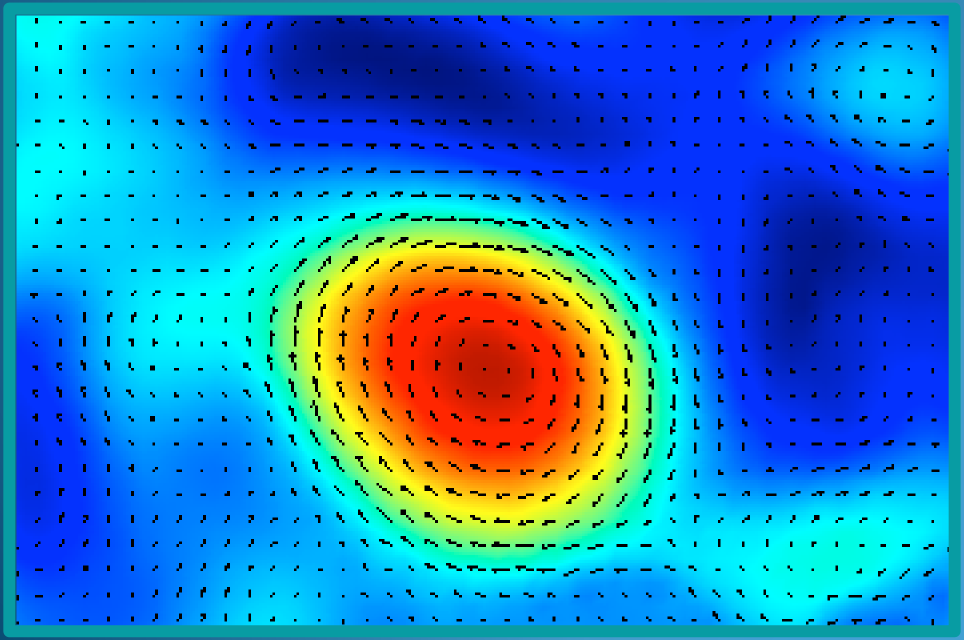
Ocean3D+1: Recent Results on Rings in the Gulf of Mexico



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Leaky Eddies

- Loop Current Rings in the GoM are thought to break down due to fluid exchange with the environment.

Where? When? How much? How fast?

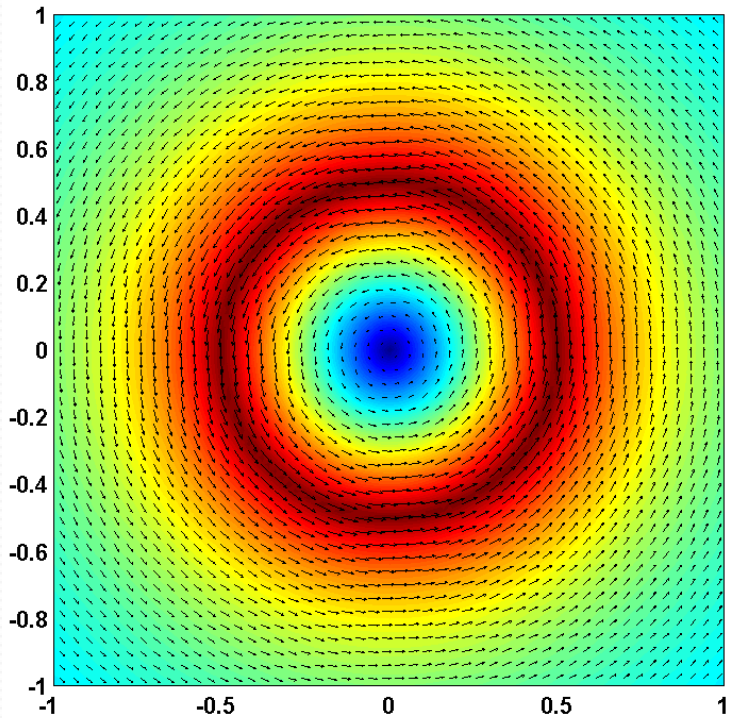
- Need Eulerian + Lagrangian approach
- First step: How do we define the eddy boundary?

What are Eddies?

- Circular currents, or coherent vortices
- Classic idealized case: VR vortex
  - Large vorticity inside & zero vorticity outside
  - Okubo-Weiss (normal + shear deformation – vorticity) negative inside & positive outside
  - Closed streamlines

    → with geostrophy = ssh contours
  - Stagnation point at center & velocity max at boundary

Speed & Velocities for a VR vortex



$$v_\theta = \begin{cases} \Omega\, r^\alpha & \text{if } r \le R \\ \Omega\, R^{\alpha+\beta}/r^\beta & \text{if } r > R \end{cases}$$

Locating Eddies: Eddy Centers

- Algorithms are based on the above observations:
  - Visual inspection…
  - Relative vorticity maximum
  - Okubo-Weiss criterion minimum
  - SSH maximum/minimum
  - Stagnation points (elliptic)
  - Multi-step velocity characteristics [*Nencioli et al., 2010*]:

    u sign reversal & increasing from center
    + *v* sign reversal & increasing from center
    + velocity minimum at center + uniform sense of rotation
    + gradual change in direction around center

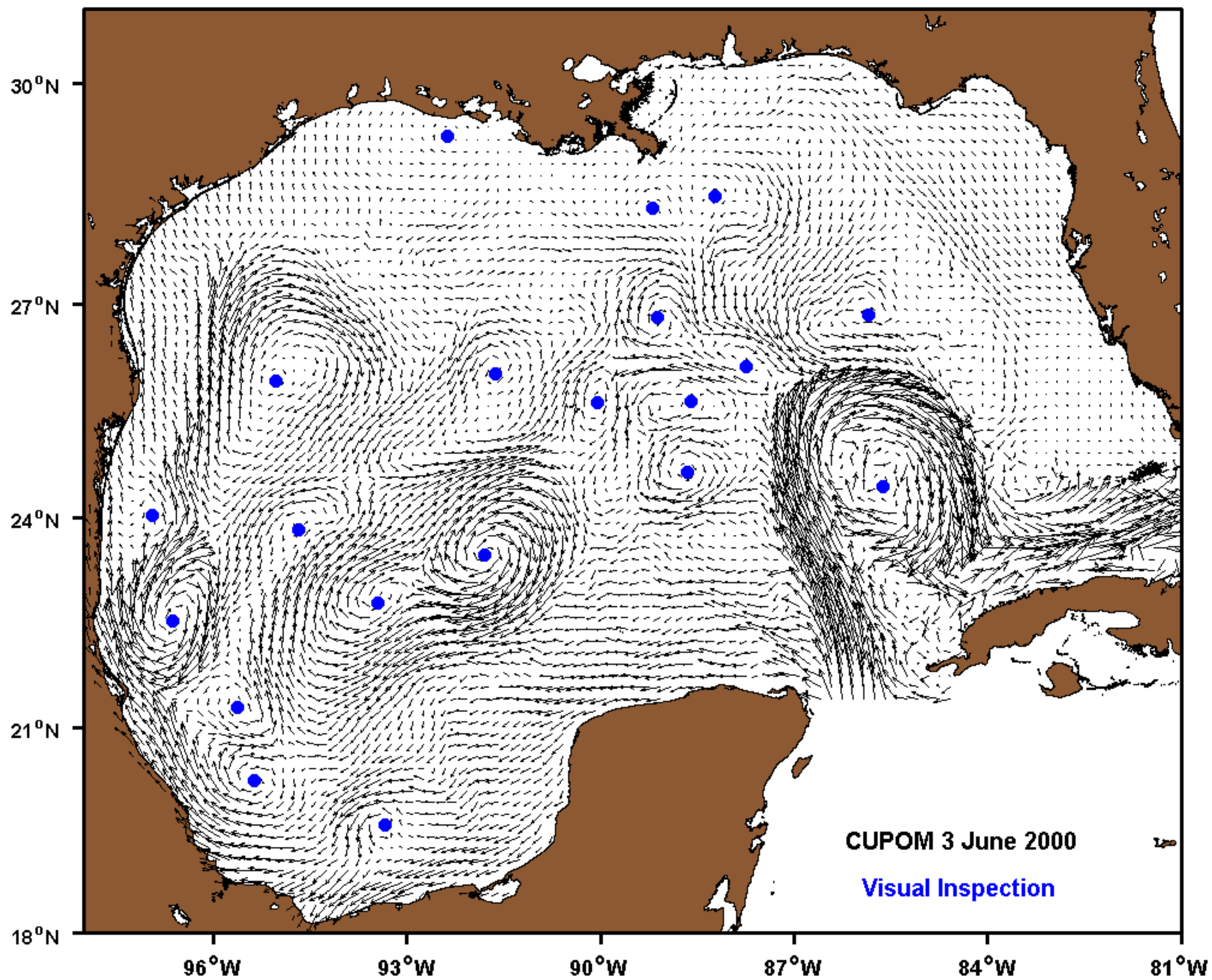
Eddy Centers: Visual Inspection

Advantage:

- Can take intuitive criteria into account
- Benchmark

Diasadvantage:

- ***Subjective***
- Manual



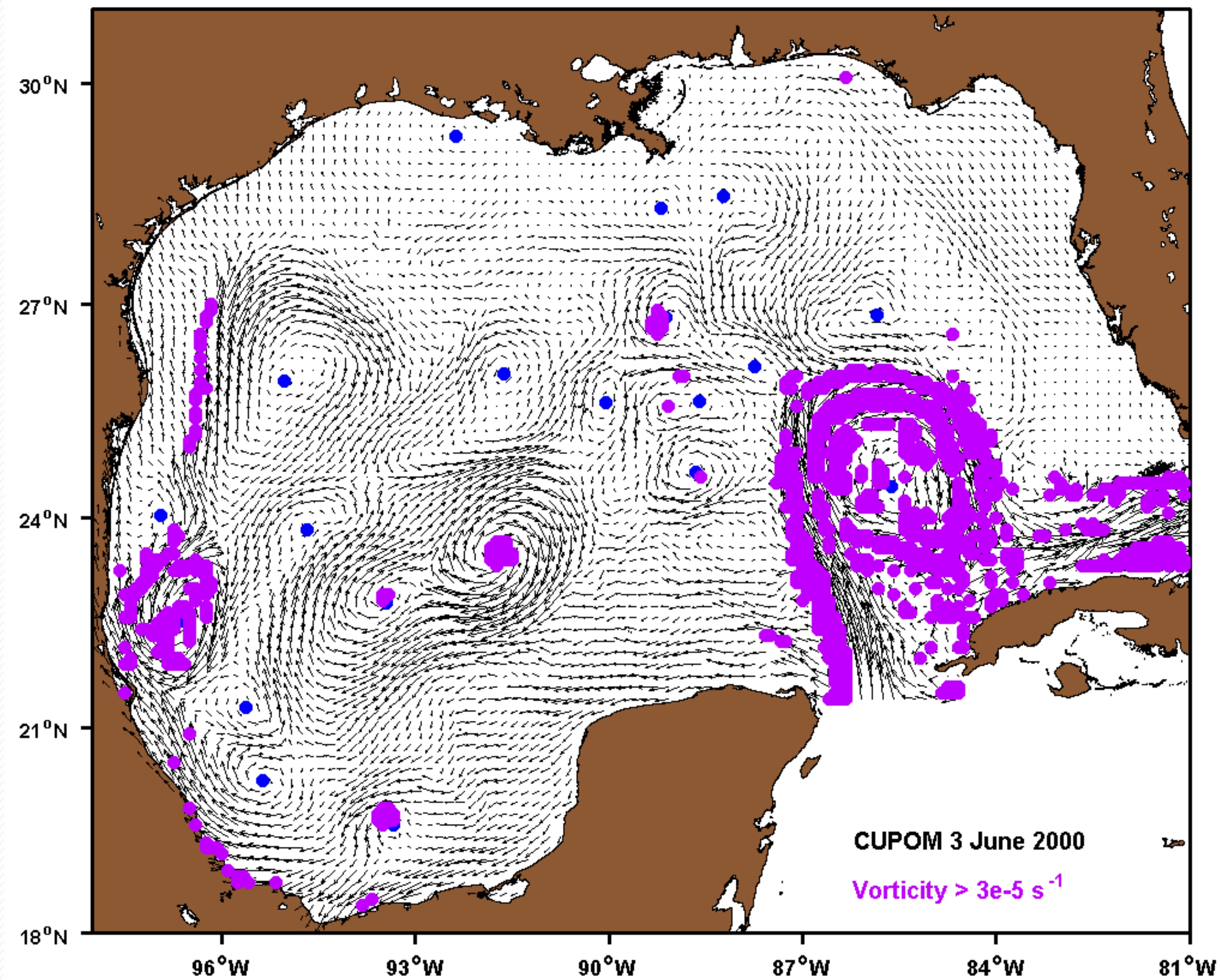
Eddy Centers: High Vorticity

Advantage:

- Objective
- Traditional definition

Diasadvantage:

- Lines & Clumps
- Underdetection & Overdetection
- Noisy if from discrete data (numerical derivatives)



