The 3D structure of Mesoscale Eddies in the Northeastern Arabian Sea, and their impact on Submesoscale Dynamics

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Motivations

- Mesoscale eddies have a strong influence on the circulation in the Arabian Sea.[1]
- Understanding their evolution is of primary importance: they carry and upwell oxygen and nutrients, modulating plankton blooms and green algae generation which impact the fishing economy, sustaining 120 million people living on the rim of the Arabian Sea.[2,3,4]
- The eddy-driven circulation strongly impacts the spreading of the dense salty water masses outflowing from the adjacent marginal seas, the Persian Gulf and the Red Sea.[5]
- These outflows[6] and the biological activities[7] are also impacted by the Submesoscale features generated by the instabilities of baroclinic flows[8].

References: [1]Fischer *et al. Deep Sea Research Part II* **49**, 2231–2264 (2002); [2]Chelton *et al. Science* **334**, 328–332 (2011); [3]Tollefson *Nature* **555**, 569–570 (2018); [4]do Rosario Gomes *et al. Nature Communications* **5**, (2014); [5]Bower *et al. JGR: Oceans* **105**, 6387–6414 (2000); [6] L'Hégaret *et al. Ocean Science* **12**, 687–701 (2016); [7]Lévy *et al. Nature Communications* **9**, (2018); [8]Klein *et al. Journal of Physical Oceanography* **38**, 1748–1763 (2008).

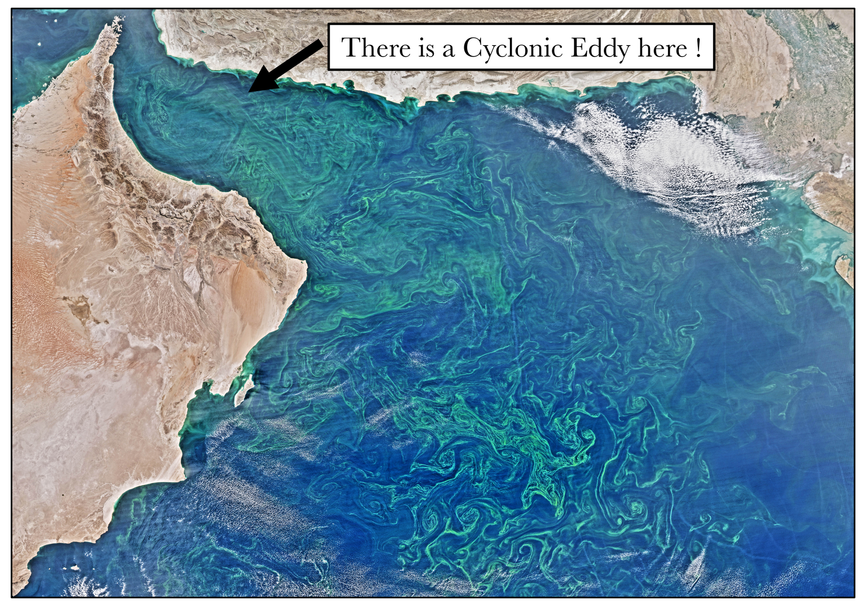

Fig. 1: Image of the Gulf of Oman acquired February 14, 2015 by the MODIS system on NASA's Aqua satellite (250m horizontal resolution), showing swirling patterns of ocean chlorophyll (NASA Earth Observatory).

