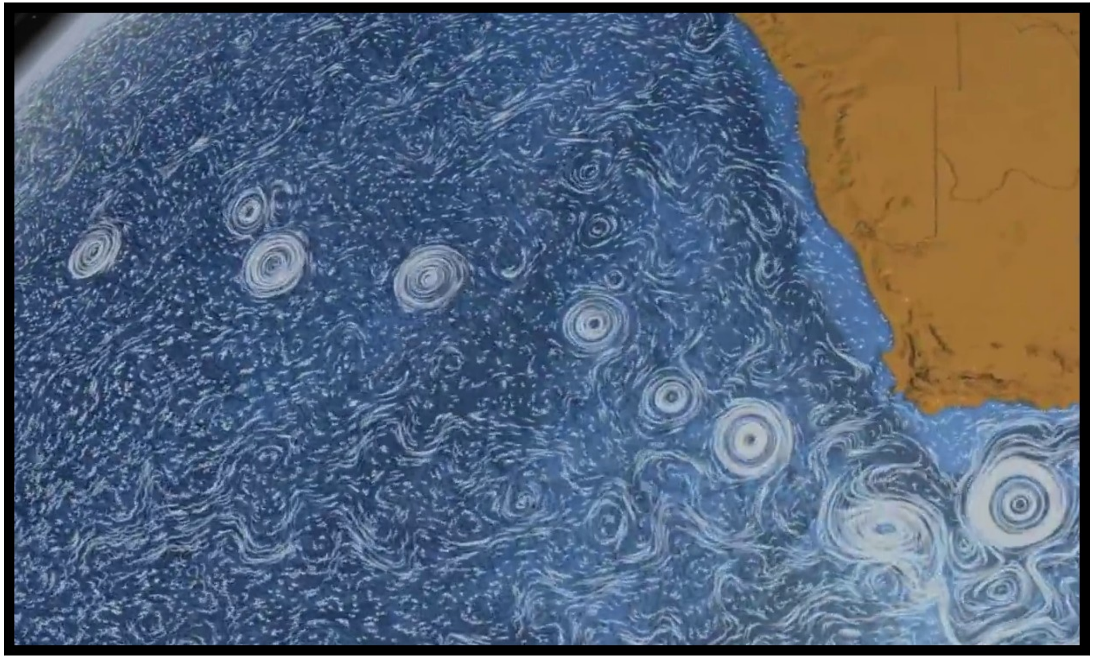
Energy decay of coherent eddies:

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

Thomas Meunier

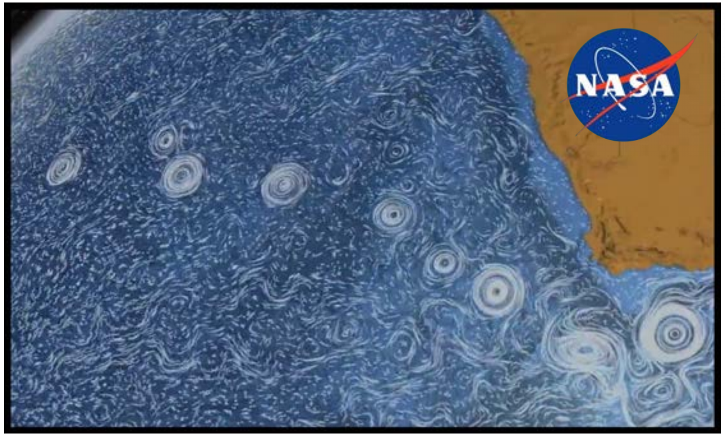
WOODS HOLE OCEANOGRAPHIC INSTITUTION 1930

NATIONAL ACADEMY OF SCIENCES



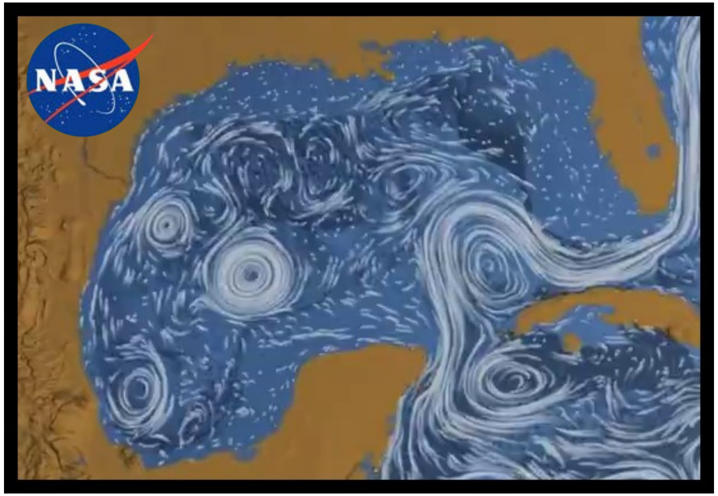
Why are coherent eddies so important?

- 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 <u>decay</u> so important ?

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

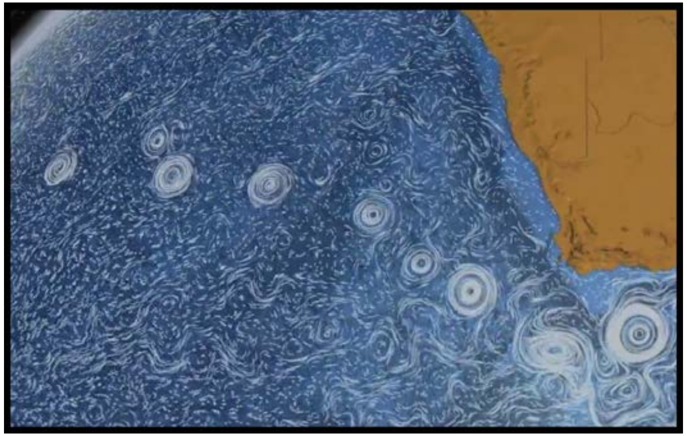
- Coherent eddies are explicitly represented.

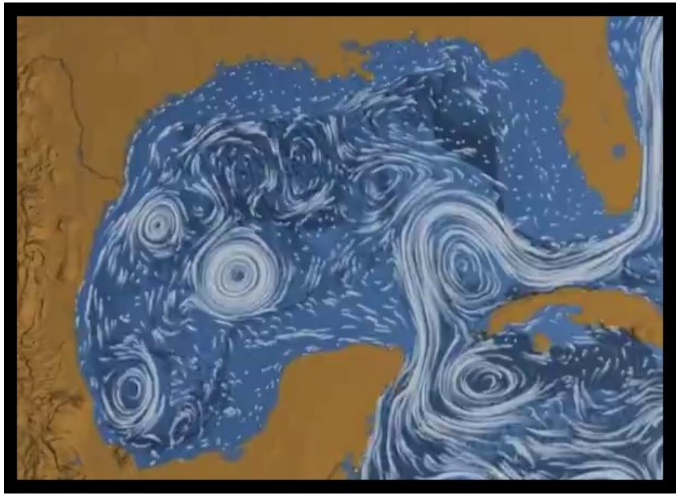
- The processes driving their decay and mixing are not well resolved.

- 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 ?

KE density change of a material fluid parcel

Buoyancy flux

Work of the pressure force

Work of the wind stress

Turbulent (unresolved) diffusivity

Dissipation

$$\frac{DE_k}{Dt} + \rho' g w = -\boldsymbol{\nabla} \cdot P'\mathbf{u} + \mathbf{u} \cdot \frac{\partial \boldsymbol{\tau}}{\partial z} + \boldsymbol{\nabla} \cdot \mathrm{K}\boldsymbol{\nabla} E_k + \rho\epsilon$$

APE density change of a material fluid parcel

Buoyancy flux

$$\frac{DE_p}{Dt} = \rho' g w$$

[Holliday and McIntyre, JFM, 1981]

How does the energy of an eddy decay ?