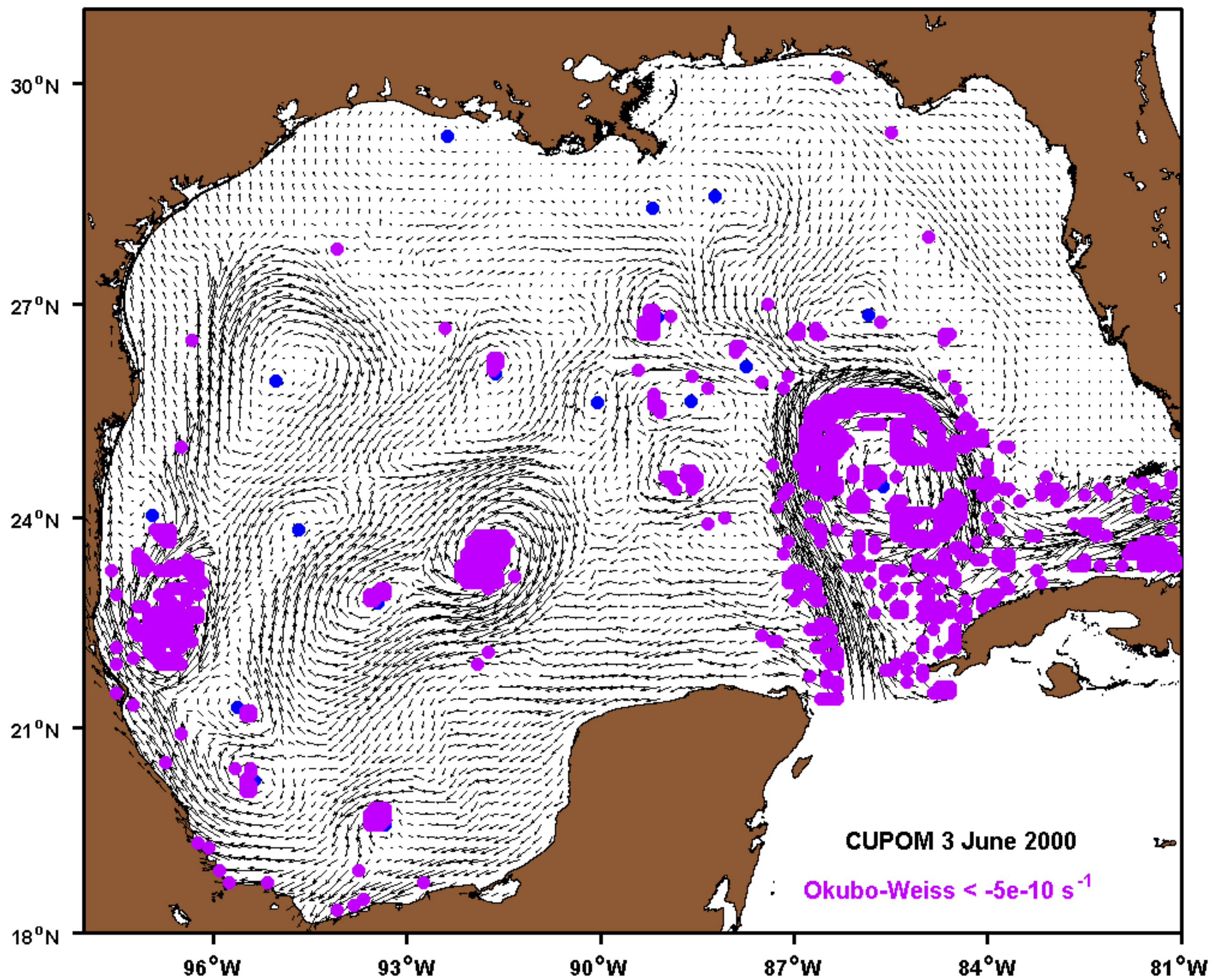
Eddy Centers: Low Okubo-Weiss

Advantage:

- Objective
- Traditional definition

Diasadvantage:

- Clumps
- Underdetection & Overdetection
- Noisy if from discrete data (numerical derivatives)



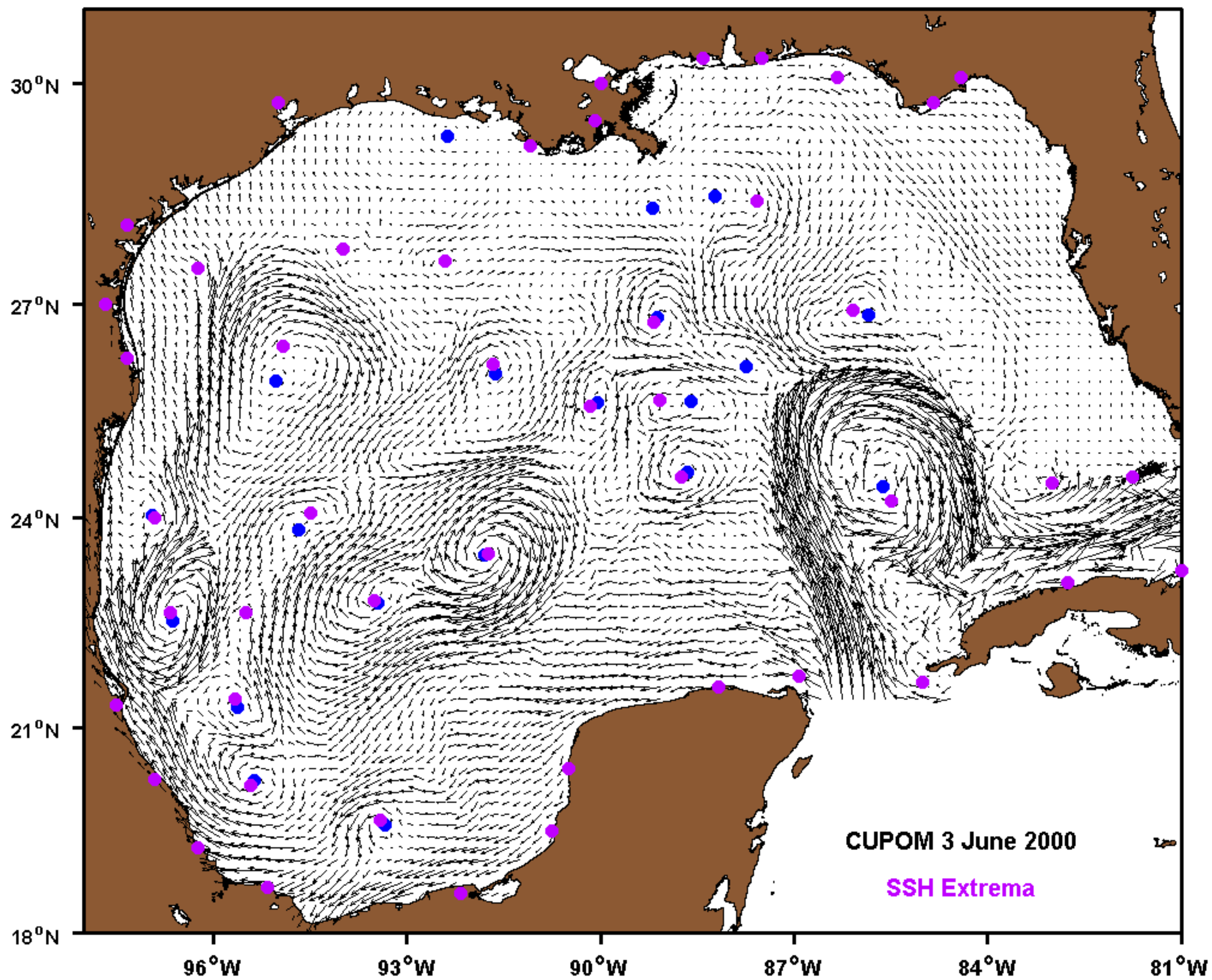
Eddy Centers: SSH Extrema

Advantage:

- Objective
- Ideal for satellite data

Diasadvantage:

- Overdetection
- Only surface layer
- Assumes geostrophy



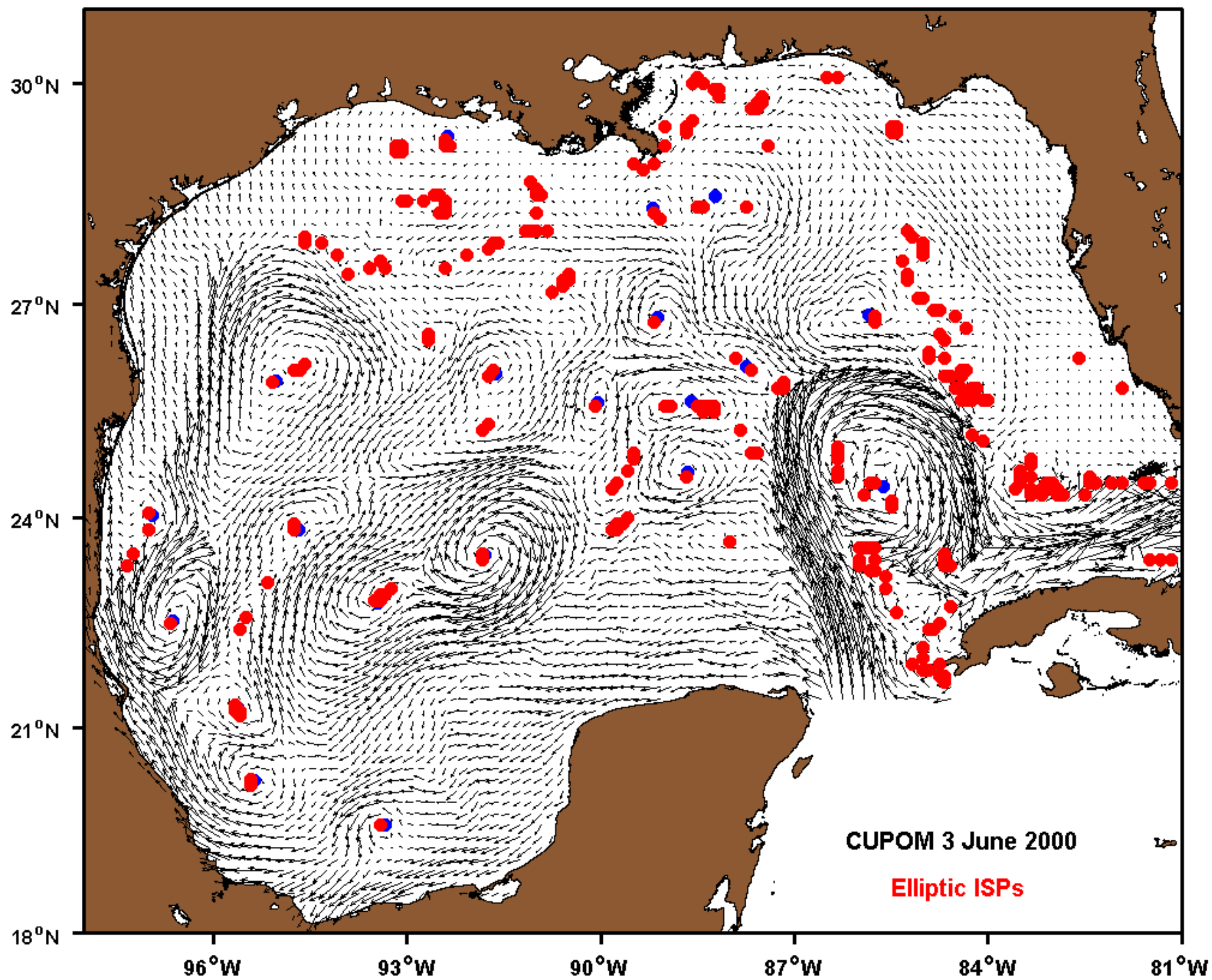
Eddy Centers: Stagnation Points

Advantage:

- Objective
- Fast algorithm

Diasadvantage:

- Lines
- Overdetection



Eddy Centers: Stagnation Points Plus

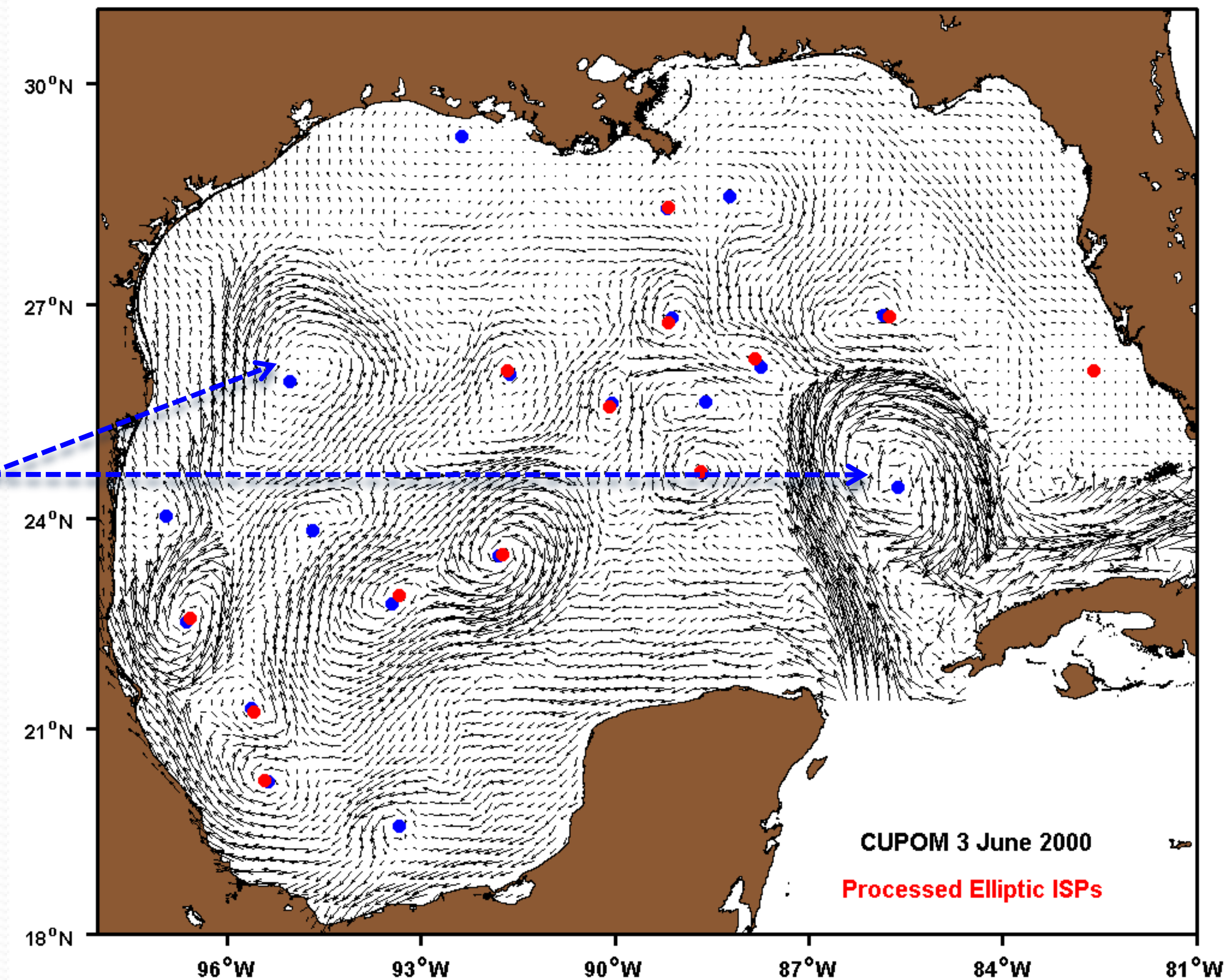
Advantage:

- Objective
- Fast algorithm

Diasadvantage:

- Underdetection (esp. of non-circular centers)

Added velocity minimization and angle check.