Methods and Dataset

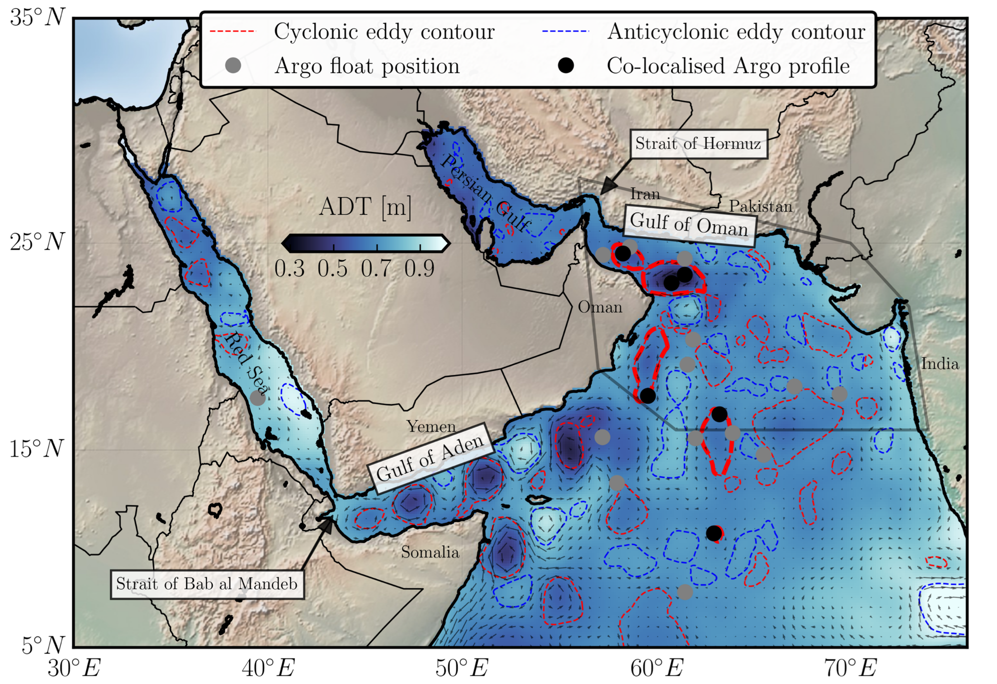

Fig. 2: Snapshot of ADT from AVISO. The contour of eddies from the AMEDA eddy detection (red and blue dashed lines), and the position of Argo Stations on the same date are superposed. Gray polygon indicates the NEAS area.

- The Angular Momentum Eddy Detection and tracking Algorithm[9] (AMEDA) to detect the mesoscale eddies from altimetric data (Regional 1/8° resolution altimetric product for the 2000-2015 period)
  → 489,562 eddies detected
- 29,516 Argo profiles to determine the vertical properties of the water column

Colocalization method: Is an Argo profile collected within an eddy ?
→ Profiles "outside eddies" define T, S and ρ climatologies
→ Profiles "inside eddies" report the water column properties in the core of eddies.

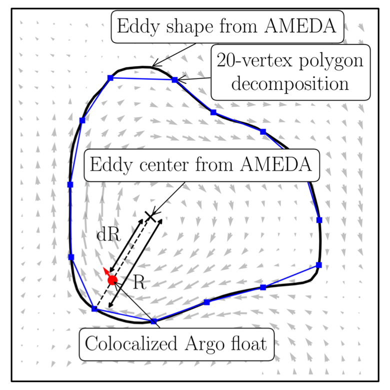

Fig. 3: Example of colocalization

Reference: [9]Le Vu *et al.* Angular Momentum Eddy Detection and Tracking Algorithm (AMEDA) and Its Application to Coastal Eddy Formation. *J. Atmospheric Ocean. Technol.* **35**, 739–762 (2018).

The composite 3D structure of mesoscale eddies[10]

- Focus on the best sampled area: the NorthEastern Arabian Sea (NEAS)
- Analyzing the 4,961 profiles colocalized inside eddies in this area:
  → most cyclonic eddies (CE) are surface intensified (75%)
  → most anticyclonic eddies (AE) are sub-surface intensified (68%)
- Focus on eddies with a radius $R_D < R < 3\,R_D$, (R_D is the Rossby deformation Radius)