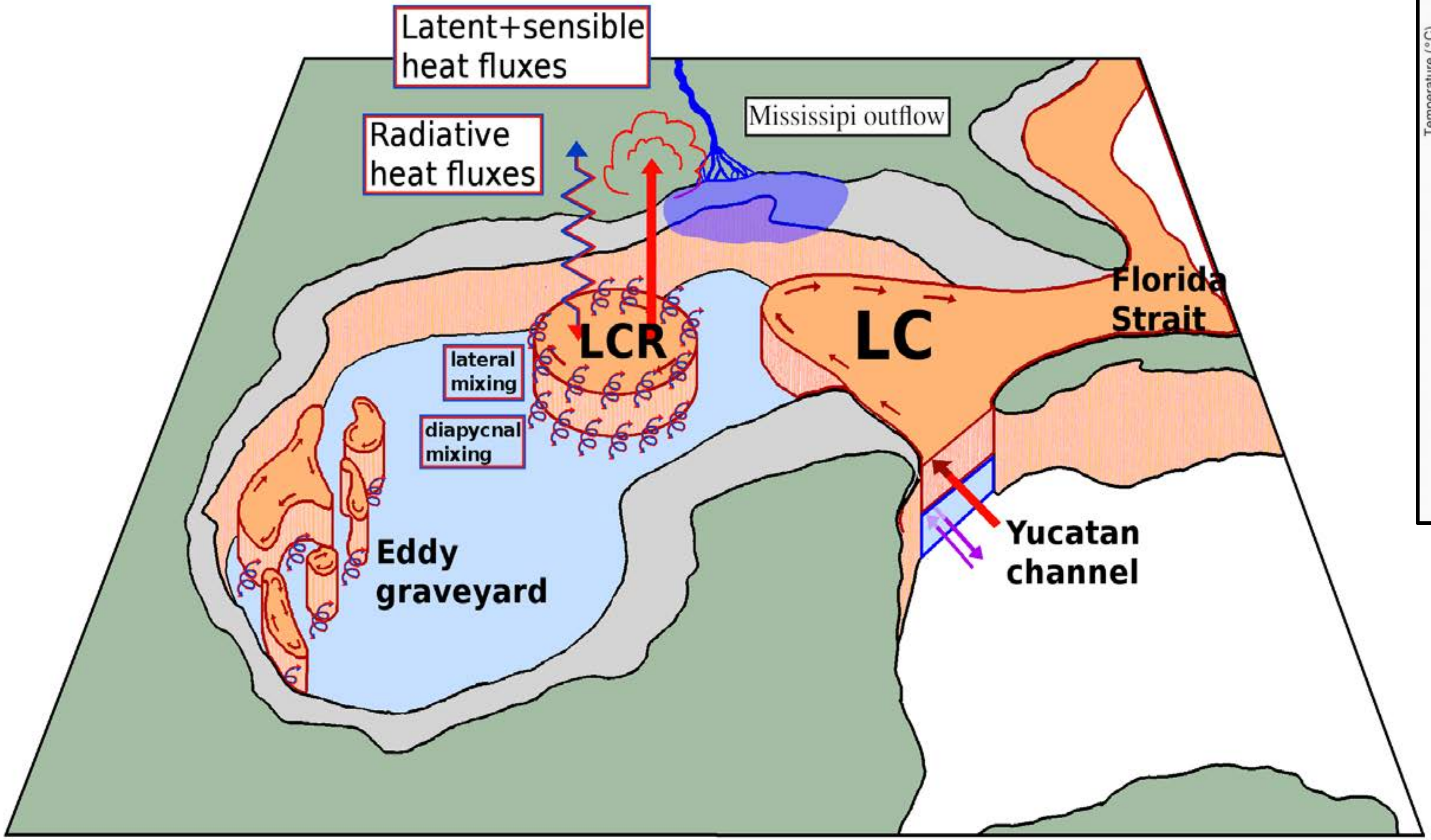
Energy flux through the eddy's boundary	Pressure force work	Wind stress work	Turbulent diffusivity	Dissipation

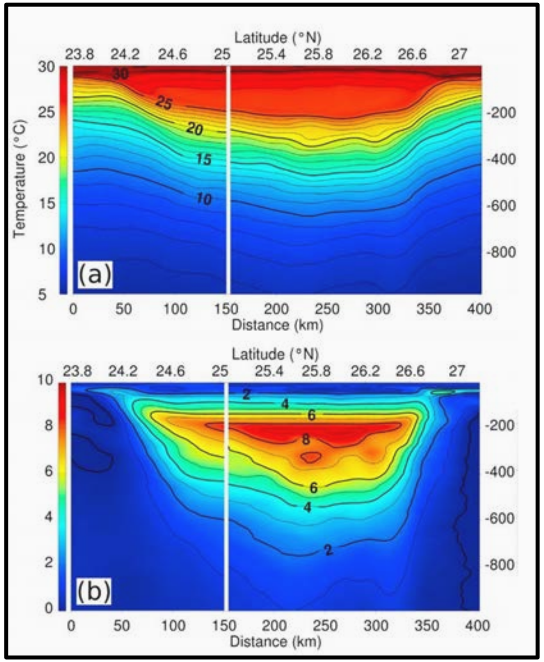
$$\frac{d\mathbb{E}_{\mathbf{m}}}{dt} = \int_{-H}^{0} \left\{ \overbrace{\oint_{\mathscr{C}} (\mathbf{u_c} - \mathbf{u}) \cdot \mathbf{n} E_m \, dl}^{(a)} - \overbrace{\oint_{\mathscr{C}} \mathbf{u} \cdot \mathbf{n} P' \, dl}^{(b)} + \overbrace{\iint_{\mathscr{S}} \mathbf{u} \cdot \frac{\partial \tau}{\partial z} ds}^{(c)} + \overbrace{\oint_{\mathscr{C}} \mathbf{K} \boldsymbol{\nabla} E_k \cdot \mathbf{n} \, dl}^{(d)} + \overbrace{\iint_{\mathscr{S}} \rho \epsilon \, ds}^{(e)} \right\} dz$$

$$\boldsymbol{\tau}_{rel} = \rho_a C_d |\boldsymbol{u}_a - \boldsymbol{u}_s| (\boldsymbol{u}_a - \boldsymbol{u}_s)$$

- 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.

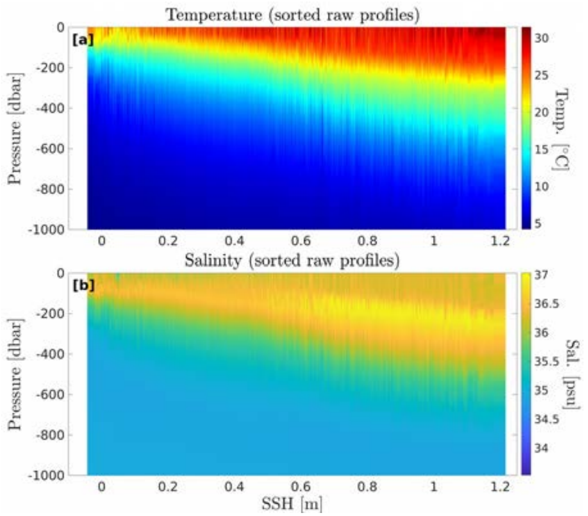


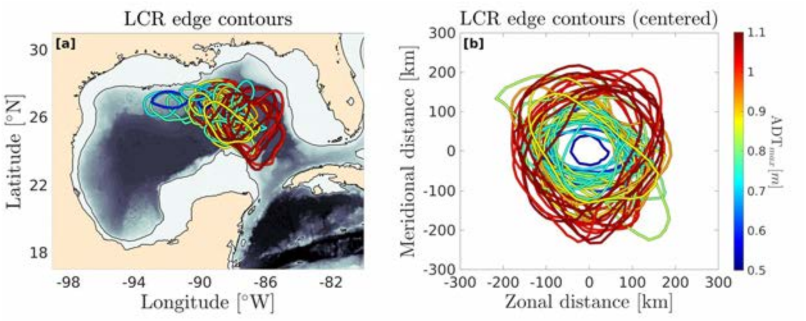


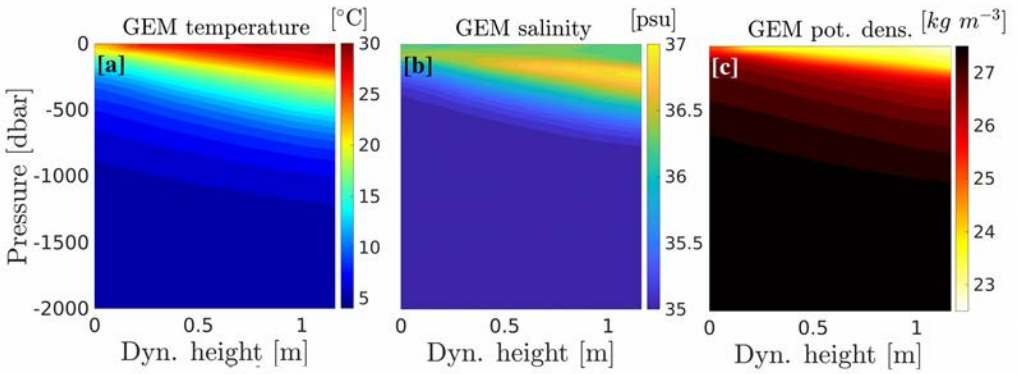
Meunier et al., *JGR*., 2018

… 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 heigh**t, 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!