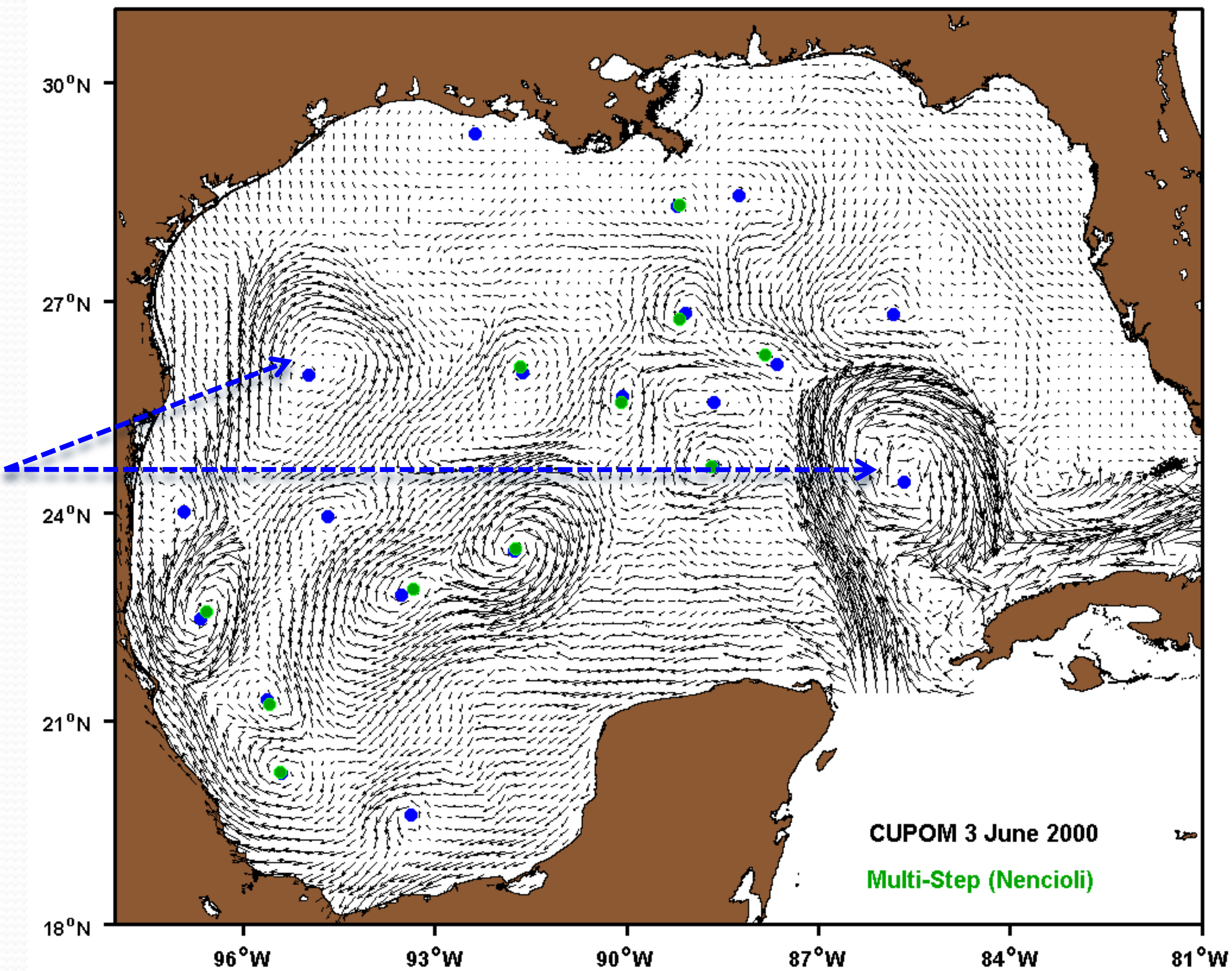
Eddy Centers: Multi-Step (Nencioli)

Advantage:

- Objective
- Fast algorithm

Diasadvantage:

- Underdetection (esp. of non-circular centers)



Eddy Census: GoM in the Year 2000

"Stagnation point plus" algorithm.

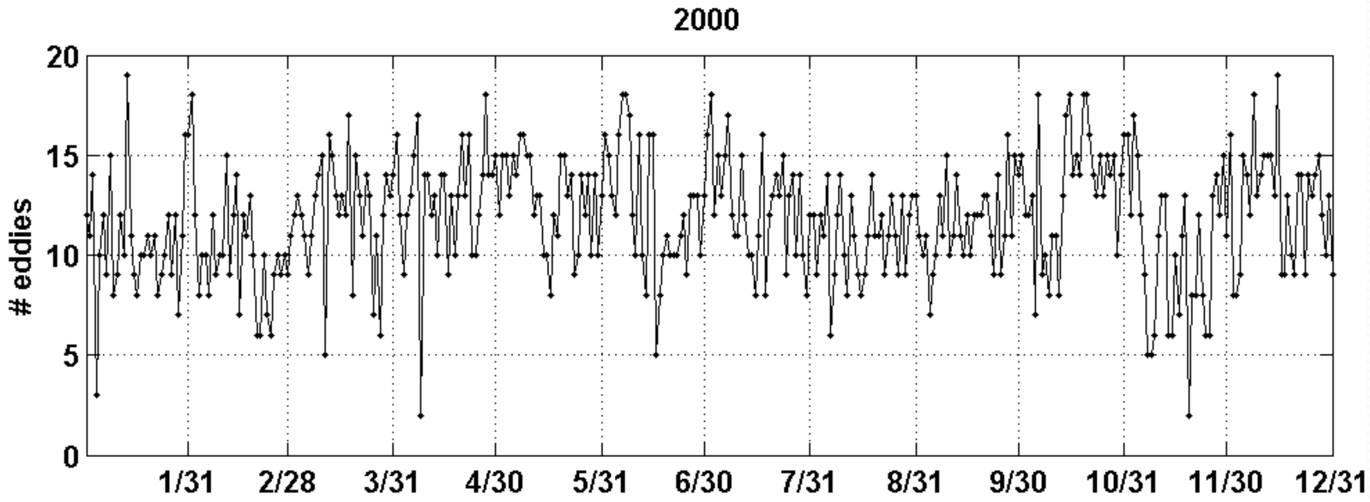
Stats:

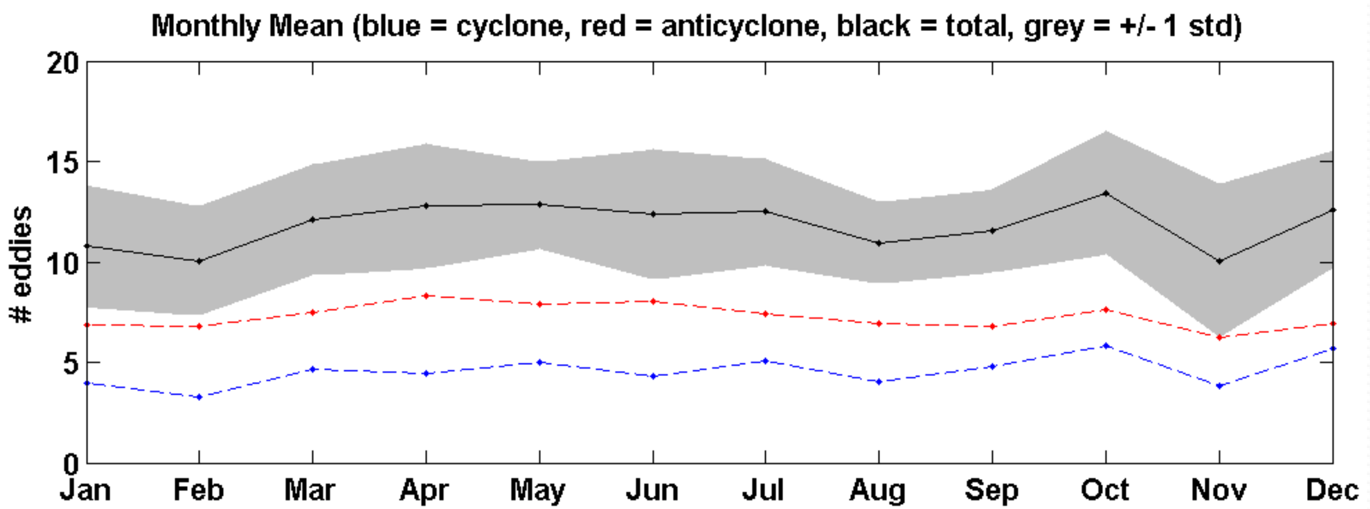
Mean = 12

STD = 3

Cyclones: 5 +/- 2

Anti-cyc: 7 +/- 2

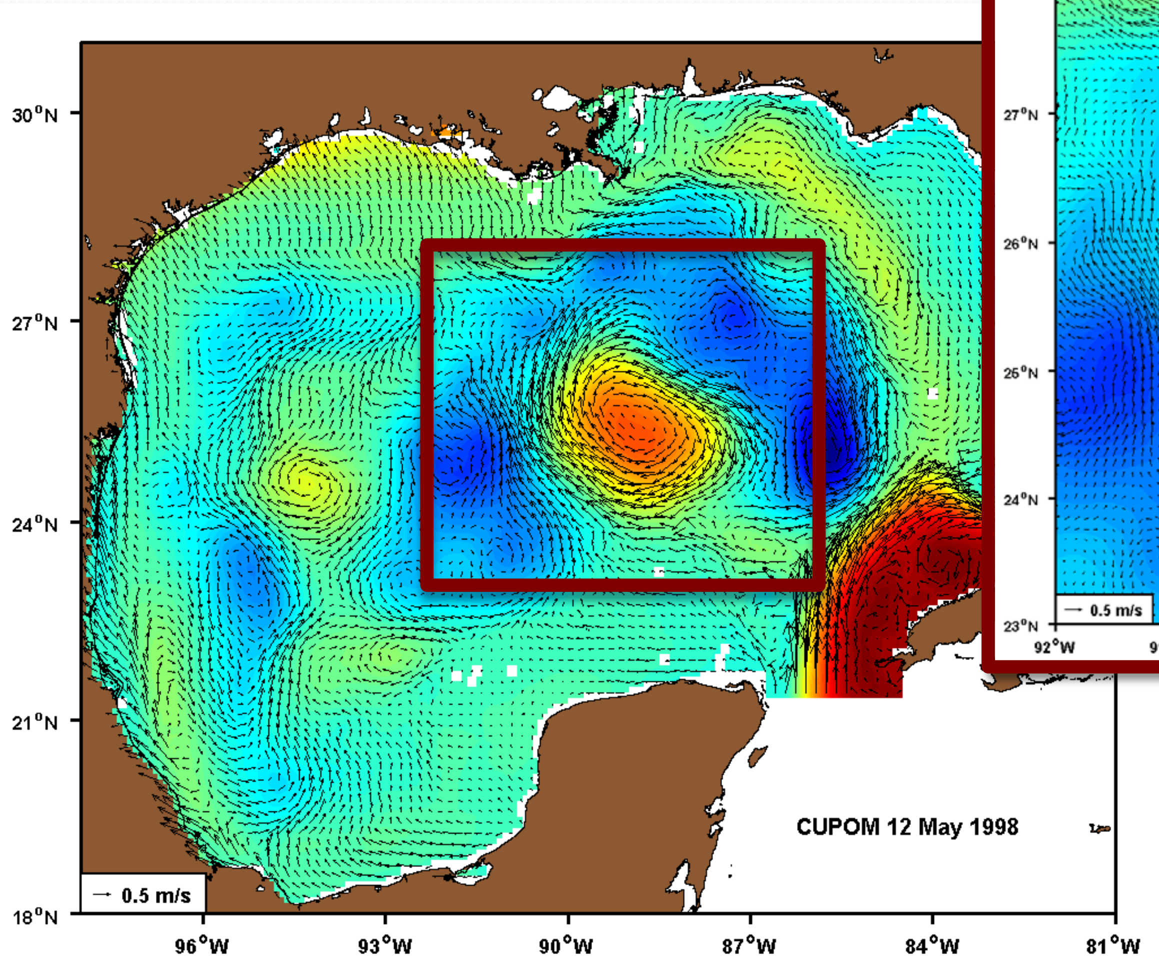


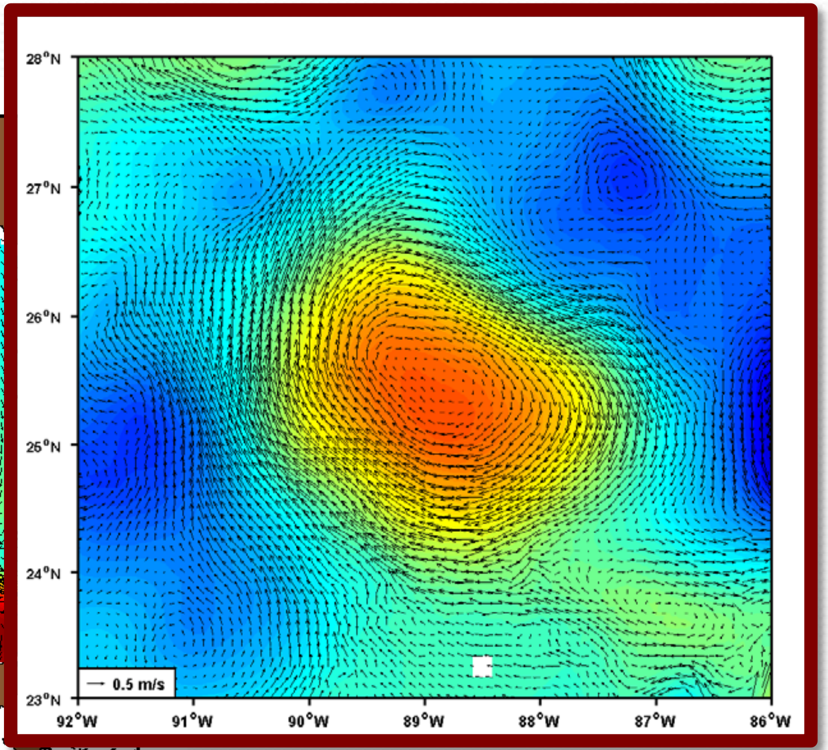


Locating Eddies: Eddy Boundaries

- In order to study fluid exchange ("leakiness"), we need to define the eddy boundary.
- Again, there are various algorithms:
  1. Relative vorticity < 20% of center [*McWilliams, 1990*]
  2. Okubo-Weiss = 0 (vorticity = deformation)
  3. Speed Maximum
  4. SSH contour (fixed or largest closed)
  5. Largest closed streamline
  6. Largest closed streamfunction contour with increasing velocities [*Nencioli et al., 2010*]
- Let's focus on one Loop Current Ring.