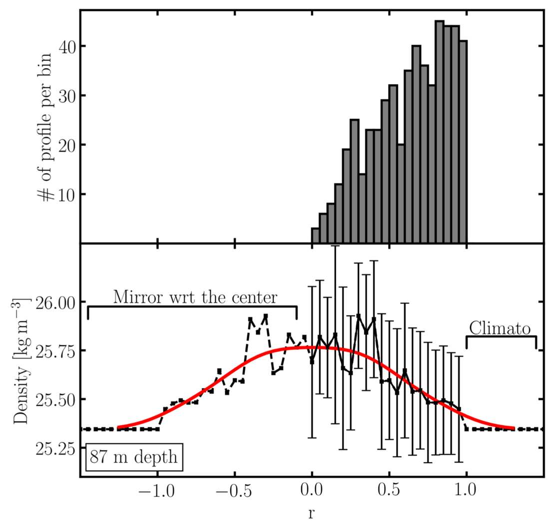

Fig. 4: Composite CE calculation. (top) Number of profile in each bin. (bottom) Smoothing of the density at a given level.

Composite approach[11] to compute the mean 3D shape of mesoscale eddies in the NEAS
→ estimation of the velocity field induced by eddies over all the water column, from 1500 m up to the surface.
→ CE have a larger angular velocity than AE
→ CE are surface intensified, and their maximal velocity is at the surface.
→ AE have an angular velocity increasing from the surface to 50 m depth and vanishing at depth.

How would the composite CE evolve if it was isolated in the stratified environment corresponding to the NEAS ?

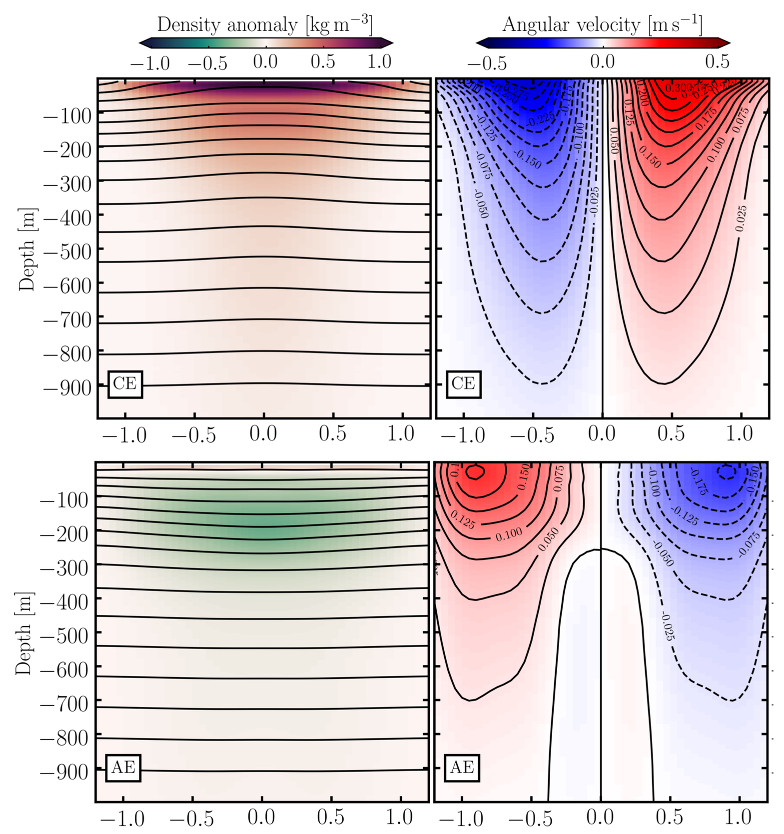

Fig. 5: Composite surface intensified CE (top) and sub-surface intensified AE (bottom) in the NEAS

Reference: [10]de Marez *et al.* On the 3D structure of eddies in the Arabian Sea. *Submitted to Deep Sea Research Part. I*.(under review); [11]Chaigneau *et al. JGR* **116**, (2011).