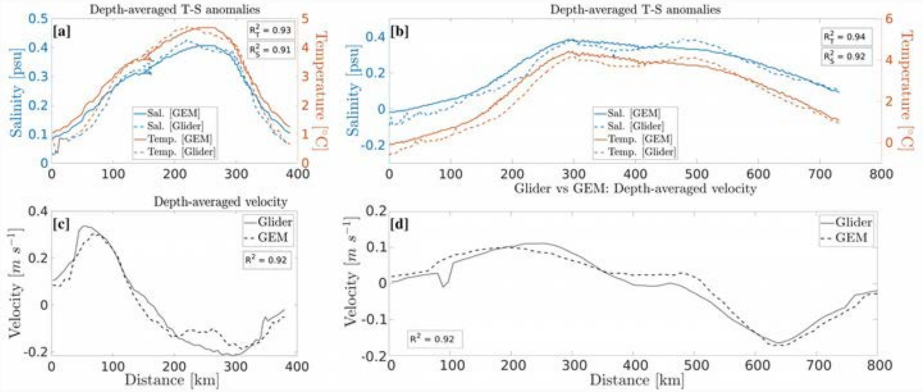
Meunier et al., *Remote. Sens.*, 2022

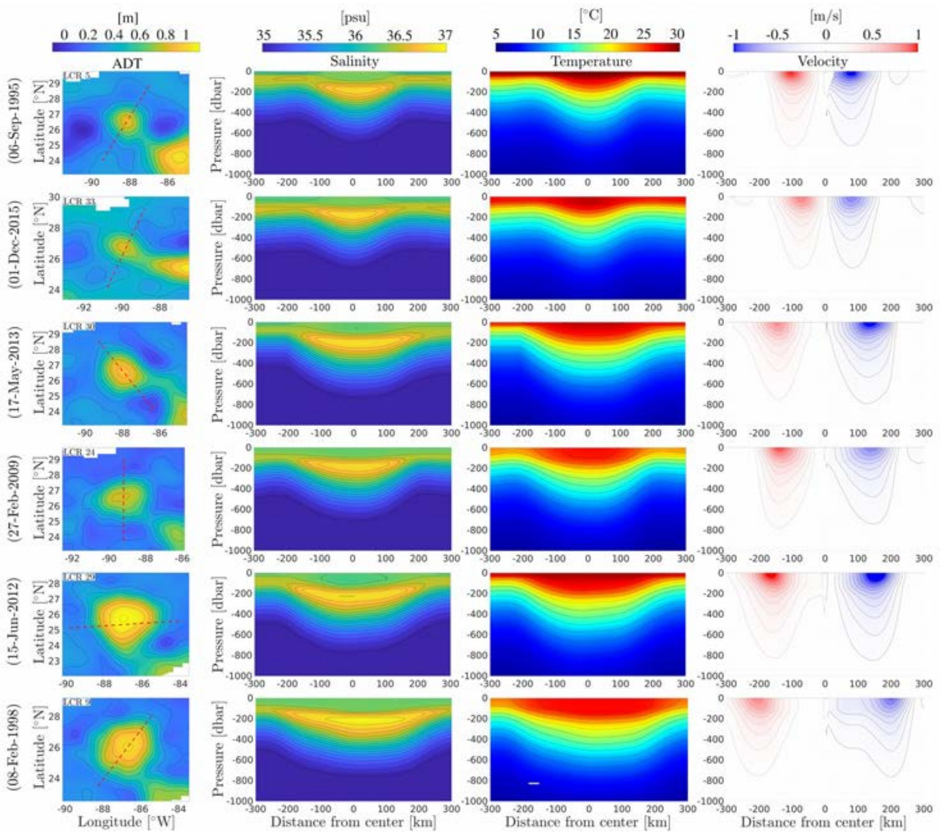
Selected examples of “reconstructed” LCRs

- 40 eddies detected between 1993 and 2022

Validation against glider observations

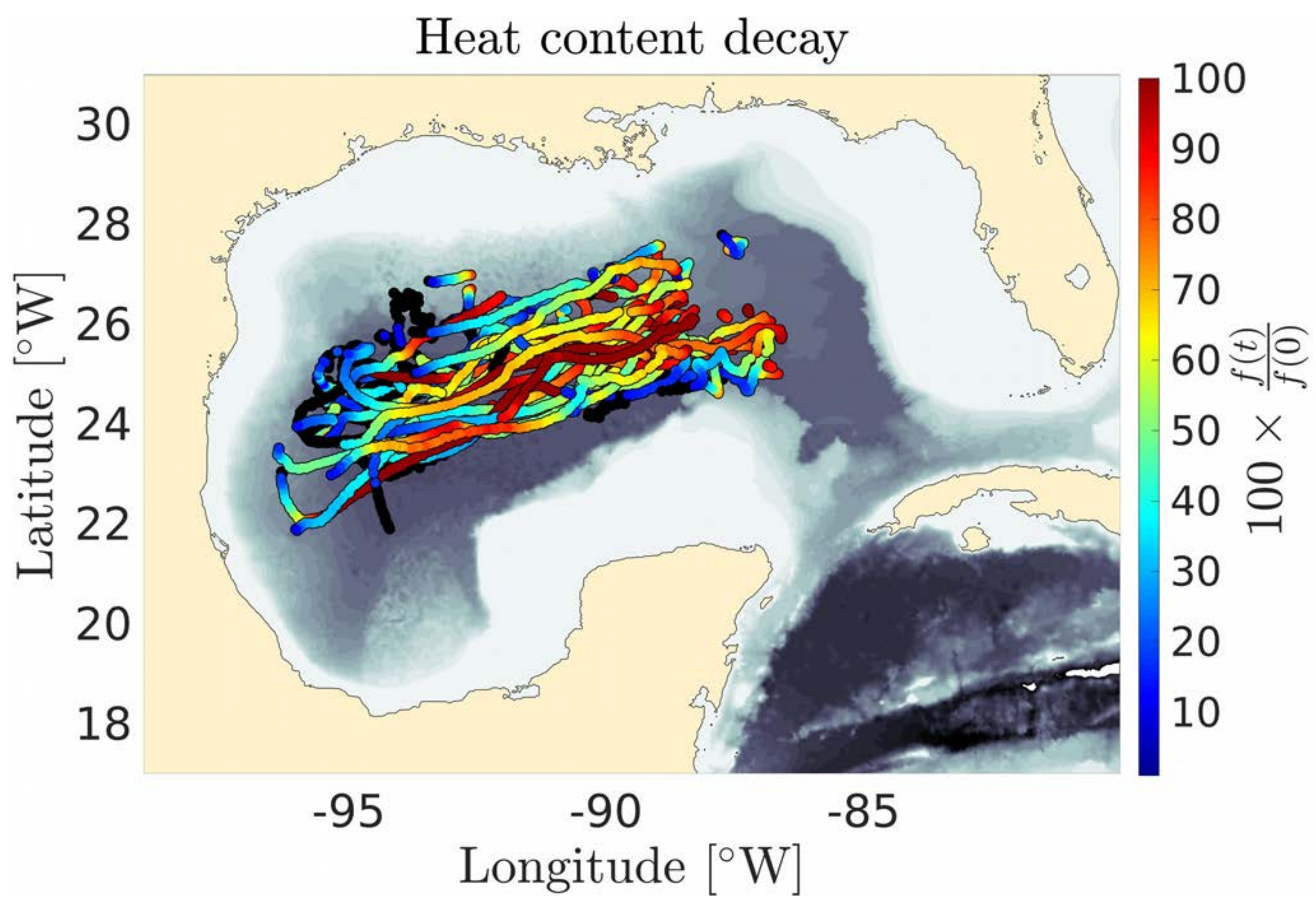
=> 2 full cross-sections through LCR Poseidon
=> $0.91 < R^2 < 0.94$

