Energy decay of coherent eddies:

Estimating the impact of wind-current coupling from in situ observations and satellite altimetry

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Why are coherent eddies so important?

- Agulhas rings participate in the transport of water masses that impact large-scale circulation and climate. [Biastoch et al., Nature, 2008]

- Loop Current rings are the only source of external water in the Gulf of Mexico and control hurricane intensification and Eastern US climate. [Molina et al., GRL, 2016] [Jaimes et al., Dyn. Atm. Oce., 2016] [Hamilton et al., JPO, 2018]
Why is their decay so important?

- OGCMs are now eddy-permitting, and Coupled Climate models are nearly there.

- Coherent eddies are explicitly represented.

- The processes driving their decay and mixing are not well resolved.

- The transport properties of coherent eddies is directly related to their longevity, diffusive properties and decay rate.

- Bad representation of Agulhas ring decay in models may impact AMOC!

- We need observation-based estimates of the decay of coherent eddies!
How does energy density decay?

\[
\frac{D E_k}{Dt} + \rho' gw = -\nabla \cdot P' u + u \cdot \frac{\partial \tau}{\partial z} + \nabla \cdot K \nabla E_k + \rho \epsilon
\]

APE density change of a material fluid parcel

\[
\frac{D E_p}{Dt} = \rho' gw
\]

[Holliday and McIntyre, JFM, 1981]
How does the energy of an eddy decay?

\[
\frac{d\mathcal{E}_m}{dt} = \int_{-H}^{0} \left\{ \oint_{\mathcal{C}} (u_c - u) \cdot n \mathcal{E}_m \, dl - \oint_{\mathcal{L}} u \cdot n' P' \, dl + \iint_{\mathcal{L}} u \cdot \frac{\partial \tau}{\partial z} \, ds + \oint_{\mathcal{C}} K \nabla E_k \cdot n \, dl + \iint_{\mathcal{L}} \rho \epsilon \, ds \right\} \, dz
\]

\[\tau_{rel} = \rho_a C_d |u_a - u_s|(u_a - u_s)\]

- If the eddy's boundary is a material line, term (a) is null.
- For a geostrophic eddy, term (b) is null.
- At the scale considered here, term (e) is negligible.
... Now let’s apply this to the Gulf of Mexico.

Meunier et al., JGR, 2018
... But how can we get statistical estimates of the energy, heat and salt contents of LC rings?

- If we take all ARGO profiles within the Gulf of Mexico and sort them by steric height, we get a clear pattern.

- We sort them by month and fit a spline interpolant to the T and S fields against SSH at a given pressure. => monthly GEM fields

- For each couple [pressure-dynamic height], we get one single value of temperature and salinity.

- We can reconstruct the whole 3D thermohaline structure of the GoM from gridded altimetry!
Selected examples of “reconstructed” LCRs

- 40 eddies detected between 1993 and 2022

Validation against glider observations

⇒ 2 full cross-sections through LCR Poseidon
⇒ $0.91 < R^2 < 0.94$
Heat and salt content decay of LCRs

Heat content decay

Heat and Salt vs time

Heat and Salt vs longitude
Energy decay of LCRs

Kinetic Energy decay

Mech. Energy vs time

Mech. Energy vs longitude
Energy decay of LCRs

Mechanical Energy decay

Mechanical Energy decay rate

\[ \frac{dE}{dt} \] [GW]

Time [Days]

-95
-90
-85
-94
-92
-90
-88

Latitude [°W]

Longitude [°W]
The effects of wind-current interactions on the eddy’s energy

1. Wind stress work.

Wind stress depends on the relative wind speed.

Integrating relative wind stress work over the eddy’s area systematically provides an energy sink.

\[
\tau_{\text{rel}} = \rho_a C_d |u_a - u_d|(u_a - u_d)
\]

2. Ekman buoyancy flux

\[
\frac{DE_p}{Dt} = \rho' g w,
\]

\[
w_e = \frac{1}{\rho_0} \nabla \times \left( \frac{\tau}{f + \zeta} \right)
\]

Adapted from Wilder et al., JPO, 2022

Dewar and Flierl, JPO, 1987 ; Duhaut and Straub, JPO, 2006 ; Renault et al., JPO, 2016 ; Renault et al., JPO, 2017; Wilder et al., JPO, 2022

Gaube et al., JPO, 2015 ; Wilder et al., JPO, 2022; Renault et al., Nat. Sci. Reports, 2018
The effects of wind-current interactions on the eddy’s energy

- Wind stress work was computed using ERA5 reanalysis and gridded scatterometer wind fields.
- ...Wait a minute ... KE decay is EXACTLY equal to wind stress work energy extraction ???!!!
The effects of wind-current interactions on the eddy’s energy

- It’s not that simple … and there is more to the story ….
- There may be APE to KE energy conversion! Wind stress work should be compared to total mechanical energy!
- WSW only accounts to a bit less than 1/3 of total mechanical energy loss!
The effects of wind-current interactions on the eddy’s energy

- Ekman buoyancy flux converts APE to KE.
- APE decay is entirely controlled by Ekman buoyancy flux !!! (No trick this time !)
Using Lagrangian “objective” eddy framing methods

- Eulerian eddy framing methods are subject to biases and “leakiness” 
  (Haller, JFM, 2005, Haller and Beron-Vera, JFM, 2013 ; Beron-Vera et al., GRL, 2008 ; Liu et al., JPO, 2019).

- The energy flux through the eddy's boundary can not be exactly estimated because $u_c$ can not be computed.

- Using Lagrangian “objective” eddy framing methods, the eddy's boundary becomes a material line and term (a) disappear.

- We use Haller and Beron-Vera (JFM, 2013)’s Null Geodesic Ring method.

- As of now, only 4 eddies were extracted using objective framing.
Using Lagrangian “objective” eddy framing methods

- APE decay is still driven by Ekman buoyancy flux.
Using Lagrangian “objective” eddy framing methods

- Wind stress work does not participate anymore to mechanical energy decay!
Why is wind stress work negligible in Lagrangian coherent vortices decay?

- The long-term coherent material boundary is located far inside the eddy’s core.
- The high velocity ring is excluded from this boundary.
- The effect of current on wind stress becomes negligible in the inner core of the eddy.
- ... In the end, the portion of the eddy where wind stress work is extracting energy (the periphery) gets ripped off by mesoscale straining and does not participate in long-range transport.

=> Is wind stress work an important process in coherent eddy decay after all?
## Take home message

- Coherent Warm-core rings do lose heat, salt and energy as they drift.

- \( \frac{3}{4} \) of mechanical energy is lost before the eddies reach the western boundary.

- Energy decay is maximum in the interior basin.

- Wind-current interactions play a major role in energy decay/conversion.

- Ekman buoyancy fluxes control APE decay (conversion to KE).

- Wind stress work is responsible for ~1/3 of energy loss when using Eulerian eddy framing ...

- ... But wind stress work has no impact at all when using Lagrangian eddy framing.

- We still have a lot to do! Especially in the Lagrangian framework.
Thank you for your attention!
How do coherent eddies decay?