Loop Current Ring Fourchon

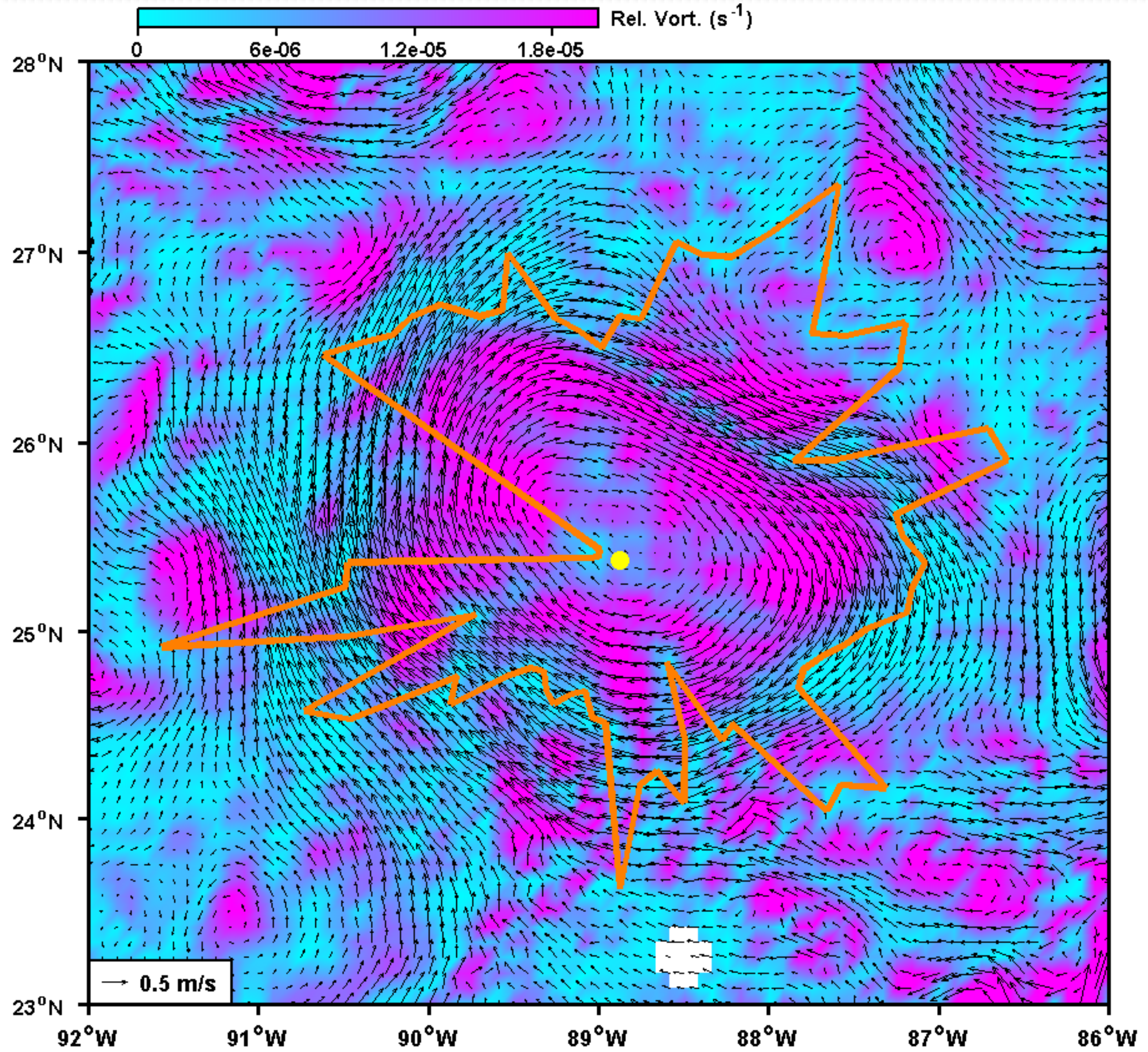




Nice, round shape

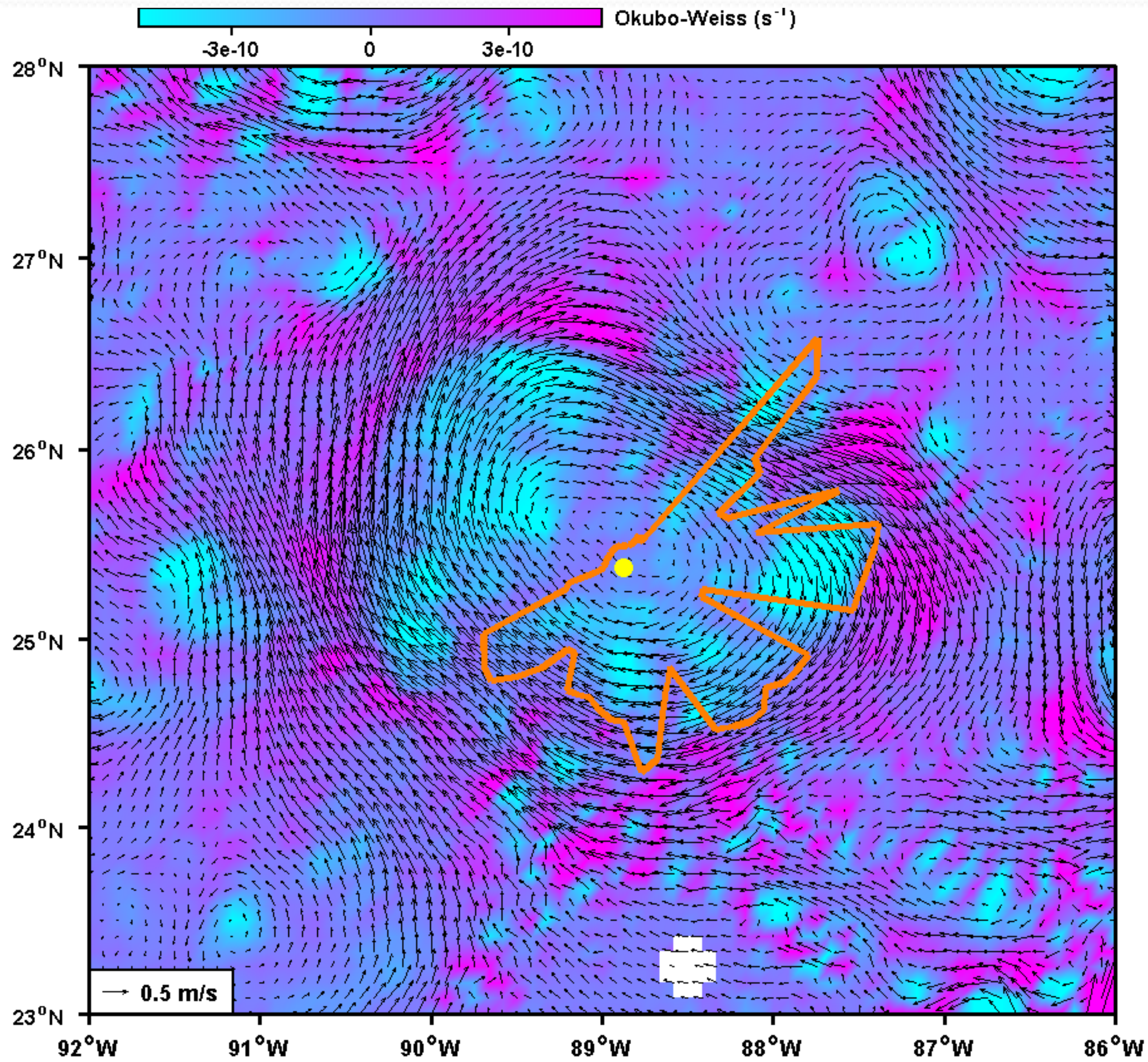
Ring Boundary: (1) Relative Vorticity

- 30% of center
- Value at center not a max!



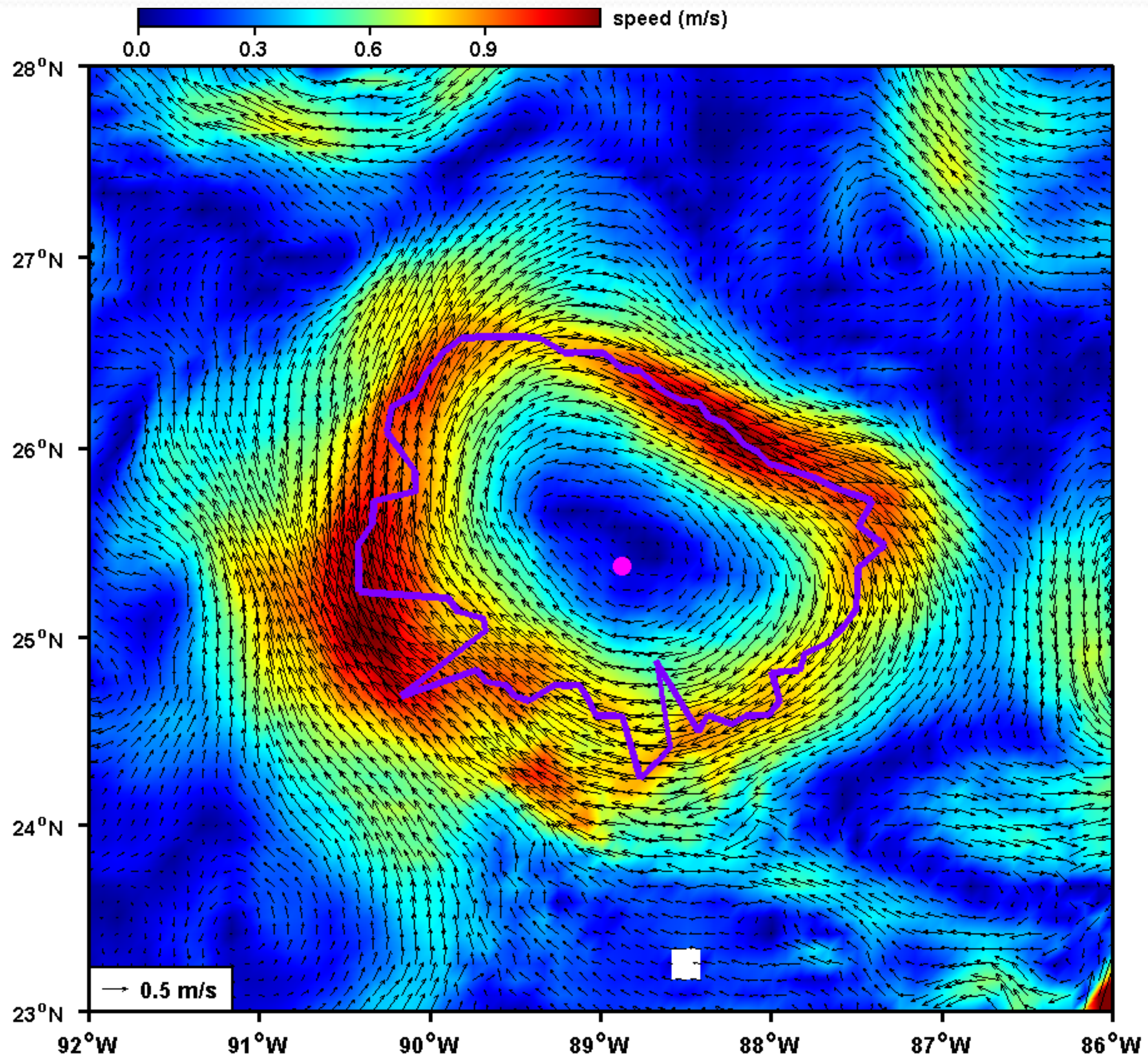
Ring Boundary: (2) Okubo-Weiss

- Allow for small error tolerance
- Value at center not a min!



Ring Boundary: (3) Speed

- Speed > 0.5 m/s and decreasing outwardly
- Simple max along radials is no better.



Ring Boundary: (4)-(6) Comparison

4) **Closed streamlines**

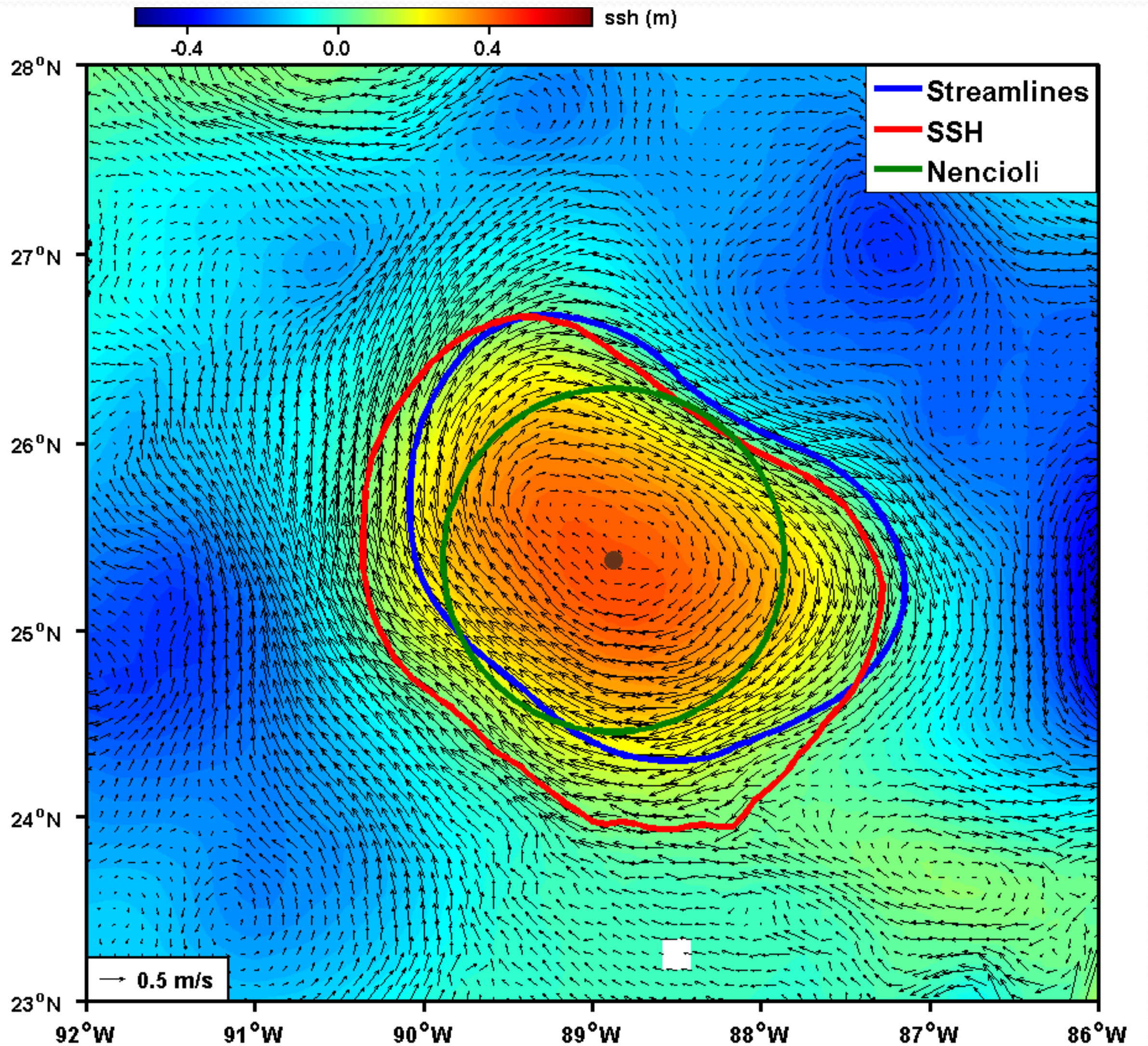
- Initialized along radials every 5º.
- Spiraling tolerance of 70 km.
- Max area fraction change btw adjacent streamlines: ¼