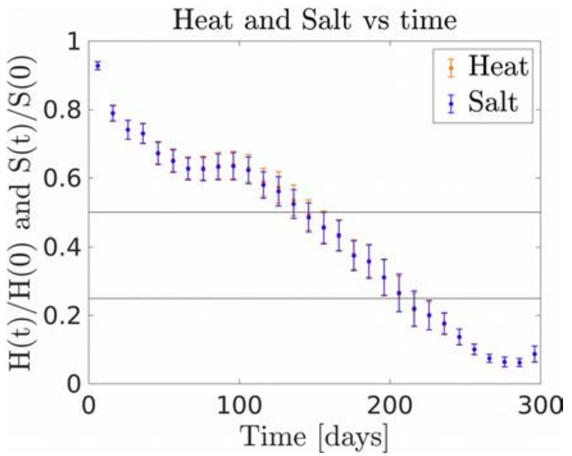


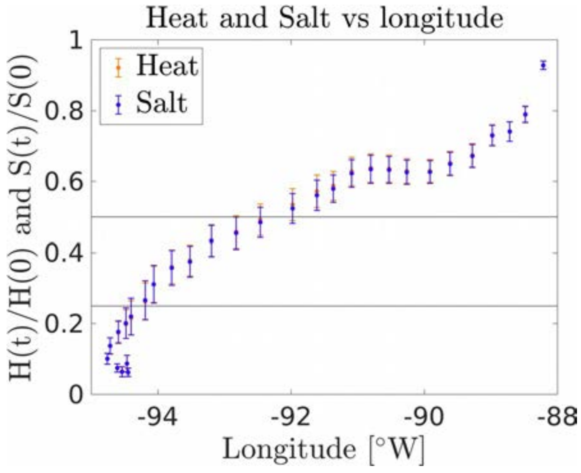


Meunier et al., Remote. Sens., 2022

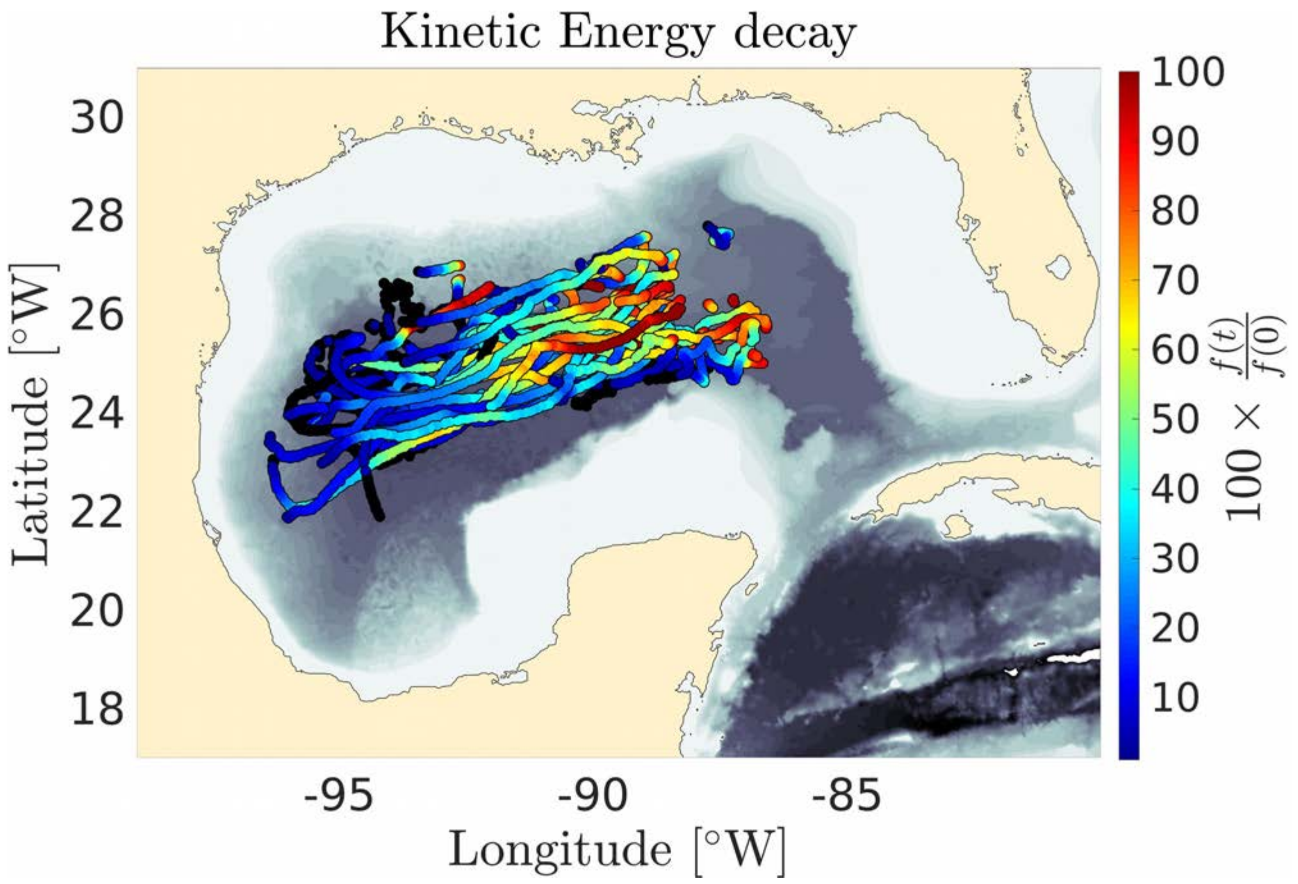
Heat and salt content decay of LCRs

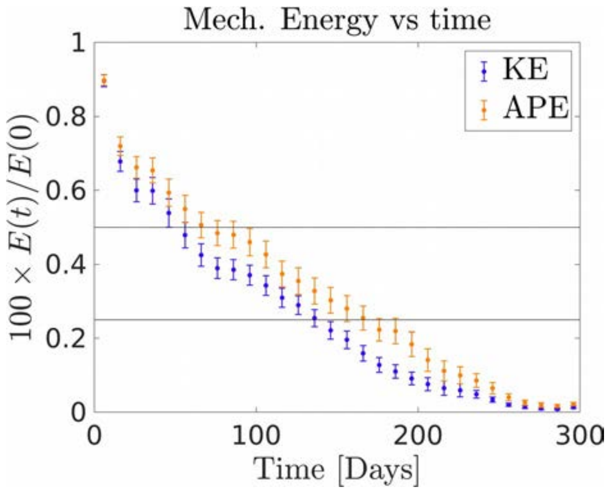


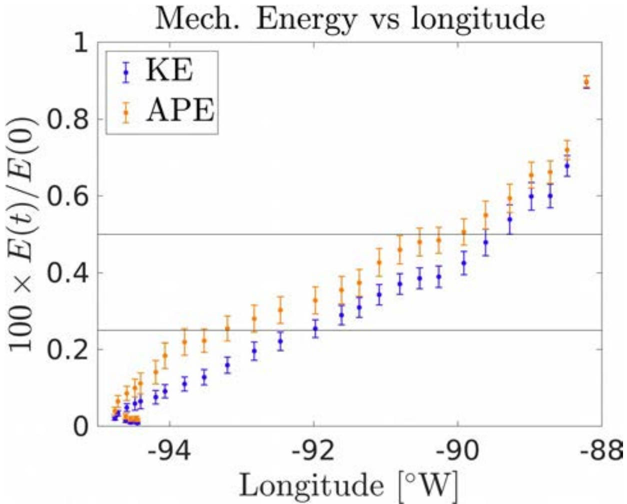




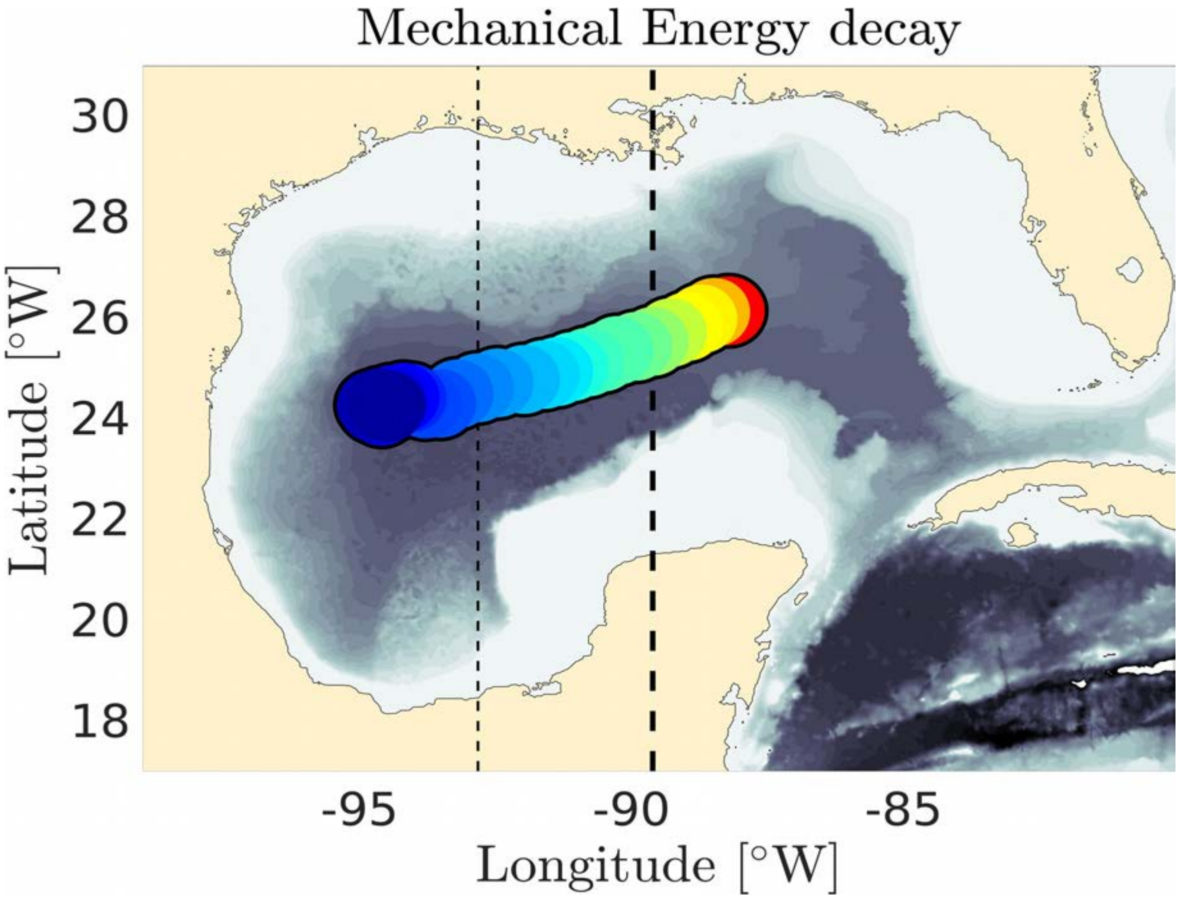
Energy decay of LCRs

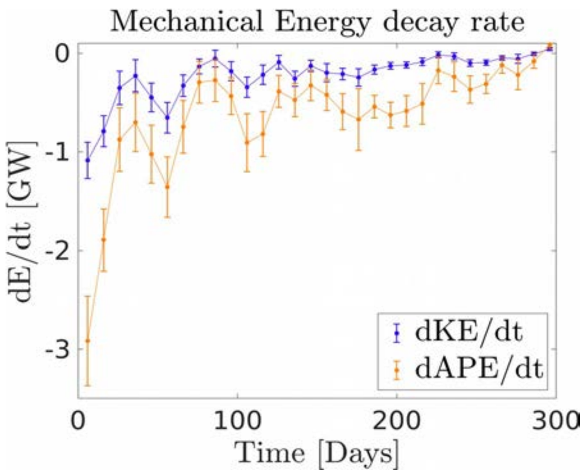


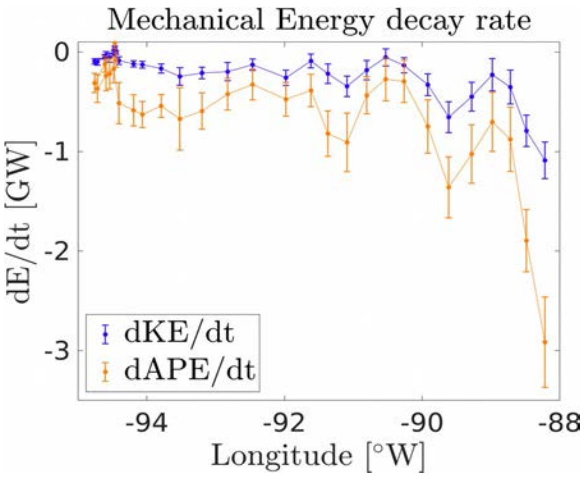




Energy decay of LCRs







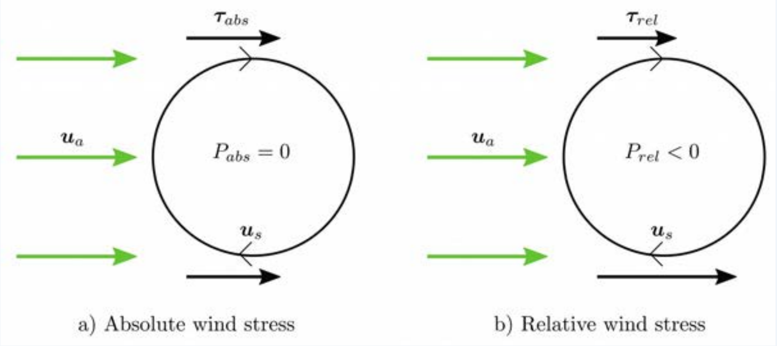
The effects of wind-current interactions on the eddy's energy

Adapted from **Wilder et al., *JPO*, 2022**

1. Wind stress work. $\int_{-H}^{0}\iint_{\mathscr{S}} \mathbf{u}\cdot\frac{\partial \tau}{\partial z}ds$

