based on the vertical structure of the Sverdrup flow (Rhines and Young, 1982) and local linear stability analysis for westward and eastward Sverdrup flow (Figure 2C and 2D).

Strong Stratification ($\xi < 1$):
Baroclinic instability is supressed. The density difference between the two layers is strong enough to completely confine the Sverdrup gyre to the upper layer.

Intermediate Stratification ($1 < \xi < 1/\delta$):
Baroclinic instability of westward Sverdrup flow occurs, but eastward Sverdrup flow remains stable. The gyre remains surface-intensified.

Weak Stratification ($1/\delta < \xi$):
Eastward Sverdrup flow also becomes unstable, and potential vorticity starts to homogenize in the lower layer. The gyre becomes barotropic.

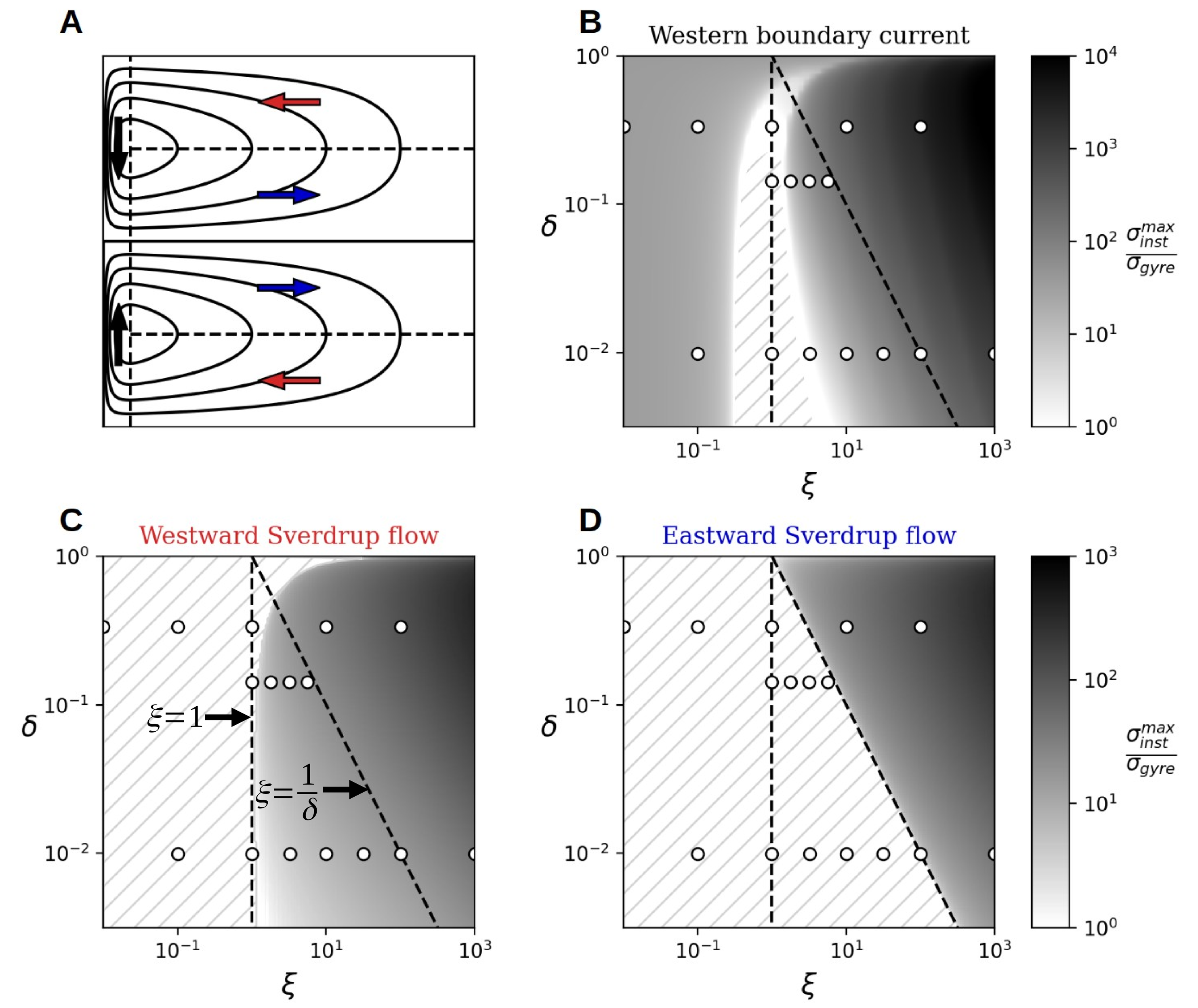

Figure 2: Separation of parameter space spanned by δ and ξ. The white dots indicate the simulations carried out during the study. **A:** Schematic of Sverdrup Gyre. **B:** Maximum growth rate σ of instability of the inertial western boundary current. Bottom Row: Maximum growth rate of baroclinic instability of (**C**) westward Sverdrup flow and (**D**) eastward Sverdrup flow.

