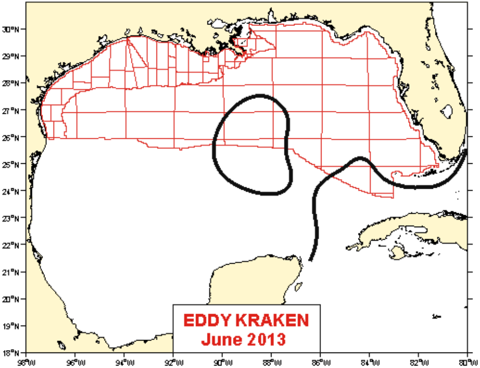
Genesis, evolution, and apocalypse of Loop Current rings*

Fernando Andrade-Canto,[1] Daniel Karrash,[2] Francisco J. Beron-Vera[3]
[1] *IIO, Universidad Autónoma de Baja California*
[2] *Technische Universität München*
[3] *RSMAS, University of Miami*

October 18, 2020

*Submitted to *Physics of Fluids* (ePrint arXiv:physics/2009.09050).

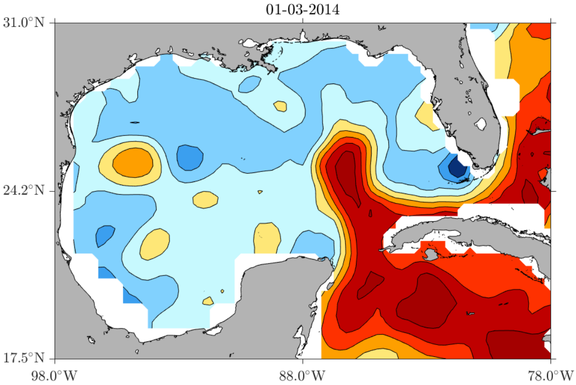
Horizon Marine's EddyWatch® Program



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.

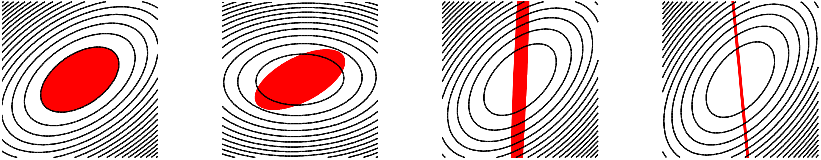
AVISO+ Global Mesoscale Eddy Atlas



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.
Haller (2005) *JFM* 525, 1.
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

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

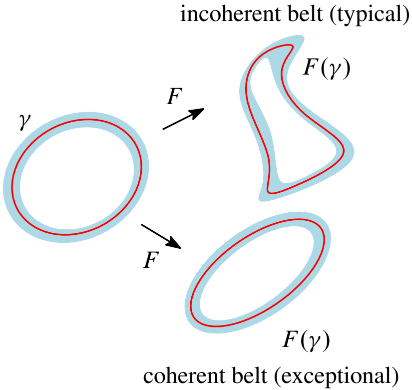
which takes the positions of fluid particles at time t_0 to positions at time t, whose motion is controlled by:

$$\frac{\mathrm{d}x}{\mathrm{d}t} = v(x,t) = \frac{g}{f}\nabla^{\perp}\eta(x,t).$$

Null-geodesic (NG) rings—defy *stretching*

$$\delta \oint_{\gamma_0} \frac{|\,\mathrm{d}F_{t_0}^{t_0+T}(x_0)|}{|\,\mathrm{d}x_0|} = 0$$

$$|\,\mathrm{d}F_{t_0}^{t}(x_0)|^2 = \mathrm{d}x_0{}^\top \left(\mathrm{D}F_{t_0}^{t}(x_0)^\top\, \mathrm{D}F_{t_0}^{t}(x_0)\right) \mathrm{d}x_0 \ :\ \text{objective!}$$

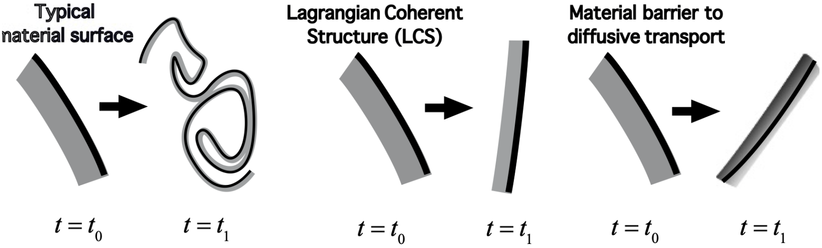


Haller & FJBV (2014). *JFM* 731, R4.