=> Wind stress depends on the relative wind speed.
=> Integrating relative wind stress work over the eddy's area systematically provides an energy sink.

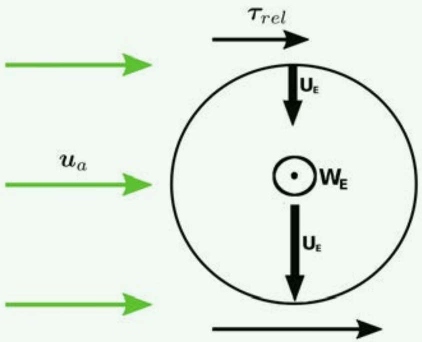
Dewar and Flierl, *JPO*, 1987 ; Duhaut amd Straub, *JPO*, 2006 ; Renault et al., *JPO*, 2016 ; Renault et al., JPO, 2017; Wilder et al., *JPO*, 2022



$$\tau_{abs} = \rho_a C_d |u_a| u_a \qquad \tau_{rel} = \rho_a C_d |u_a - u_s|(u_a - u_s)$$

2. Ekman buoyancy flux

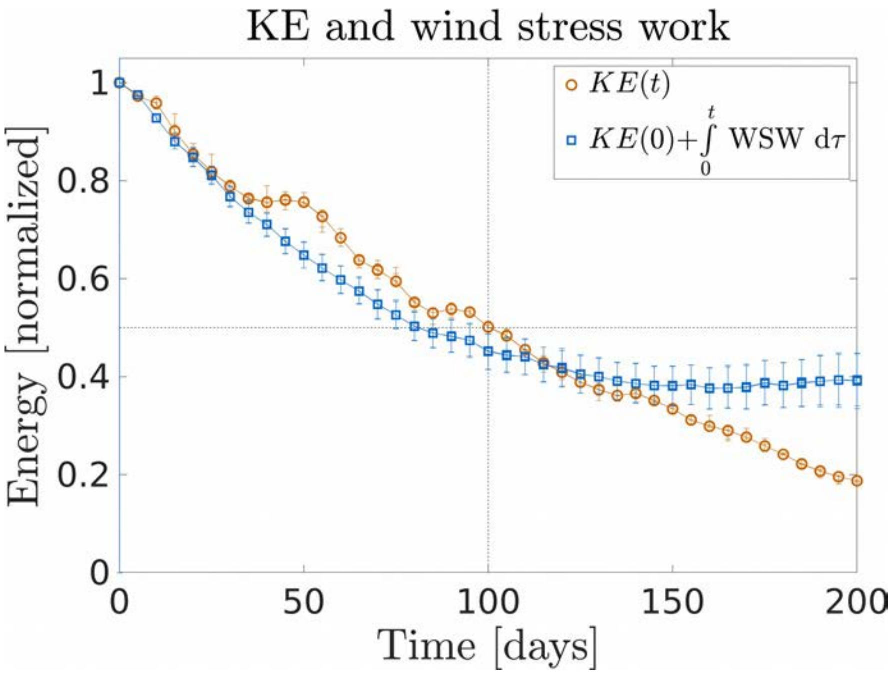
$$\frac{DE_p}{Dt} = \rho' g w, \qquad w_e = \frac{1}{\rho_0}\nabla \times \left(\frac{\tau}{f+\zeta}\right)$$