Non-linear Flow: Jets as a Transition

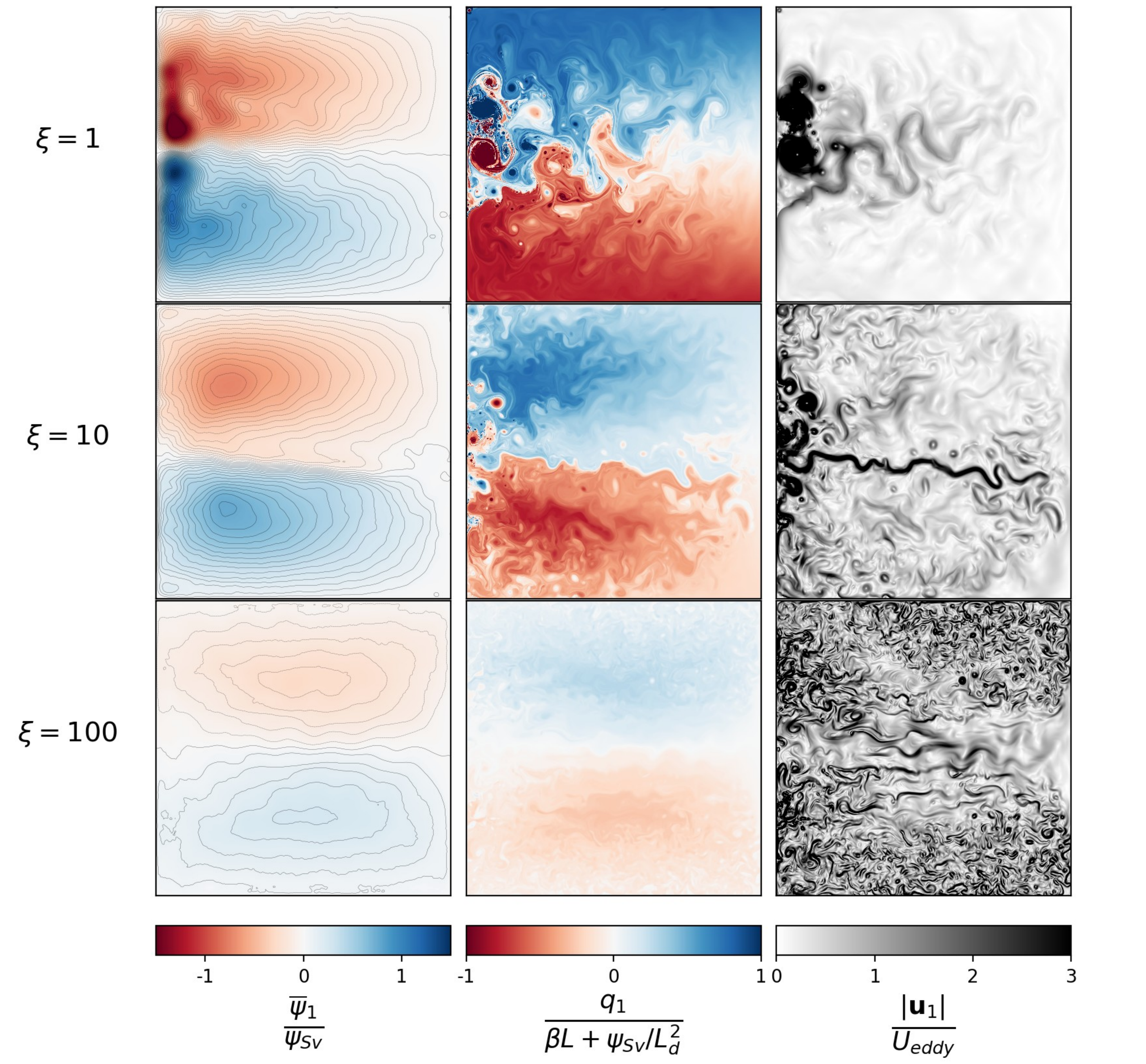

Figure 3: Time-average stream function (left) and snapshots of potential vorticity (center) and speed (right) in the upper layer for simulations at $\delta = 0.01$, in the intermediate stratification regime.

Turbulent Eastward Jets form only in the regime of intermediate stratification, in the midst of a turbulent transition from a vortex gas (Miller, 2024) to a zonostrophic regime with multiple eastward jets (Figure 3).

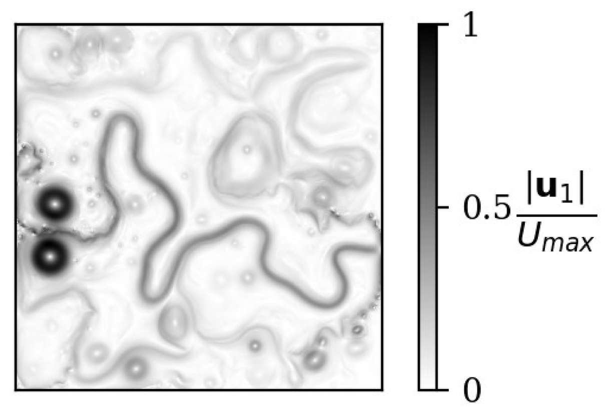

Figure 4: 1.5-layer flow at $\xi = 3.3$ (intermediate stratification) with east- and westward jets.

Eastward jets appear in a region of the parameter space where the western boundary current is stable (Figure 2B), which occurs also in the 1.5-layer model (Figure 4). However, in the 1.5-layer model eastward jets are accompanied by westward jets. We conclude that Baroclinic instability leads to the erosion of these westward flows, but leaves the eastward jet intact.

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