5) **SSH contour**

- Max area fraction change btw contours: 7.5%

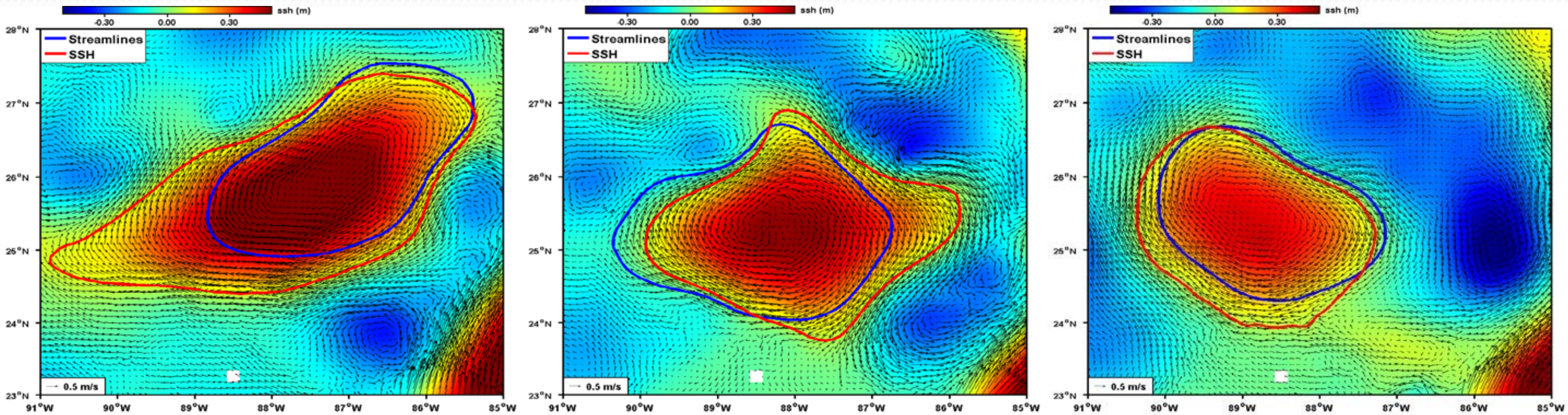
6) **Nencioli (streamfcn + increasing speed)**

- Default: Circle



Eddy Boundary: Algorithm Choice

- Envelope of closed/spiraling streamlines and ssh contours are generally similarly reasonable.

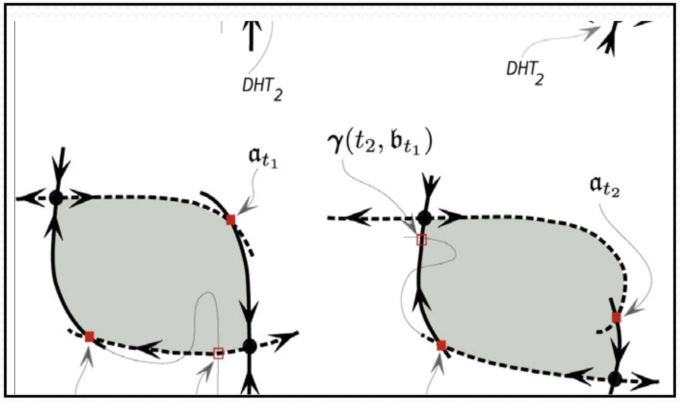


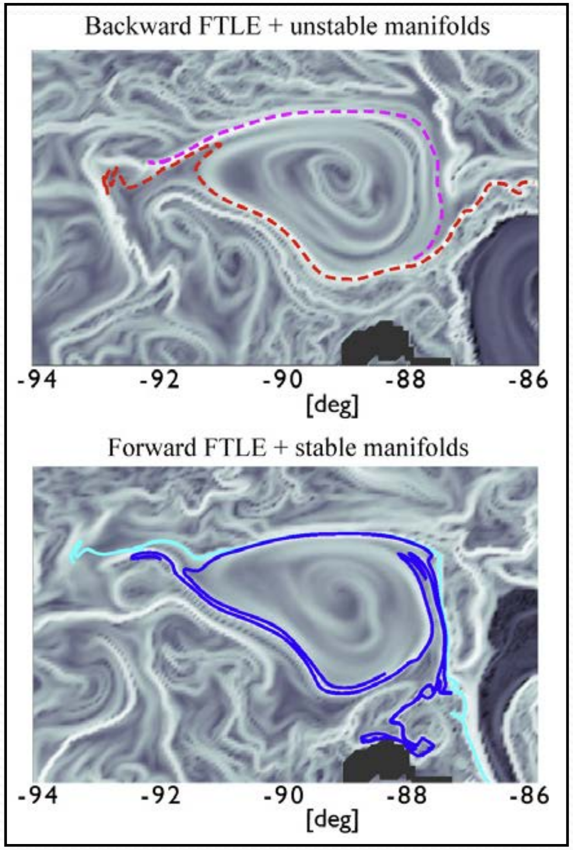
Agreement is even better at 50 m depth.

- Computing streamlines is computationally much more expensive.
- However, ssh only exists for surface layer!

→ Use geopotential for deeper layers.

Eddy Boundary: Lagrangian Approach





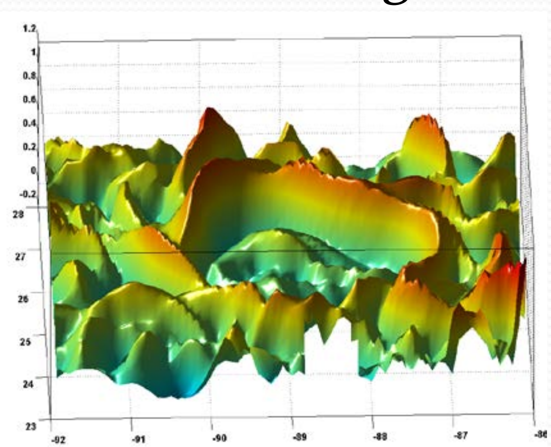
Branicki and Kirwan, 2010

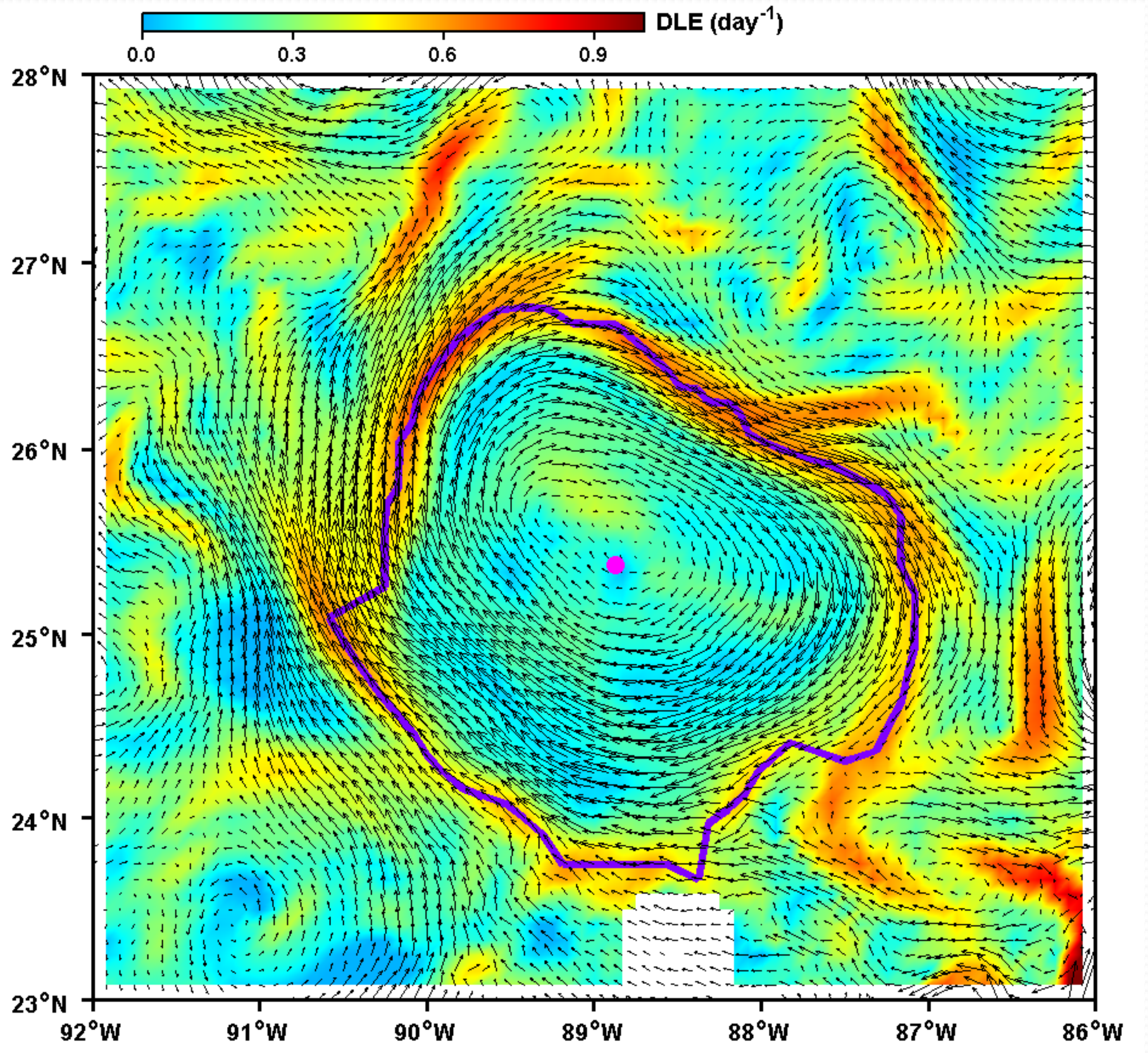
- It has been suggested that eddy boundaries can be defined as a collection of segments of stable and unstable manifolds.

- Manifolds can be approximated with DLEs
  → Eddy boundaries from DLEs?

Ring Boundary: DLE

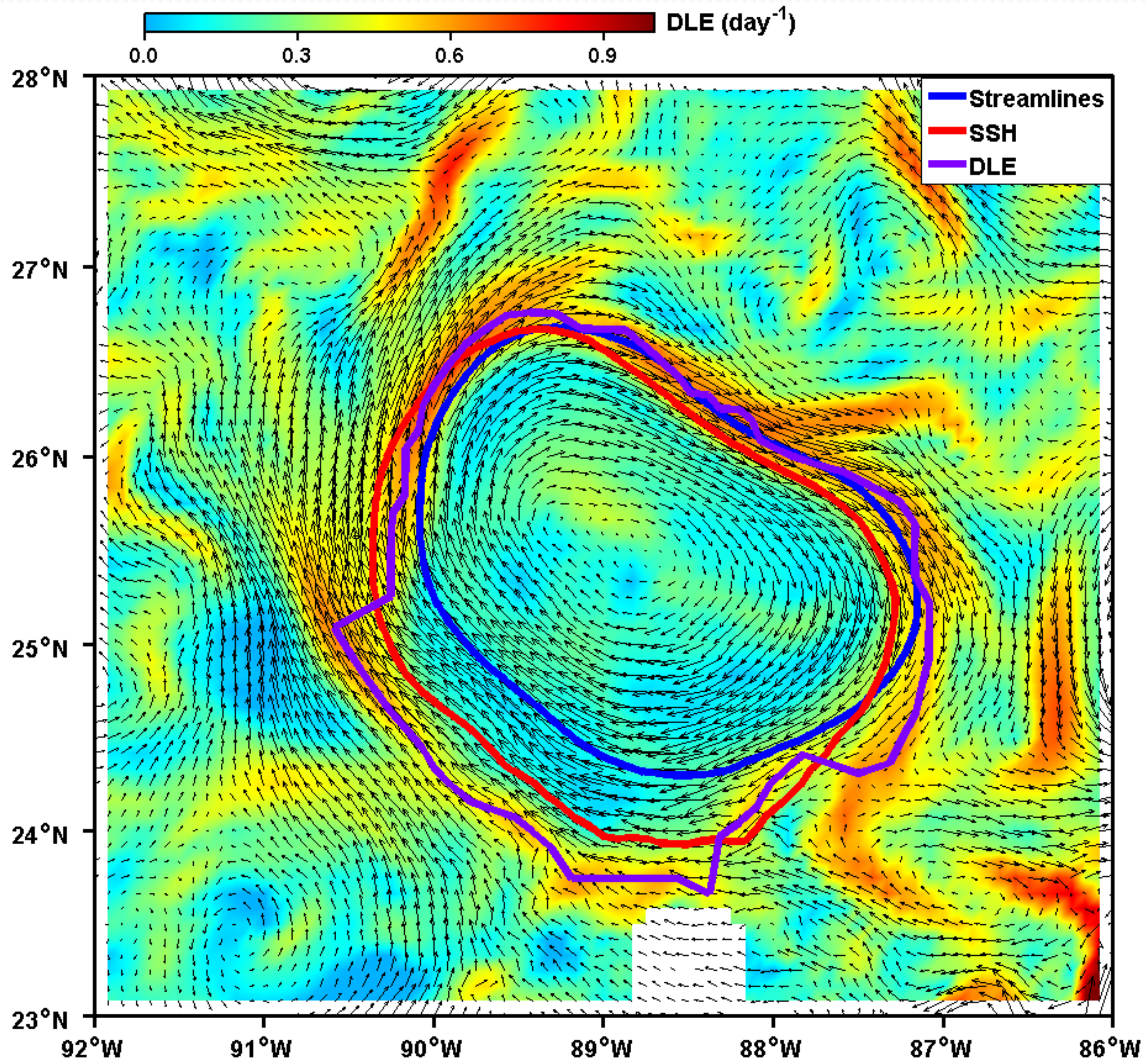
- DLE > 0.4 day^{-1} and decreasing outwardly along radials
- Ridge detection algorithms (e.g. Senatore & Ross, 2011) do not work well due to large along-ridge elevation changes.