Gaube et al., *JPO*, 2015 ; Wilder et al., *JPO*, 2022; Renault et al., *Nat. Sci. Reports*, 2018

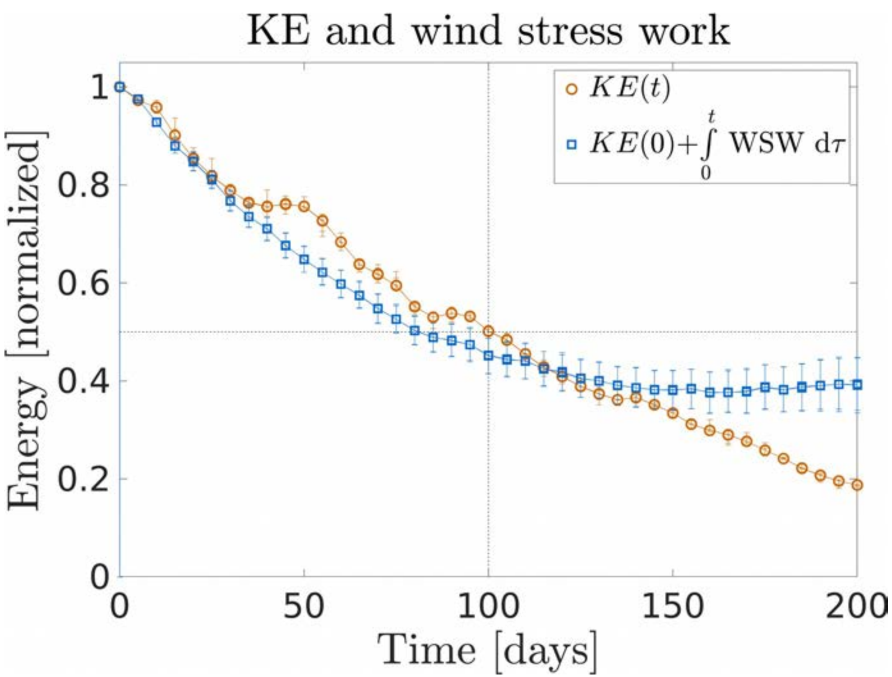
The effects of wind-current interactions on the eddy's energy

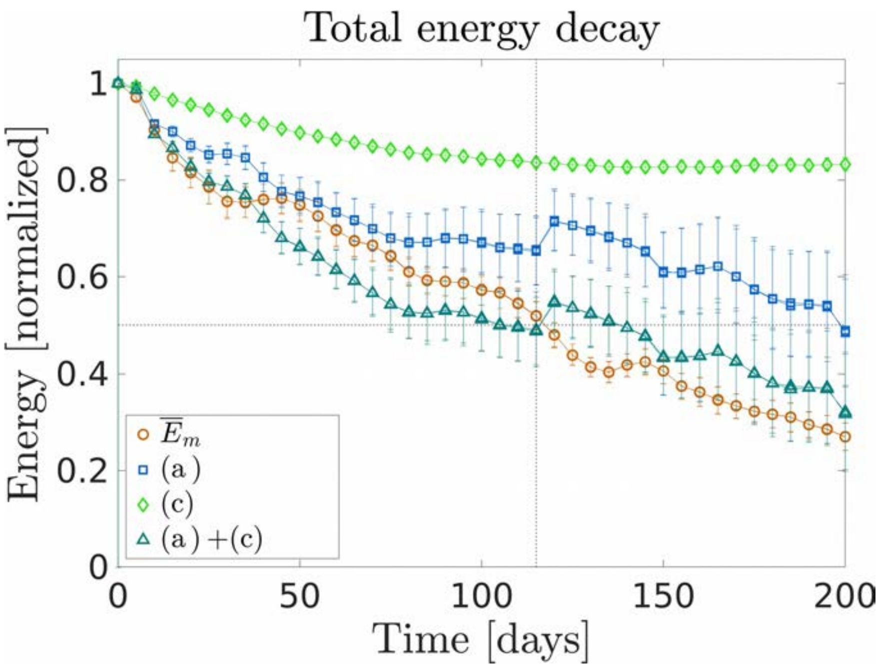
- Wind stress work was computed using ERA5 reanalysis and gridded scatterometer wind fields.
- **...Wait a minute … KE decay is EXACTLY equal to wind stress work energy extraction ???!!!**



The effects of wind-current interactions on the eddy's energy

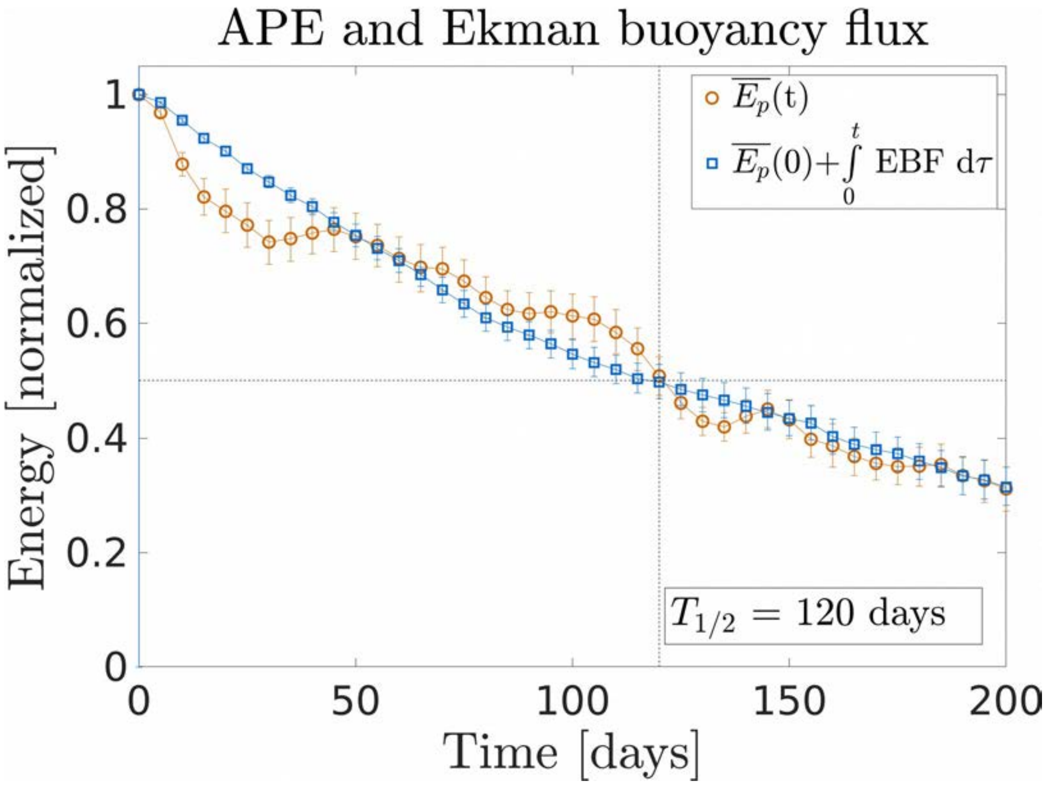
- It's not that simple … and there is more to the story ….
- There may be APE to KE energy conversion ! Wind stress work should be compared to total mechanical energy !
- WSW only accounts to a bit less than 1/3 of total mechanical energy loss!





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 **$\mathbf{u}_c$ 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.