Destabilization of the composite cyclonic eddy[12]

1- Initialization

We perform spindown idealized simulations using the Coastal and Regional Ocean COmmunity model (CROCO)[13]. It solves the hydrostatic primitive equations using a full equation of state for seawater. The model is integrated for about 300 days on the f-plane.
The domain size is 500 x 500 km on the horizontal, with a horizontal resolution dx=500 m. The bottom is flat, at 1500 m depth. The simulation has 256 vertical levels (dz=2 m from 0 to 400 m depth and dz=40 m below).

3- Frontogenesis at the surface

The perturbation is wrapped around the eddy, at the Critical Level position. As the radial component of the velocity perturbation grows, the buoyancy gradients become very steep. It is reflected by the Frontogenesis function F.
This leads to an intense imbalanced ageostrophic circulation at the edge of the eddy.

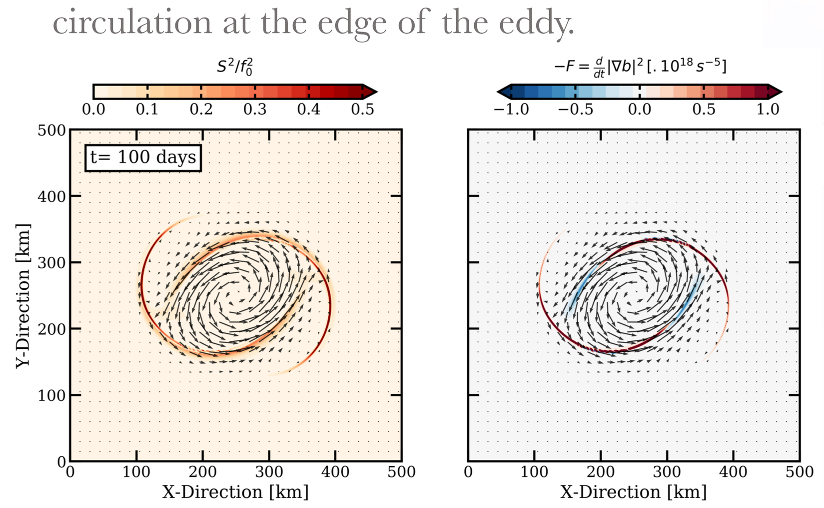

Fig. 8: Snapshot at t=100 days of (left) Stretching and (right) Frontogenesis function at the surface. Black arrows indicate the surface horizontal velocity.

5- Symmetric Instability at the edge

The frontogenesis-driven imbalanced circulation leads to the generation of negative PV. The edge of the eddy is then eroded by the development of a Symmetric instability.