Ring Boundary: DLE -- Challenges

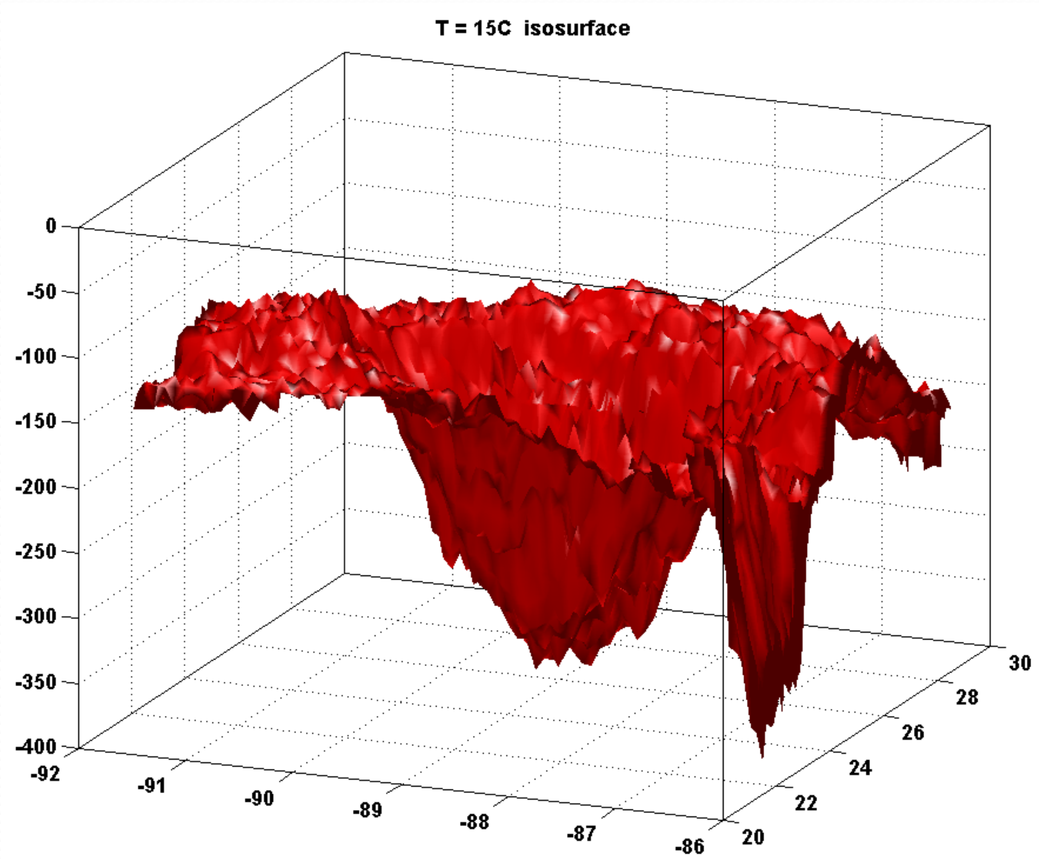
- In most cases, ridge segments from fwd & bwd DLE have to be stitched.
- Objective criterion for choosing segments does not exist.
- Computing actual manifolds is operator intensive.



Tracking a Ring in Depth

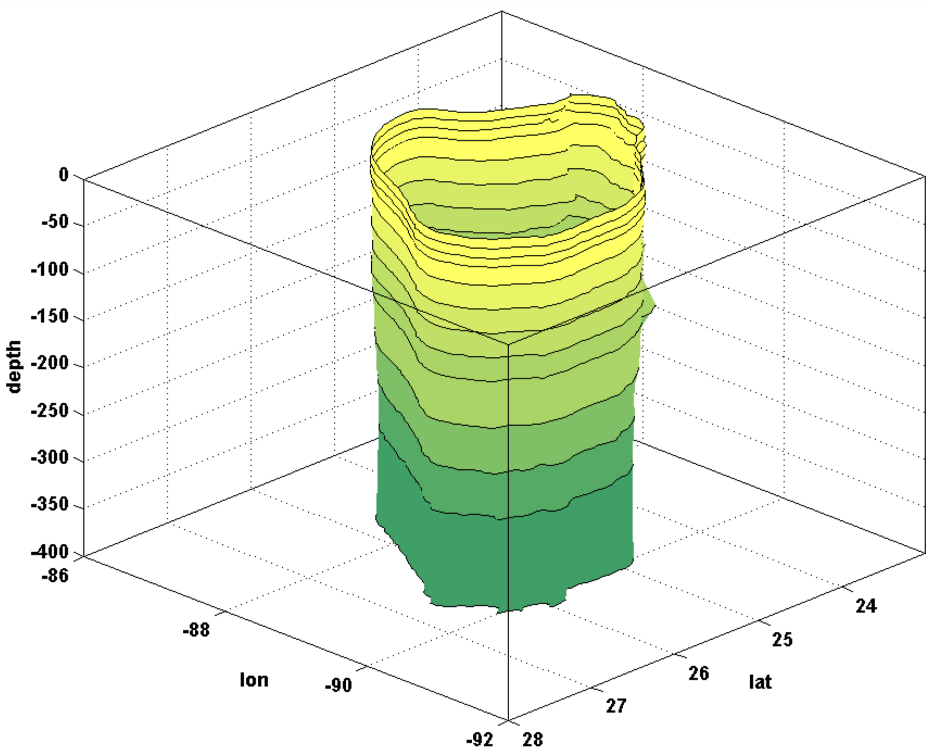
Eddies in 3D: Temperature Proxy

- Loop Current Rings are warm core eddies.
- Temperature iso-surfaces may give some insight into 3D structure of LCRs.

