Dynamics of a dipolar gyre forced by a source/sink in a rotating tank

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Rotating tank experiments
The present study seeks for the understanding of a surprising phenomenon observed when using a source and a sink to force a dipolar gyre within a rotating homogeneous flow on an inclined plane. Fluid is injected (pumped out) at a source (sink) at rate $F$ (m$^3$.s$^{-1}$). An anticyclonic (cyclonic) gyre is forced around the source (sink), with strong zonal jets on their external side connected through intensified western boundary currents. Increasing $F$ leads to an instability when the source is north of the sink. When the source is south of the sink, the circulation stays stable, even at high forcing rates.

Linear versus non-Linear dynamics
Increasing the forcing rate leads to the instability of the westward jet configuration: many eddies grow inside the zonal central jet, propagate towards the west and then get dissipated as they enter the western boundary currents, causing exchange of tracer between the two gyres.

Mechanism of the instability
The Charney-Stern criteria for barotropic instability proves to be verified within the westward zonal jet of our unstable circulations: $U_{yy} > \beta$ changes sign.

Non dimensional vorticity equation
\[
\frac{d}{dt} \left( \zeta + u \frac{\partial \zeta}{\partial x} + v \frac{\partial \zeta}{\partial y} \right) + v = -\frac{\partial \zeta}{\partial x} \frac{\partial \zeta}{\partial y} + \frac{\partial^2 \zeta}{\partial x^2} + \frac{\partial^2 \zeta}{\partial y^2} - \frac{\partial}{\partial x} \left( \frac{\partial}{\partial x} (x-x_{source}) - \delta(x-x_{sink}) \right)
\]

Origin of the instability
The spatial origin of the instability may either be in the western boundary current, in the region near the source and sink, or in the westward jet. Counter mean potential vorticity gradient eddy fluxes suggest that the instability grows within the westward jet.

Sensitivity to the distance separating the source/sink
The instability of the westward jet configuration can be inhibited by increasing the distance between the source and the sink (here $F=100$ ml/min).

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Linear stability analysis
Increasing the forcing rate leads to the instability of the westward jet configuration: many eddies grow inside the zonal central jet, propagate towards the west and then get dissipated as they enter the western boundary currents, causing exchange of tracer between the two gyres.

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Linear stability analysis
The eigen value spectrum confirms the presence of an unstable mode above a threshold forcing. As the mode becomes unstable, the real part of the complex eigen value changes sign. Nevertheless, its imaginary part (period of the oscillation) does not vary significantly, suggesting a Hopf bifurcation.

Conclusions
In our simulations, no instability occurred in the western boundary layers, although western boundary currents played a major role in the exchange of tracer between the two gyres. Having distributed sources and sinks would certainly better mimic the ocean circulation. Nevertheless, its imaginary part (period of the oscillation) does not vary significantly, suggesting a Hopf bifurcation.

According to theory, the amplitude of the oscillations should grow as $\sqrt{F-F_c}$ around the Hopf bifurcation.