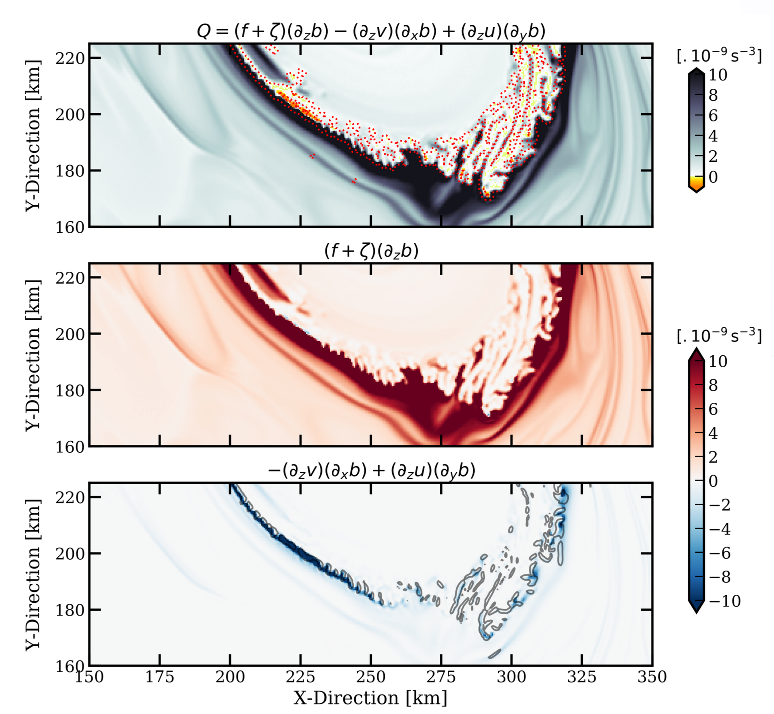

Fig. 10: Decomposition of the PV at t=190 days. (top) PV at the surface; the yellow indicates places where the PV is negative, and the red dashed lines indicate places where the criterion for SI to occur $Ri < Ri_c$ is respected. (middle) First term of the PV. (bottom) Second and third terms of the PV; grey thin lines are contours of $-F = 10^{-18}\ s^{-5}$.

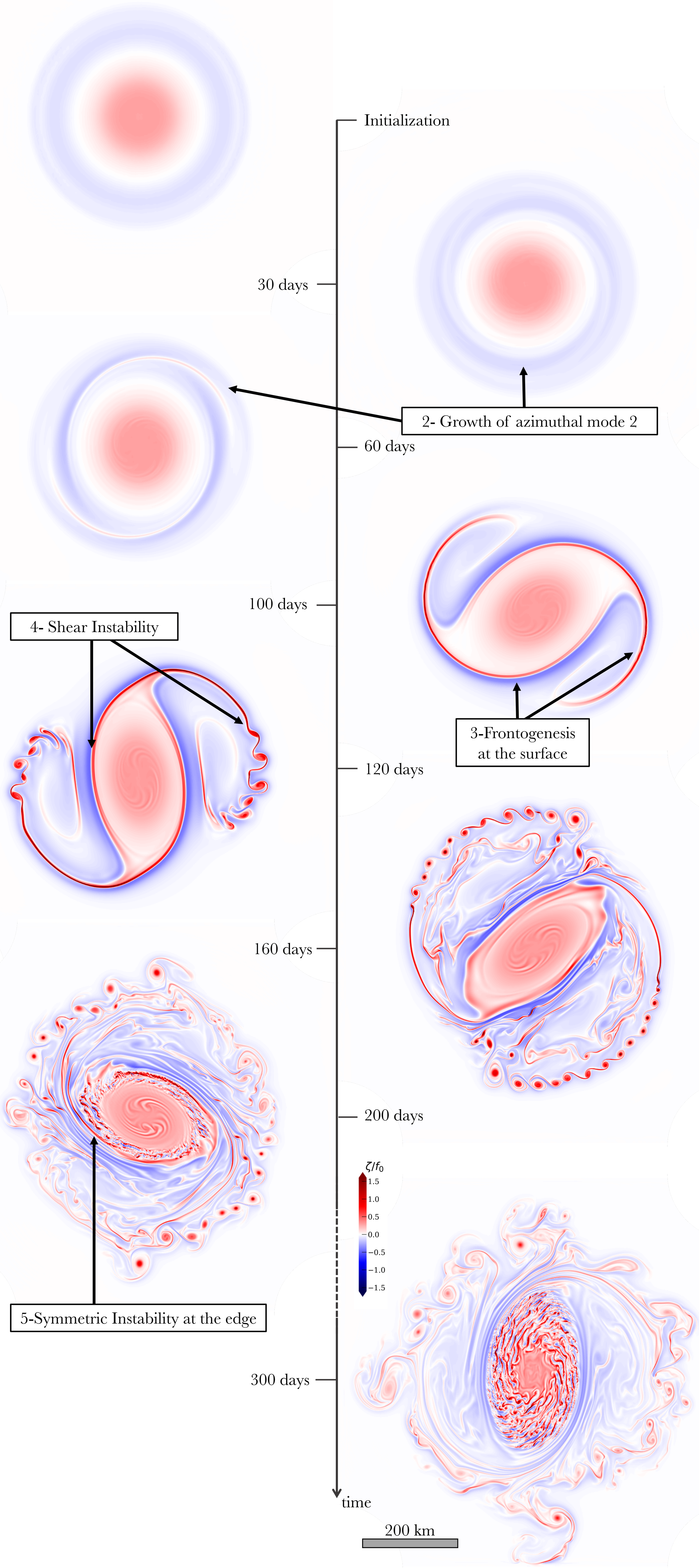

Fig. 6: Time evolution of the surface relative vorticity, from the CROCO simulation (dx=500 m)