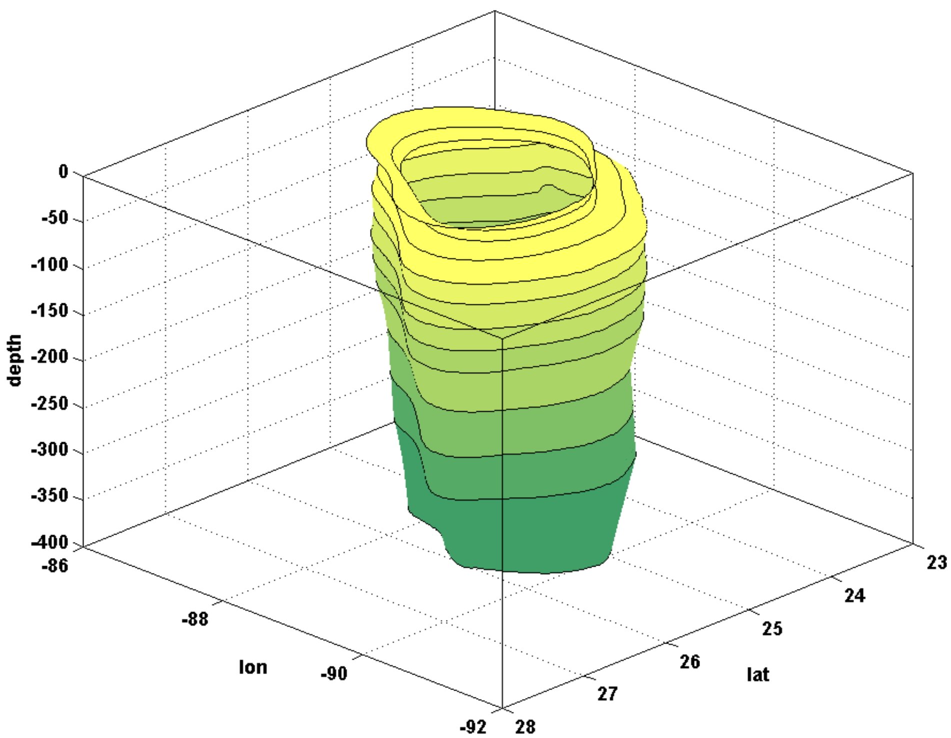


Eddies in 3D: Structure at Depth

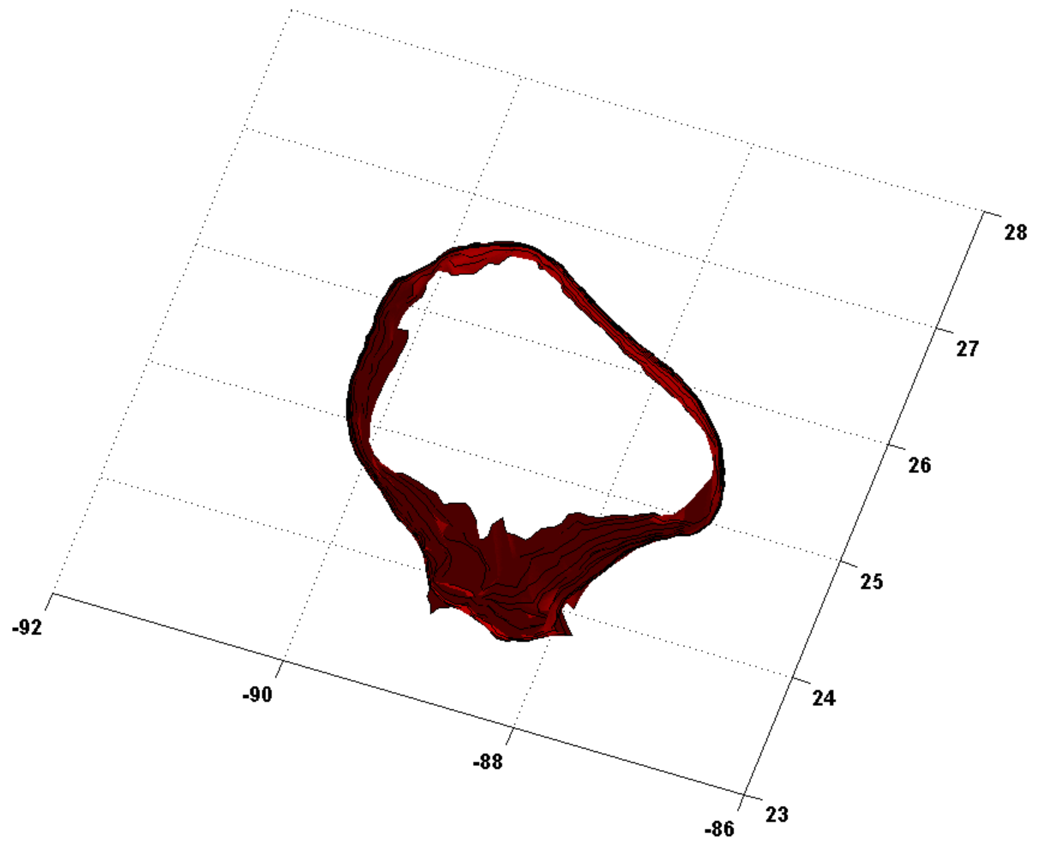
Geopotential contour



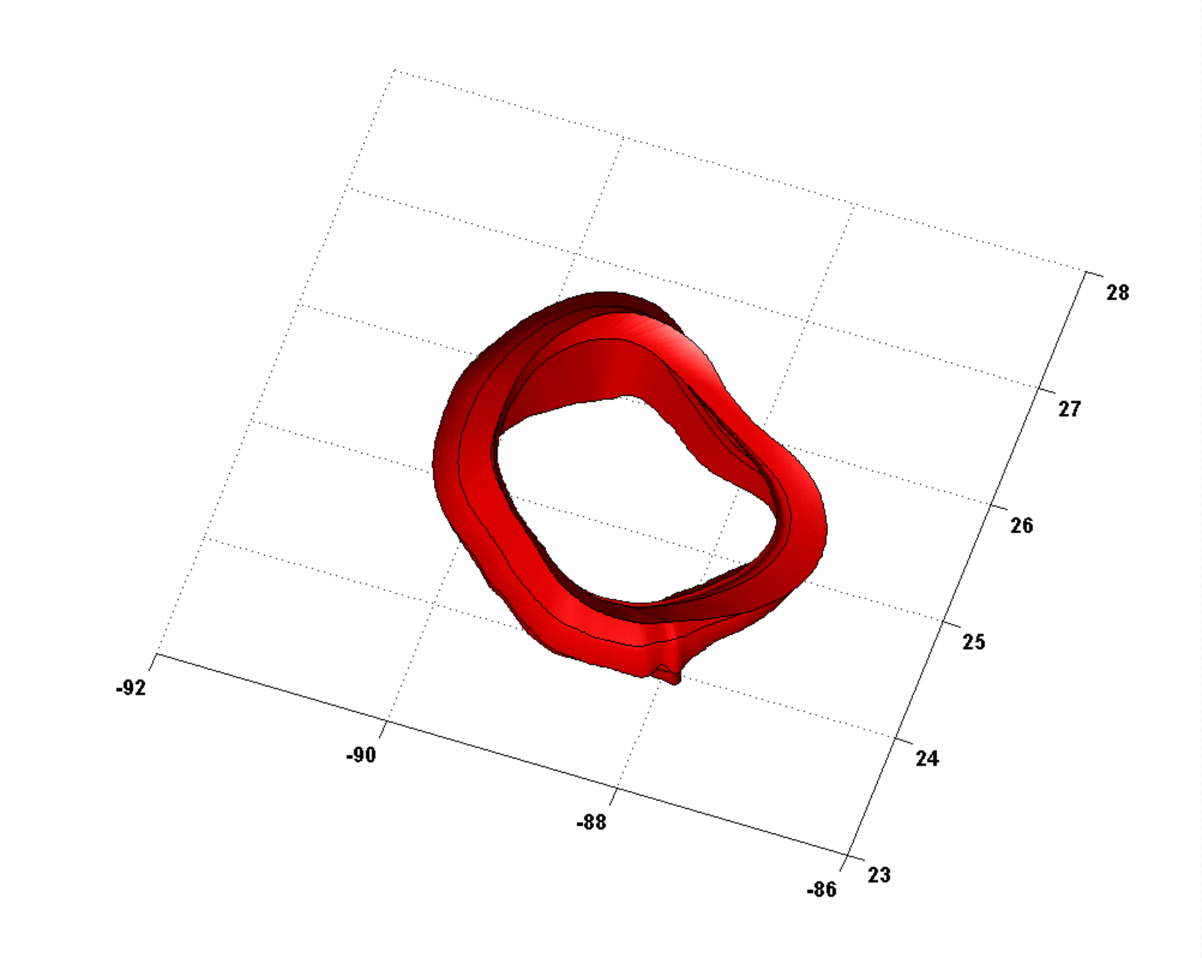
Closed streamlines



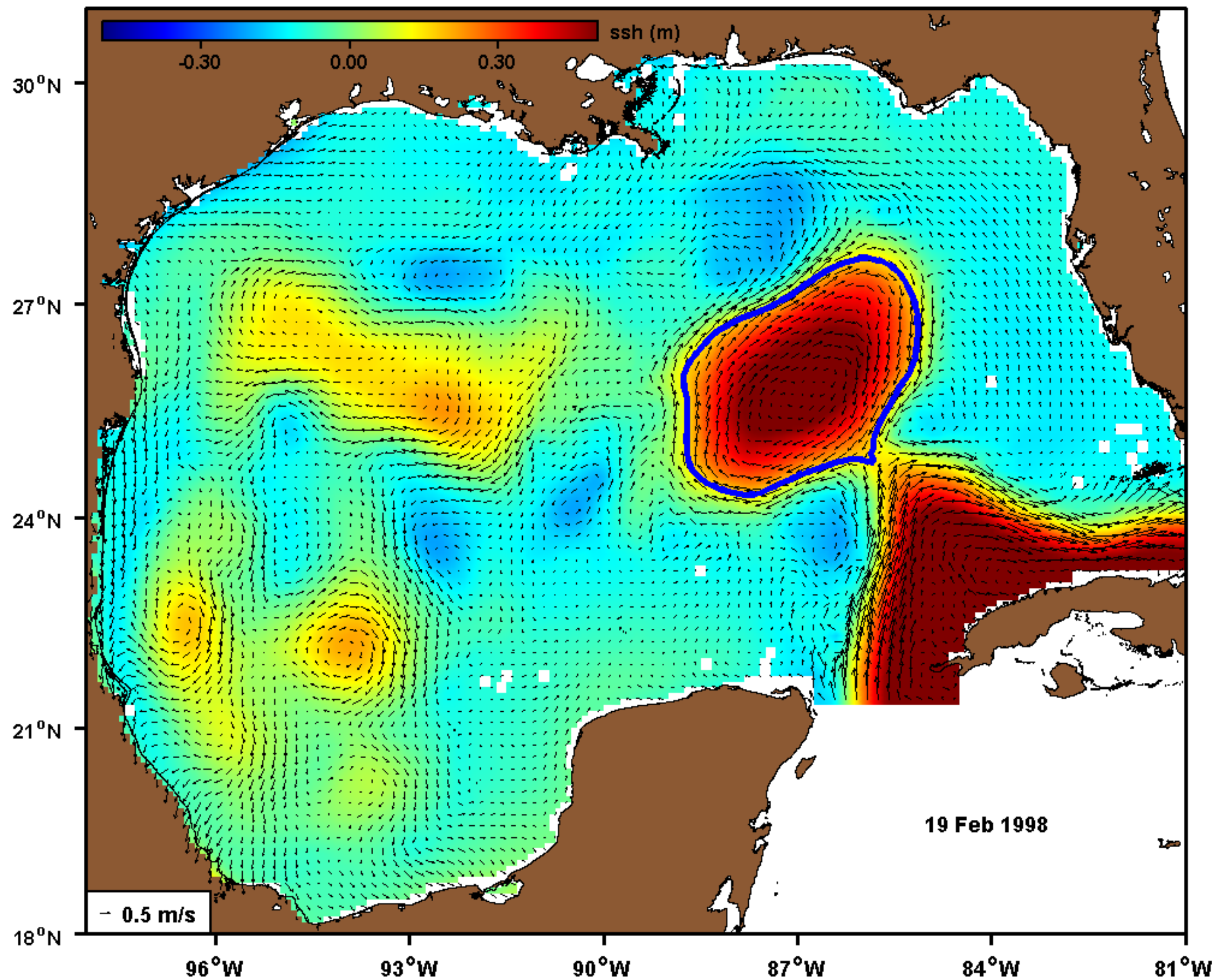
Eddies in 3D: Geopotential Contour



Eddies in 3D: Closed Streamlines

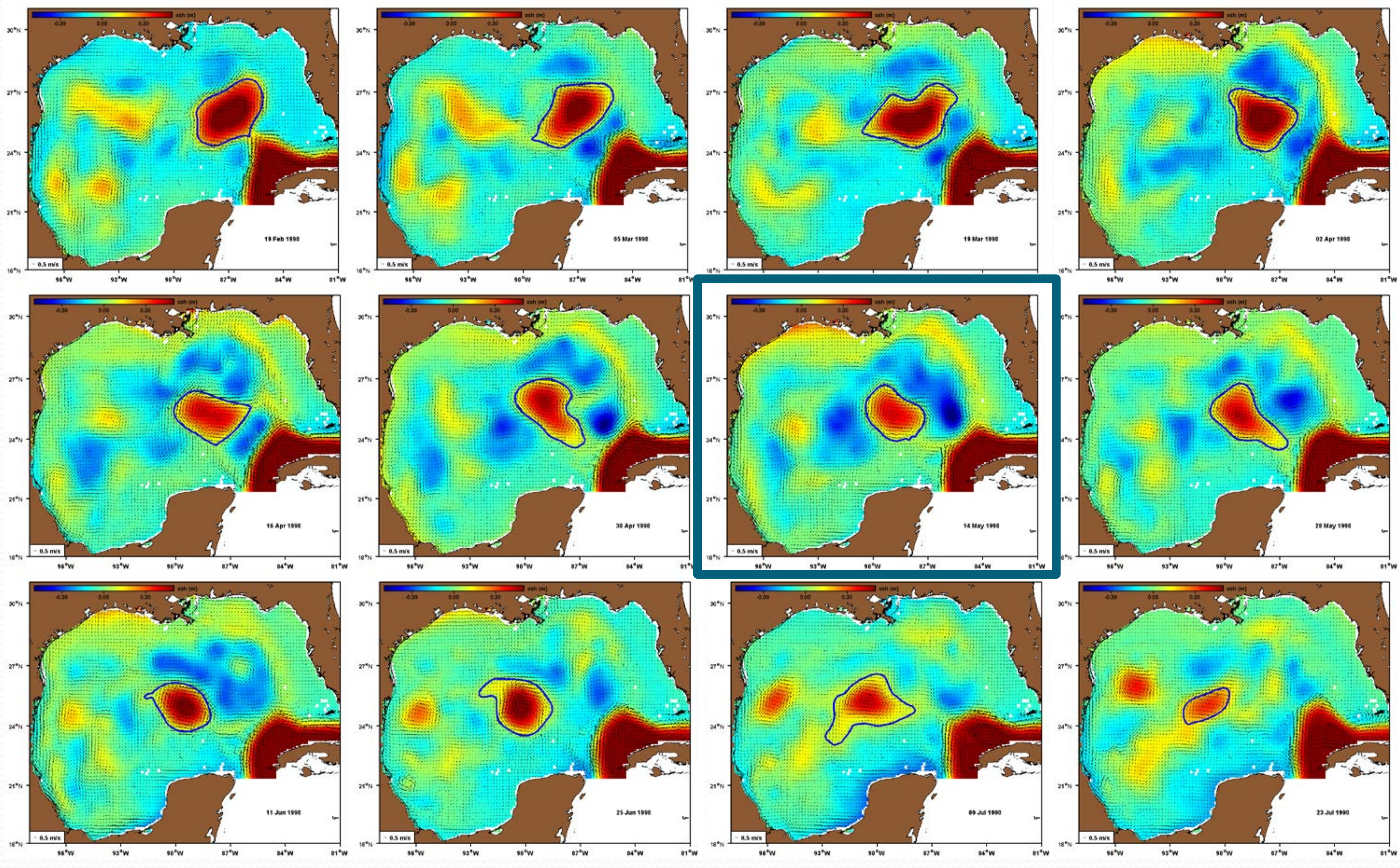


157 Days in the Life of Fourchon



SSH contour
Surface layer

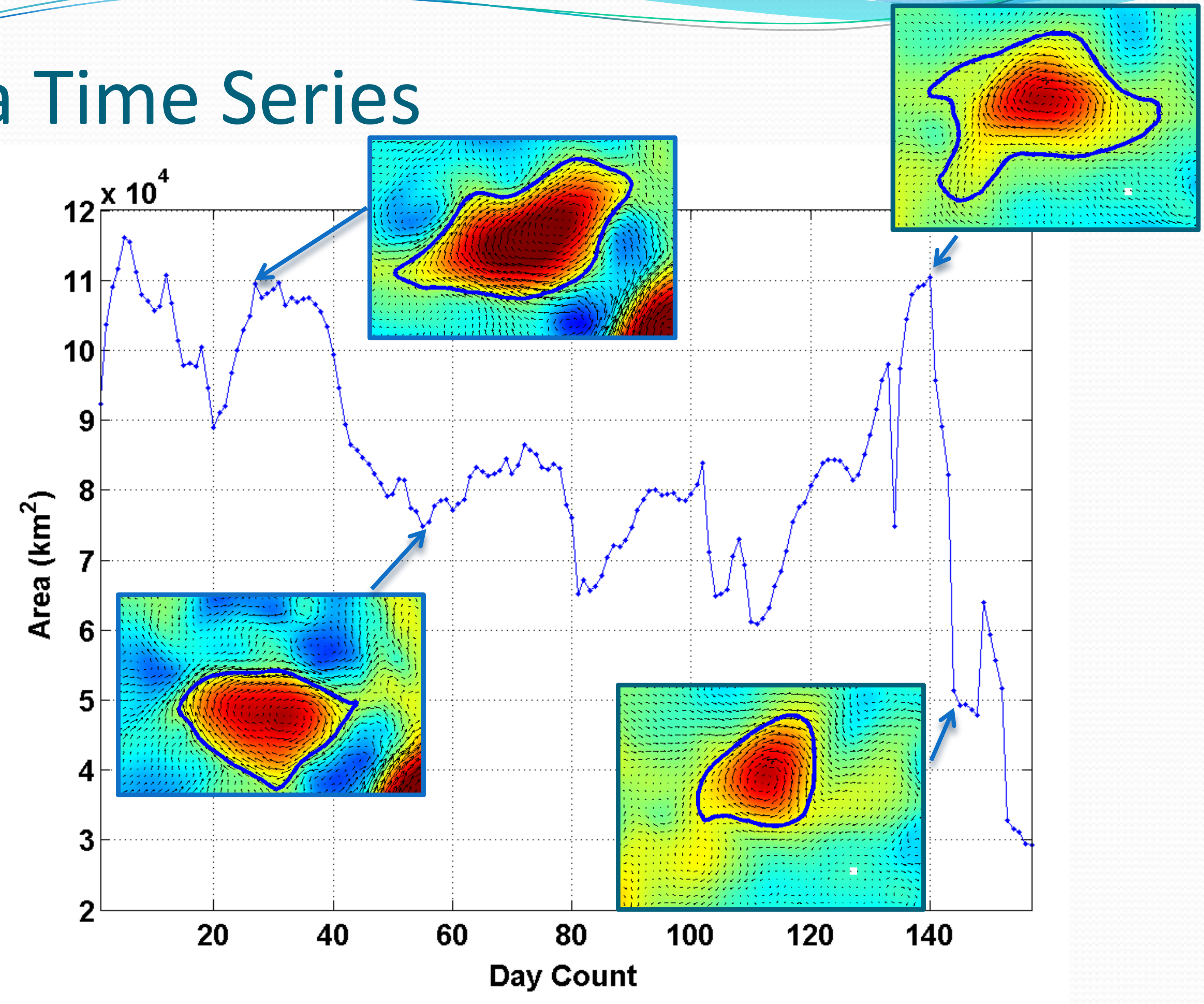
2-week intervals



Analyzing Leaky Eddies: Surface Signatures

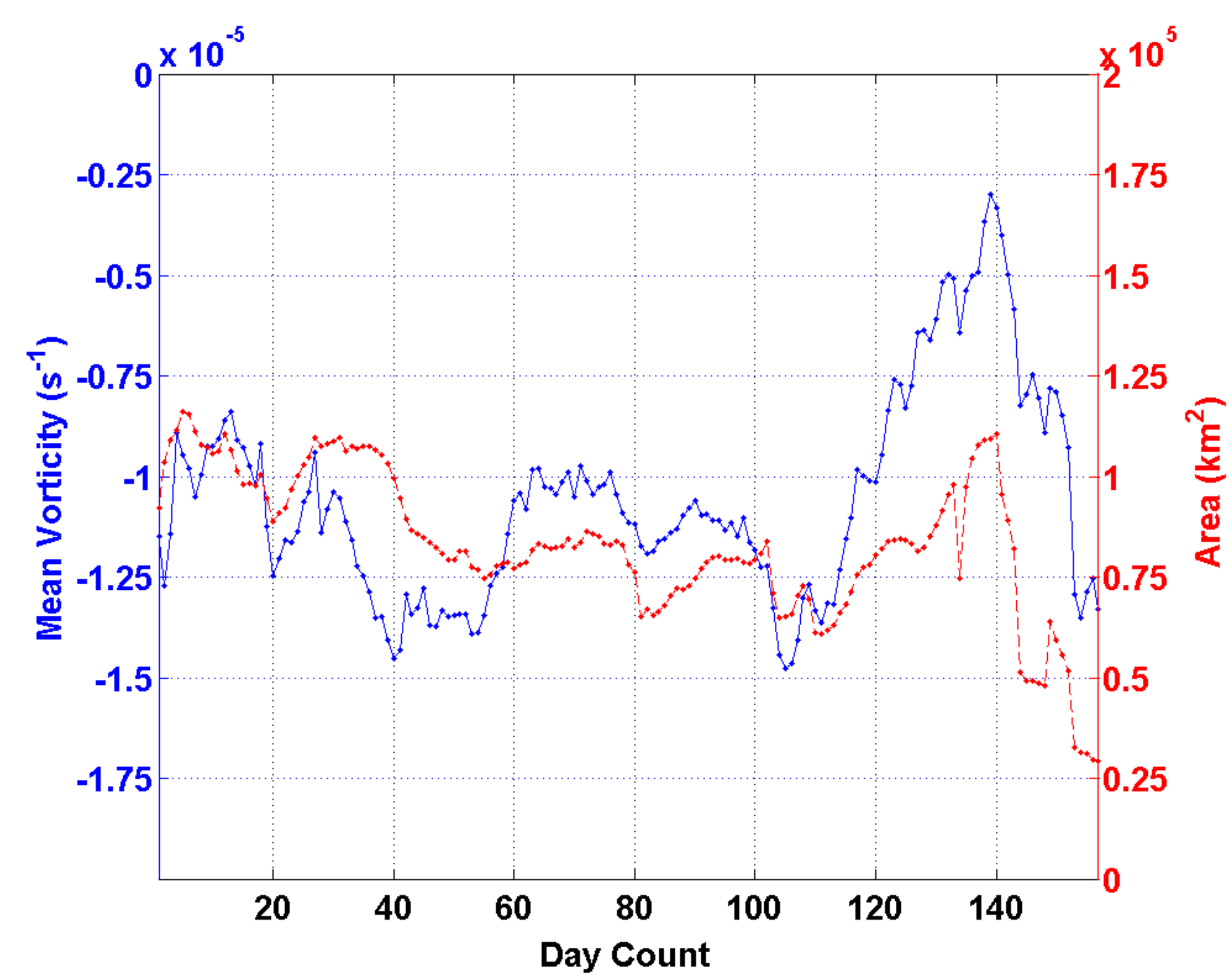
- Given a clearly defined eddy boundary, what is the fluid exchange between the interior and the exterior fluid masses?
- For now, we restrict our analyses to the surface layer.
- We choose SSH contours as the boundary algorithm (fast, easy, sensible).

Area Time Series

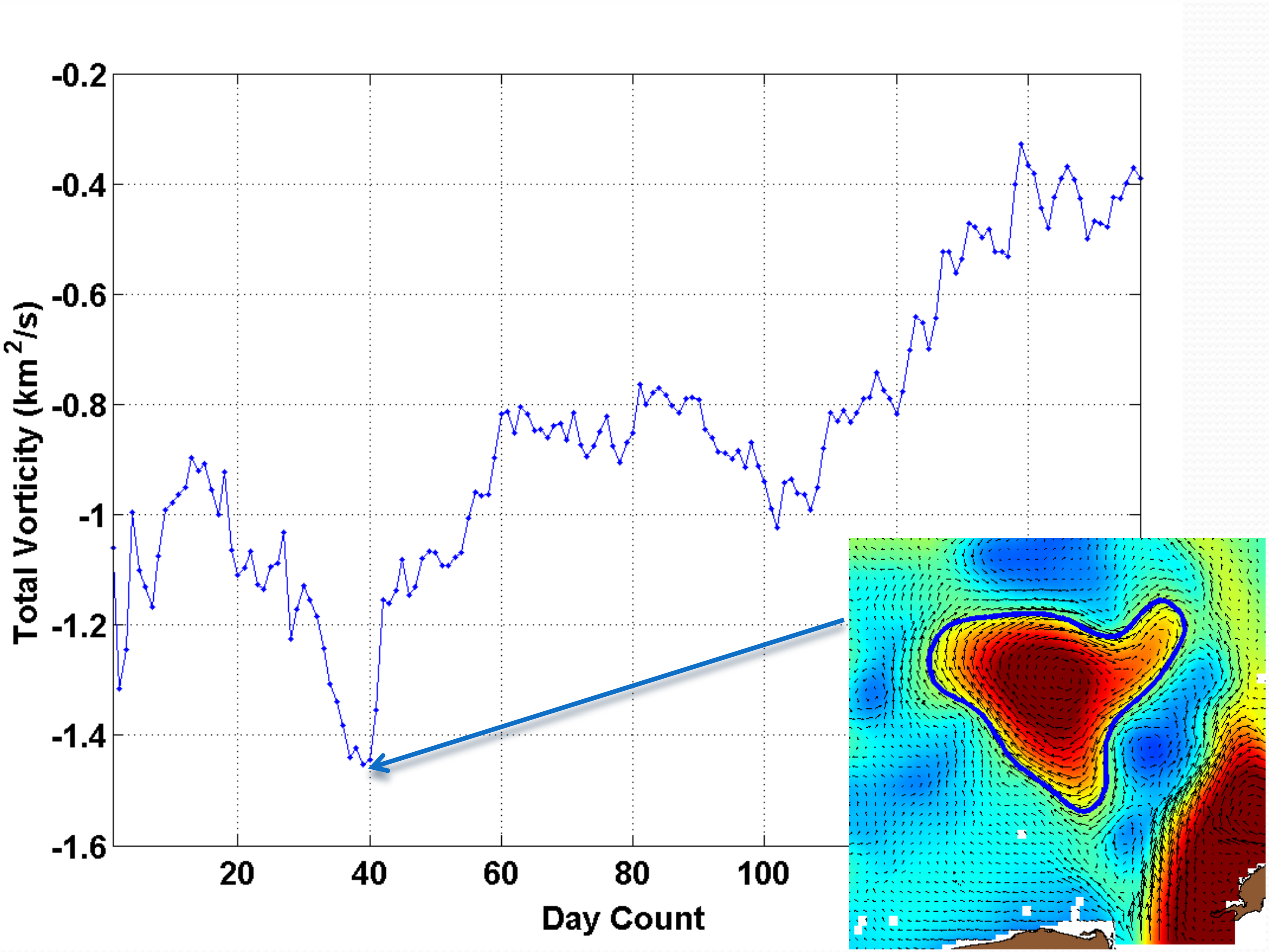


Vorticity Time Series: Area Mean

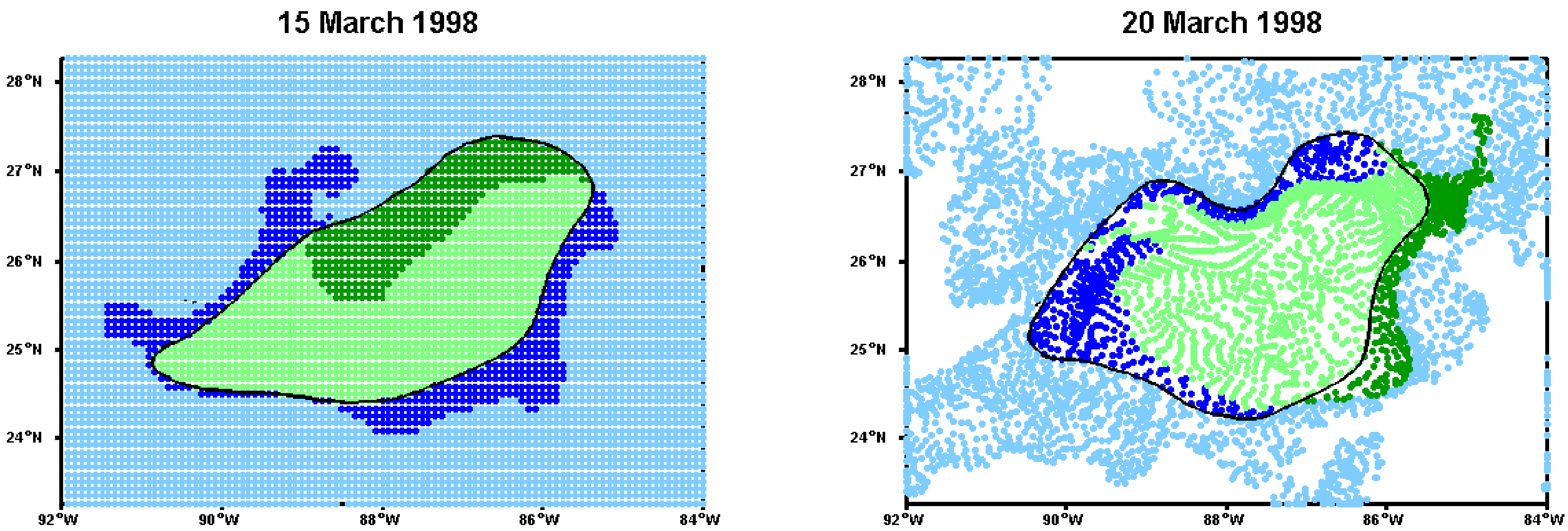
1e5 s ~ 28 hrs



Vorticity Time Series: Total



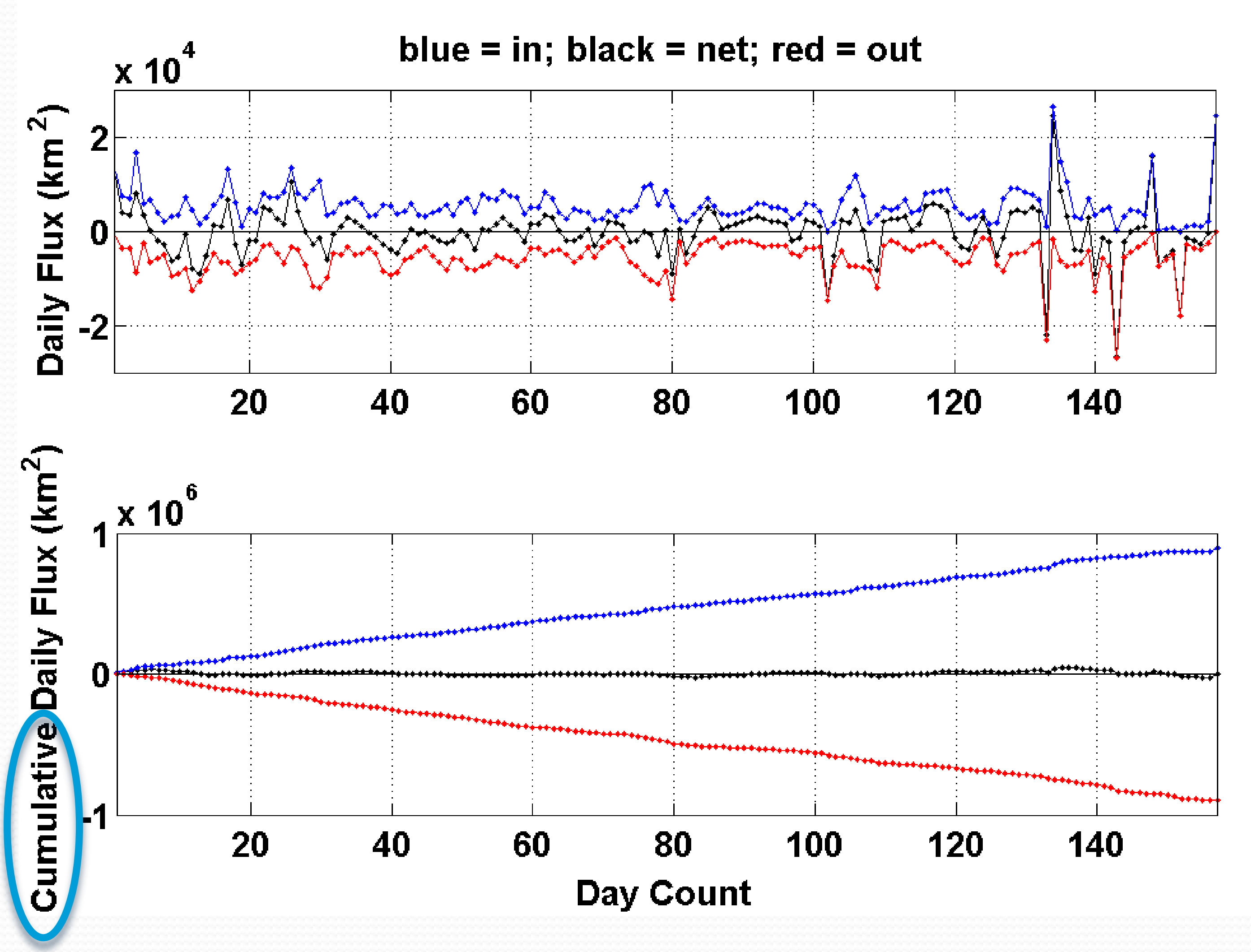
Fluid Exchange



Flux in Flux out

Note that eddy boundaries are NOT material curves!

Quantifying Fluid Exchange



Conclusions & Summary

- The Gulf of Mexico's circulation is dominated by eddies. For the typical year 2000, an average of 12 eddies on the length scale of 75 km were present at any one time, with slightly more anticyclones than cyclones.