Energy flux through the eddy's boundary

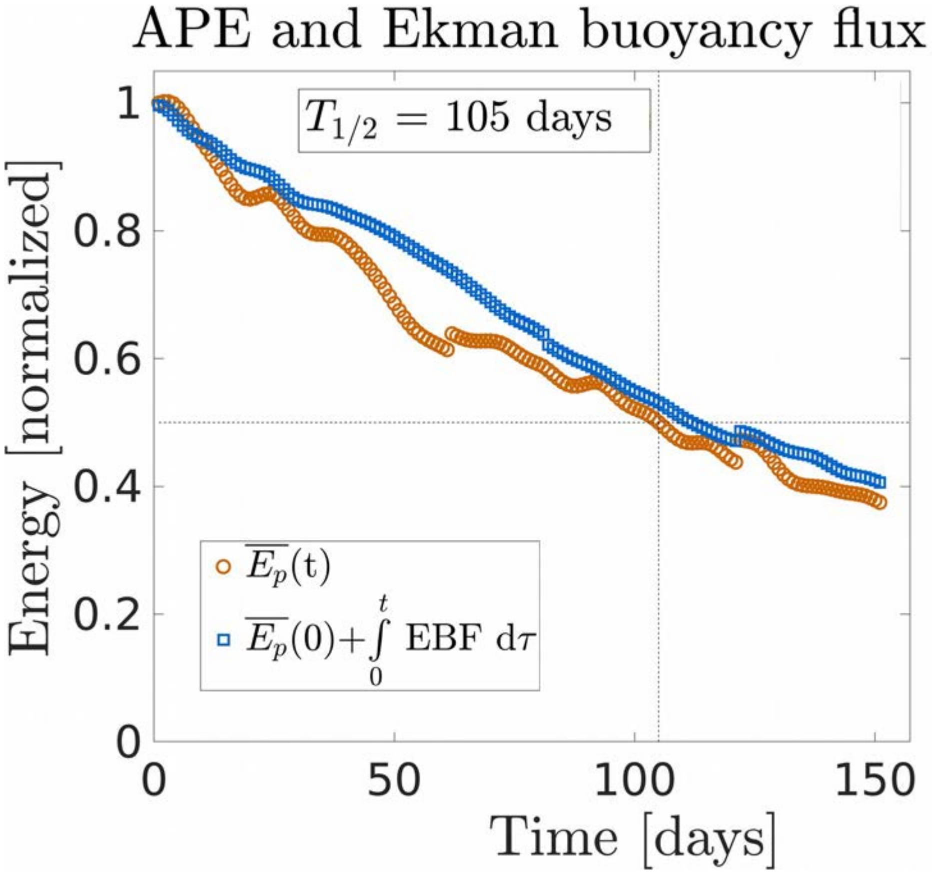
Wind stress work

Turbulent diffusivity

$$\frac{d\mathbb{E}_\mathbf{m}}{dt} = \int_{-H}^{0} \left\{ \overbrace{\oint_{\mathscr{C}} (\mathbf{u}_c - \mathbf{u}) \cdot \mathbf{n} E_m \, dl}^{(a)} - \overbrace{\oint_{\mathscr{C}} \mathbf{u} \cdot \mathbf{n} P' \, dl}^{(b)} + \overbrace{\iint_{\mathscr{S}} \mathbf{u} \cdot \frac{\partial \tau}{\partial z} ds}^{(c)} + \overbrace{\oint_{\mathscr{C}} \mathbf{K} \boldsymbol{\nabla} E_k \cdot \mathbf{n} \, dl}^{(d)} + \overbrace{\iint_{\mathscr{S}} \rho \epsilon \, ds}^{(e)} \right\} dz$$

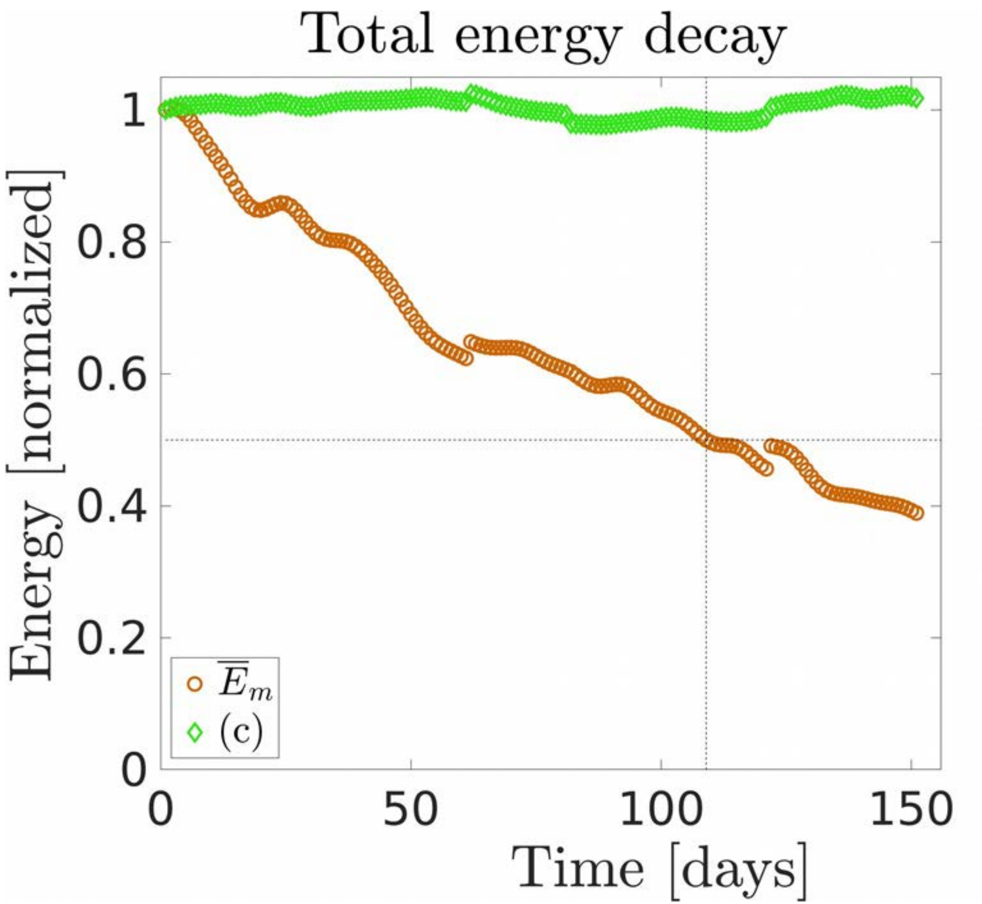
Using Lagrangian “objective” eddy framing methods

- 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 ?

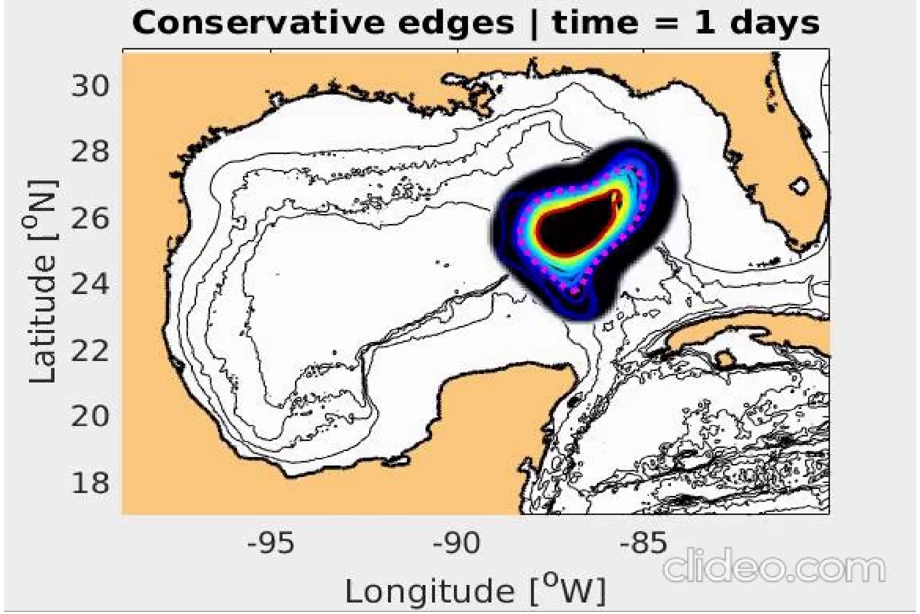
- The long-term coherent material boundary is located far inside the eddy’s core.

- 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.
- ¾ 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 !