Diffusion-barrier (DB) rings—defy *diffusion*

$$\boxed{\delta \int_{t_0}^{t_0+T} \oint_{\gamma_t} \kappa \nabla\theta \cdot \mathrm{d}x^{\perp}\, \mathrm{d}t = 0}$$

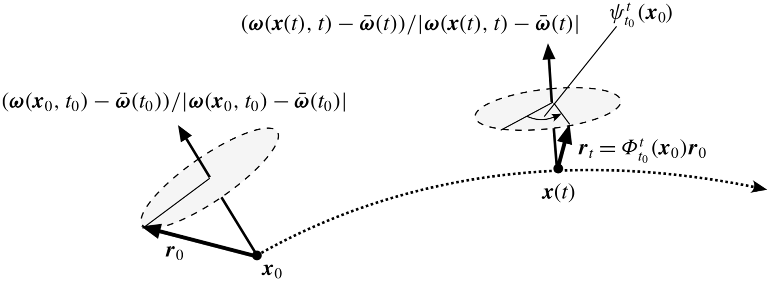
$\theta(x,t)$: (weakly) diffusive scalar
$\gamma_t = F_{t_0}^{t}(\gamma_0)$: material!



Haller et al. (2019). *PNAS* 115, 9074.

Rotationally-coherent (RC) rings—elements rotate *evenly*

$$\psi_{t_0}^{t_0+T}(x_0) = \int_{t_0}^{t_0+T} |\omega(F_{t_0}^t(x_0), t) - \bar{\omega}(t)| \, \mathrm{d}t$$



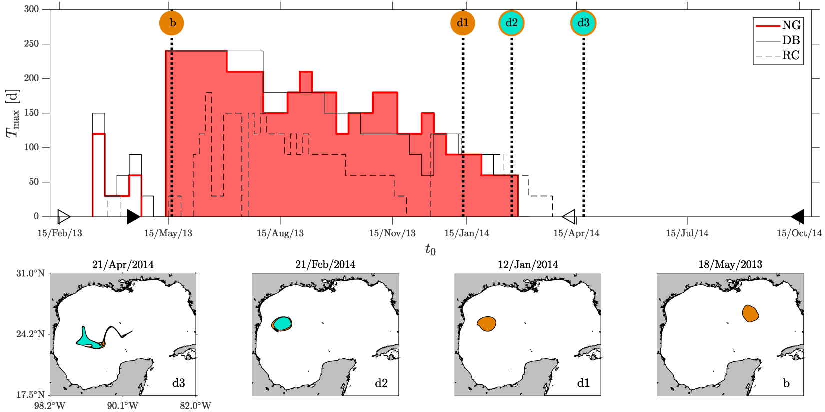
$$\boxed{\psi_{t_0}^{t_0+T}(\gamma_0) = \text{const}}$$

Haller et al. (2016). *JFM* 795, 13.

Lagrangian longevity

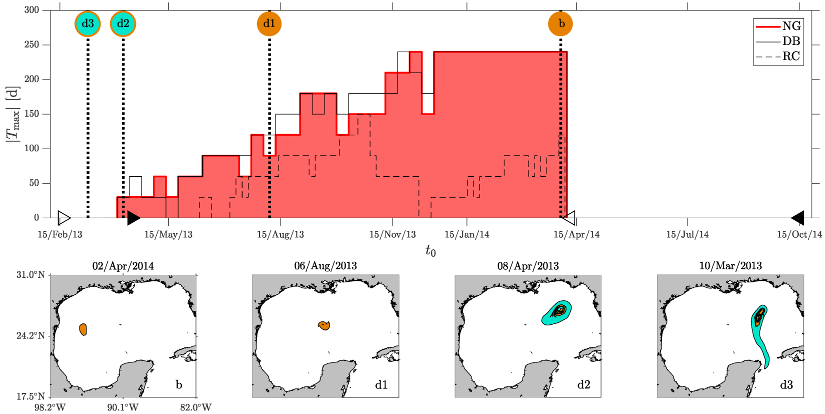
- For example, if a Lagrangian computation detects a coherent vortex over the time interval $[t_0, t_0 + T]$, it should also detect a vortex over the time interval $[t_0 + \delta t, (t_0 + \delta t) + (T - \delta t)] = [t_0 + \delta t, t_0 + T]$ for small $|\delta t|$, if $t_0 + T$ was really the date 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* $T_{\max}(t_0)$.
- Finally, in an ideal case, a Lagrangian simulation of the lifespan of a coherent vortex would therefore start with a large $T_{\max}$-value, which consistently decreases as t_0 progresses forward in time.