- Automating the detection, count, and sizing of eddies is challenging. All existing algorithms have shortcomings. This is partially due to a fuzzy definition of an "eddy".

Conclusions & Summary (cont'd)

- The structure of eddies in depth is not very well known, since few observations exist. This model suggests a depth of ~ 400 m for the LCR Fourchon, with little narrowing towards its bottom.
- LCRs do not monotonically shrink in area over the course of their lives.
- LCRs also do not monotonically lose vorticity, but a precipitous loss of vorticity portends an impending death.

Conclusions & Summary (cont'd)

- Even though the size of LCRs remains fairly constant over long periods of time, LCRs are leaky: Fluid is exchanged continuously between the eddy and its environment.
- Over the course of its life, about 10 times its average area in fluid leaks out of (and into) a LCR.

Thank you!

CUPOM

- University of Colorado implementation of the Princeton Ocean Model
- Primitive equations
- 24 sigma layers (terrain following)
- Curvilinear grid; Arakawa C staggering; $1/12^{o}$ resolution
- Mixed layer model with 2^{nd} moment turbulence closure
- Free surface dynamics through split-mode technique
- Smagorinski horizontal diffusion
- Climatological open boundary conditions
- Climatological T-S fields for initial conditions
- Wind forcing with 6-hourly ECMWF winds
- SSH and SST satellite data assimilation since 1993