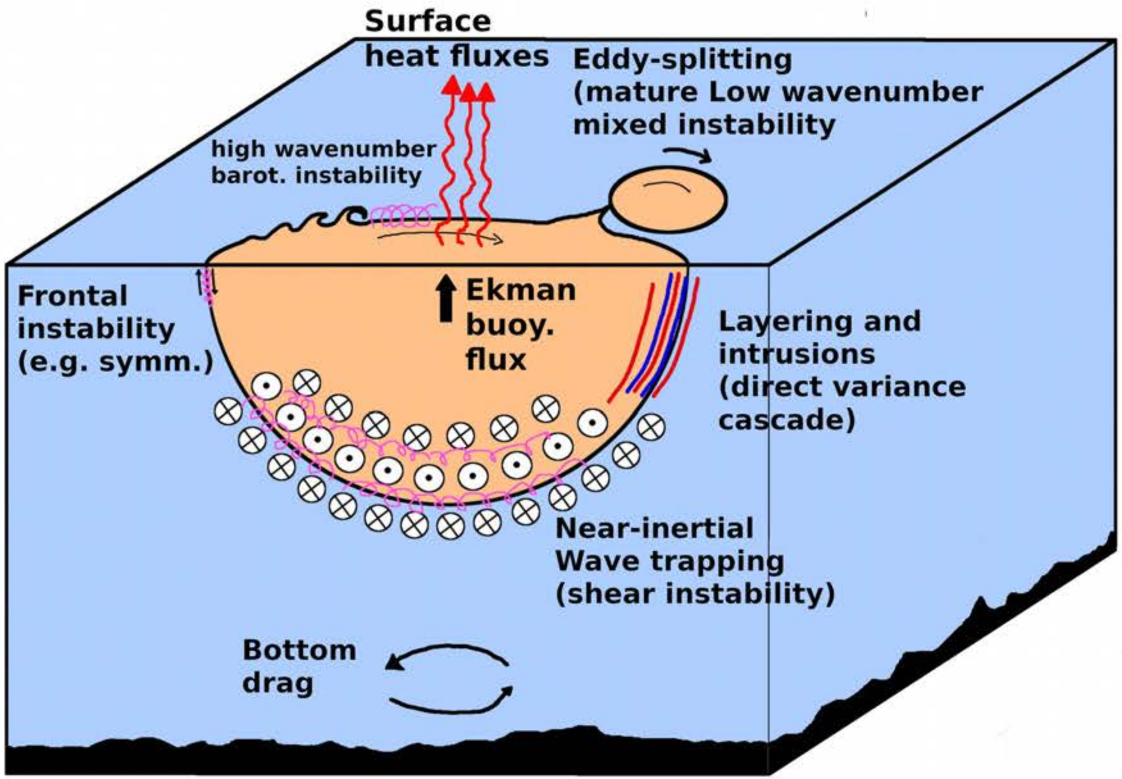
WOODS HOLE
OCEANOGRAPHIC
INSTITUTION

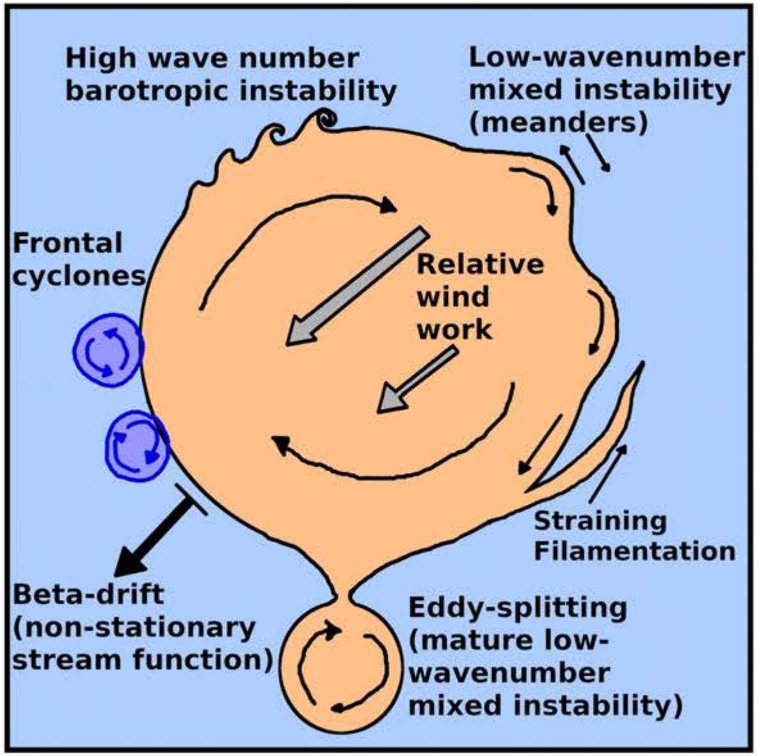
The National Academies of SCIENCES ENGINEERING MEDICINE

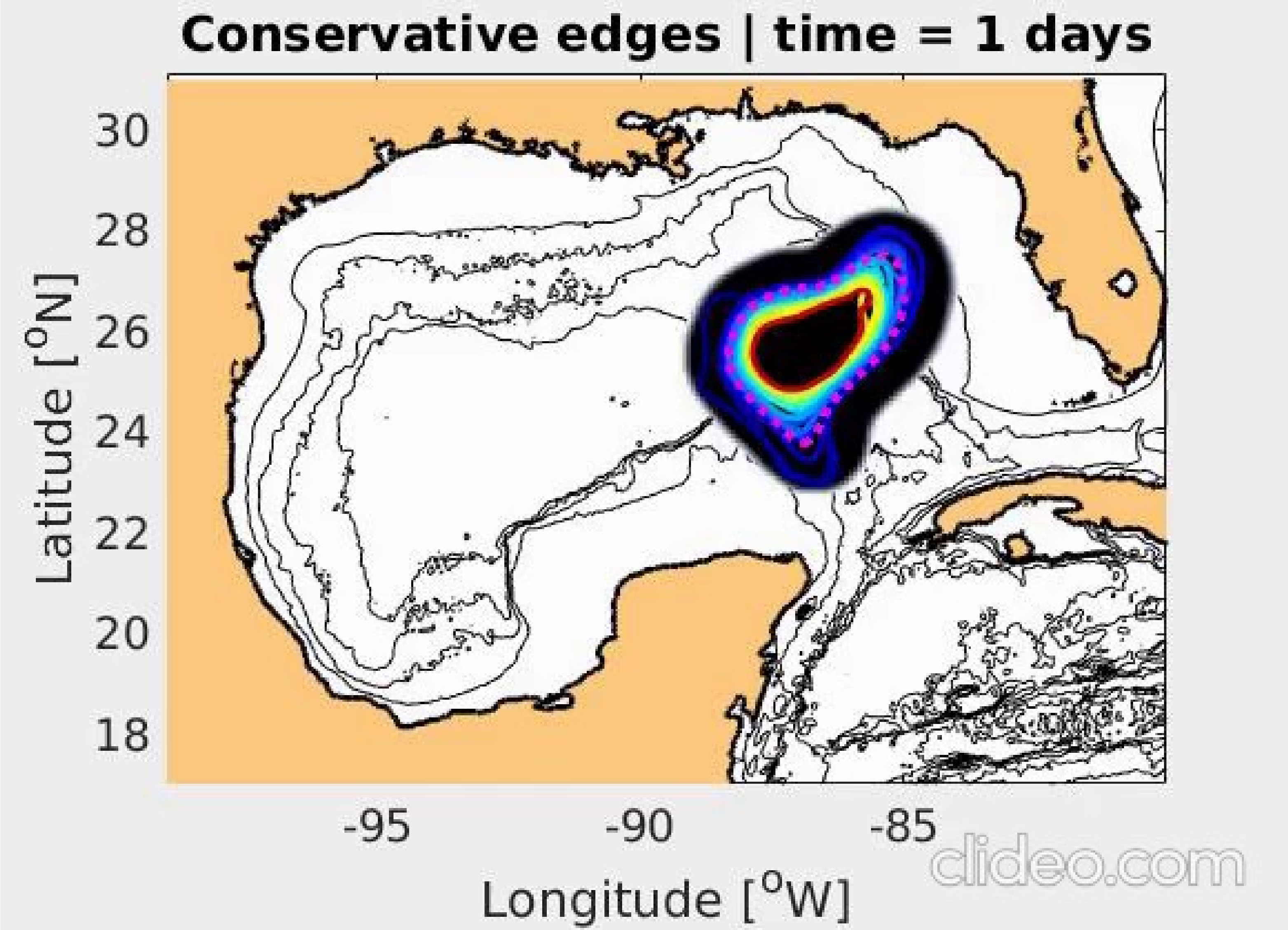
GULF RESEARCH PROGRAM

tmeunier@whoi.edu

How do coherent eddies decay ?







Conservative edges | time = 1 days
30
28
26
24
22
20
18
Latitude [°N]
-95
-90
-85
Longitude [°W]