LCR *Kraken*—Forward-time assessment



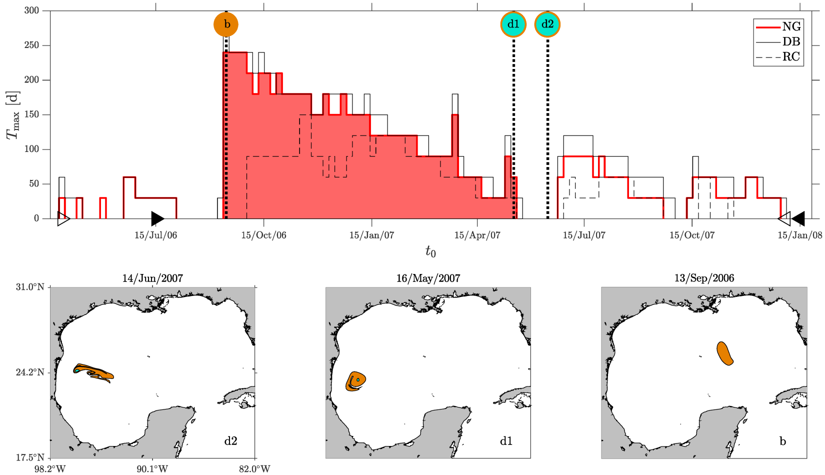
- Life expectancy as a function of screening time according NG, DB, and RC assessments.
- b indicates the birth of the ring
- d1, d2, d3 are three assessments of the ring's decease date.
- Birth and decease dates according to `EddyWatch`® (open triangle), and `AVISO+` (filled).

LCR *Kraken*—Backward-time assessment



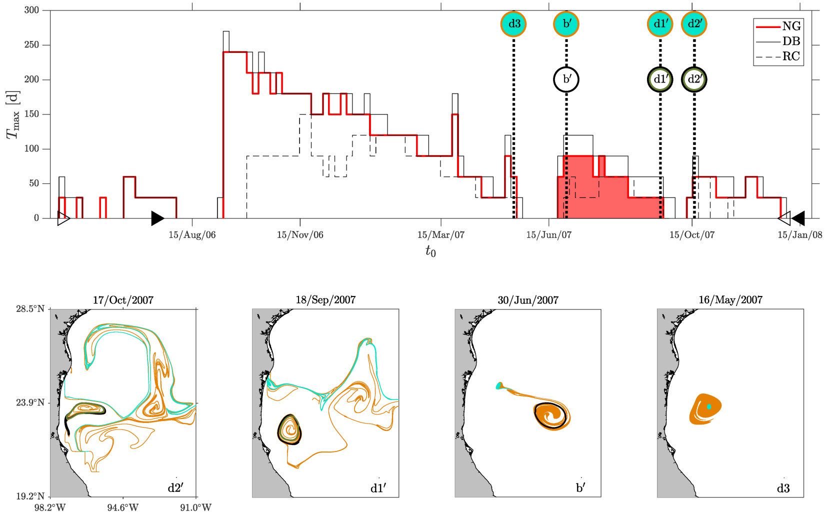
- As in previous slide, but in backward time.
- d3 can be taken to mark the *conception* date for the ring.

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.

Acknowledgments

This work was initiated during the "Escuela interdisciplinaria de transporte en fluidos geofísicos: de los remolinos oceánicos a los agujeros negros," Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, 5–16/Dec/2016. Support from Centro Latinoamericano de Formación Interdisciplinaria is sincerely appreciated. This work was supported by CONACyT–SENER (Mexico) under Grant No. 201441 (FAC, FJBV) as part of the Consorcio de Investigación del Golfo de México (CIGoM) and the U.S. National Academy of Sciences, Engineering and Medicine's Gulf Research Program under Grant No. UGOS2000011056 (FJBV). FAC thanks CICESE (Mexico) for allowing him to use their computer facilities throughout the CIGoM project.

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