Genesis, evolution, and apocalypse of Loop Current rings*

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Horizon Marine’s EddyWatch® Program

The Loop Current and the anticyclonic mesoscale eddies shed from it (“rings”) strongly influence the circulation, thermodynamics, and biogeochemistry of the Gulf of Mexico (GoM) (Sturges and Lugo-Fernandez, 2005). LCRs are routinely monitored by Horizon Marine as they can produce structural damage in offshore oil platforms.
AVISO+ Global Mesoscale Eddy Atlas

Identifies eddies from their Eulerian footprints in the altimetric SSH field (Chelton et al., 2011).
SSH rings

Regions instantaneously filled with closed streamlines of \( f^{-1} g \nabla \perp \eta \).
Traditional approach to ring detection (AVISO+, EddyWatch®).
Problem!

Solution to the 2-d N-S (streamlines in black; red is a tracer).
Rotation dominates over strain instantaneously everywhere.
There is a rotating observer which sees a steady deformation flow!
In true unsteady flow there exist no such distinguished observer.
FJBV (Lagrangian coherent structure - Wikipedia, Fig. 4.)
Goal

Since, the trajectory and life cycle for the LCRs determined by instantaneous metrics are invariably surrounded by an halo of uncertainty.

▶ Our goal here is to carry out objective (i.e, observer-independent) assessments of the life cycle of LCRs.

▶ We will specifically apply three methods which define *coherent Lagrangian vortex* boundaries as material loops that (i) defy stretching (Haller and Beron-Vera, 2013, 2014), (ii) resist diffusion (Haller et al., 2018), and (iii) whose elements rotate evenly (Haller et al., 2016).
Coherent Lagrangian ring detection

Let’s begin by fixing some notation. Consider the flow map

\[ F_{t_0}^t : x_0 \mapsto x(t; x_0, t_0), \]

which takes the positions of fluid particles at time \( t_0 \) to positions at time \( t \), whose motion is controlled by:

\[ \frac{dx}{dt} = v(x, t) = \frac{g}{f} \nabla \perp \eta(x, t). \]
Null-geodesic (NG) rings—defy stretching

\[ \delta \oint_{\gamma_0} \frac{|dF_{t_0}^T + T(x_0)|}{|dx_0|} = 0 \]

\[ |dF^t_{t_0}(x_0)|^2 = dx_0^\top \left( DF^t_{t_0}(x_0)^\top DF^t_{t_0}(x_0) \right) dx_0 : \text{objective!} \]

incoherent belt (typical)

coherent belt (exceptional)

Diffusion-barrier (DB) rings—defy diffusion

\[ \delta \int_{t_0}^{t_0+T} \oint_{\gamma_t} \kappa \nabla \theta \cdot d\mathbf{x}^\perp \, dt = 0 \]

\( \theta(x, t) \): (weakly) diffusive scalar

\( \gamma_t = F^t_{t_0}(\gamma_0) \): material!

Rotationally-coherent (RC) rings—elements rotate evenly

\[
\psi_{t_0}^{t_0+T}(x_0) = \int_{t_0}^{t_0+T} |\omega(F_{t_0}^t(x_0), t) - \bar{\omega}(t)| \, dt
\]

\[
(\omega(x(t), t) - \bar{\omega}(t))/|\omega(x(t), t) - \bar{\omega}(t)|
\]

\[
(\omega(x_0, t_0) - \bar{\omega}(t_0))/|\omega(x_0, t_0) - \bar{\omega}(t_0)|
\]

\[
\psi_{t_0}^{t_0+T}(\gamma_0) = \text{const}
\]

Lagrangian longevity

- For example, if a Lagrangian computation detects a coherent vortex over the time interval $[t_0, t_0 + T]$, it should also detect a vortex over the time interval $[t_0 + \delta t, (t_0 + \delta t) + (T - \delta t)] = [t_0 + \delta t, t_0 + T]$ for small $|\delta t|$, if $t_0 + T$ was really the date of breakdown.

- Then, for each $t_0$, we progress $T$ in 30-day steps as long as the Lagrangian method successfully detects a coherent vortex. Then for each $t_0$ we obtain a life expectancy $T_{\text{max}}(t_0)$.

- Finally, in an ideal case, a Lagrangian simulation of the lifespan of a coherent vortex would therefore start with a large $T_{\text{max}}$-value, which consistently decreases as $t_0$ progresses forward in time.
Life expectancy as a function of screening time according NG, DB, and RC assessments.

- b indicates the birth of the ring
- d1, d2, d3 are three assessments of the ring’s decease date.
- Birth and decease dates according to EddyWatch® (open triangle), and AVISO+ (filled).
As in previous slide, but in backward time.

- d3 can be taken to mark the *conception* date for the ring.
LCR Yankee—Forward-time assessment

▶ b is an assessment of birth date.
▶ d1 and d2 are two assessments of decease date.
LCR Yankee—Life after death?

Does b’ mark resurrection date?

No! It’s a different vortex (contains a small fraction of the fluid transported by Yankee).
Conclusions

▶ We have carried out an objective Lagrangian assessment of the life cycle of the Loop Current rings (LCRs) in GoM detected from satellite altimetry.

▶ Based on Lagrangian methods (NG and DB) a simple metric was developed to objectively determine the birth and death of a ring. Where, the Eulerian assessments were found incapable to distinguish conception from birth of the rings.

▶ Our results can find value in drawing unambiguous evaluations of material transport and should represent a solid metric for ocean circulation model benchmarking.
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