2- Growth of azimuthal mode 2

During the first 100 days of the simulation, the eddy destabilizes, with a domination of the even azimuthal modes. Mode 2 is the most unstable and grows linearly from t=40 to t=90 days.
The study of radial PV gradients indicates that the eddy is unstable with respect to a mixed Barotropic/Baroclinic instability.

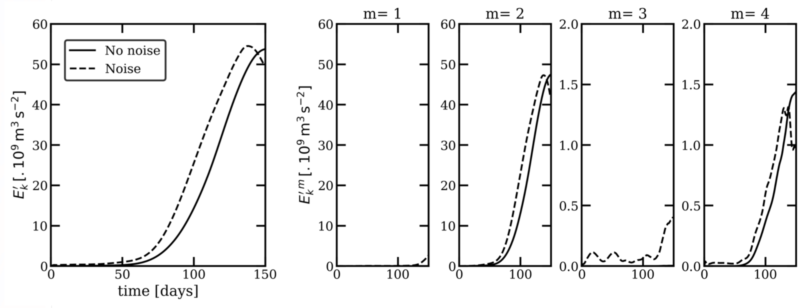

Fig. 7: Time evolution of the perturbation kinetic energy. The left panel shows the total kinetic energy while the panels on the right show the kinetic energy of the four first normal modes.

4- Shear Instability

In the two spiral arms and at the edge of the eddy, the steep PV gradients create suitable conditions for Shear instability. The instability then develops forming rows of Submesoscale Vortices surrounding the eddy.

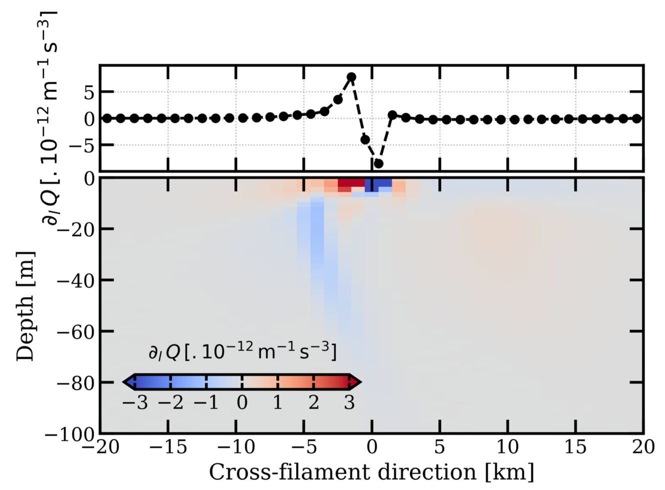

Fig. 9: Mean derivative of the PV along the cross filament direction at the surface (top) and in the first 100 meters (bottom).

Conclusion:

The composite cyclone extracted in the NEAS is unstable.
After 300 days of simulation, it evolved into a tripole with an eroded elliptic core and Submesoscale Vortices around it.
Using a realistic shape for this study allows to illustrate the predominance of numerous types of instabilities in geophysical flows.

In areas where the eddy activity dominates the circulation, isolated eddies can generate small scale (O(<10) km) features: Submesoscale Vortices and intense fronts.
These features then modify the transport of water masses and can impact locally the biological activities in the water column.

Reference: [12]de Marez *et al.* Destabilization of a large realistic Cyclonic Eddy. *In prep. for Ocean Modelling.*; [13]Shchepetkin *et al. Ocean Modelling* **9**, 347–404 (2005).