Study of the stability of a large realistic cyclonic eddy

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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]. Mesoscale eddies are deep-reaching and therefore also impact the spreading of the dense salty water masses outflowing at intermediate depth from the adjacent marginal seas, *viz* the Persian Gulf and the Red Sea.[5,6]

- **The 3D structure of mesoscale eddies has been estimated using a composite approach[7]. This composite structure is shown to be representative of the mesoscale eddies sampled by *in situ*, altimetric, and autonomous platform measurements in the region.**

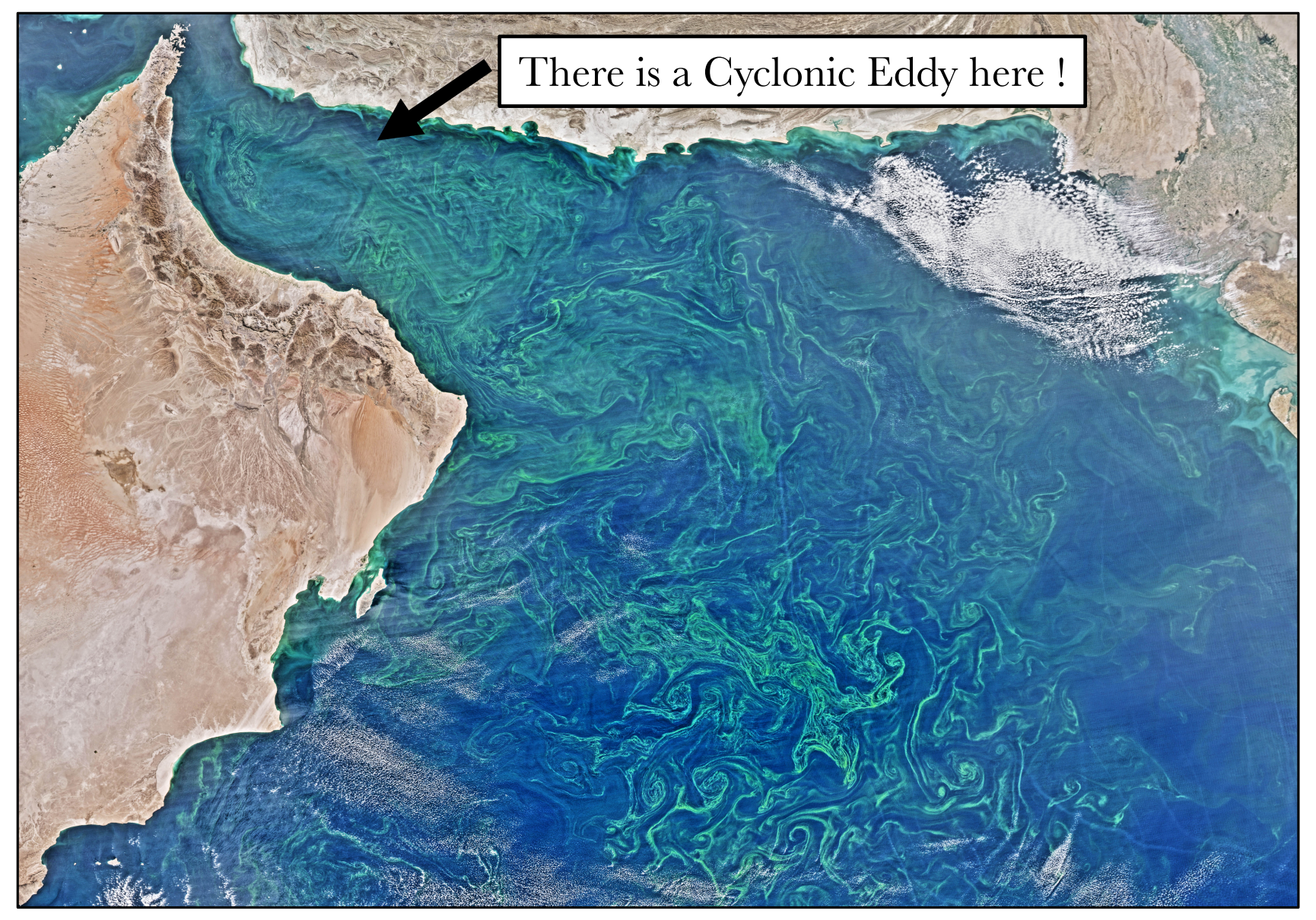

Fig. 1: Image of the Gulf of Oman acquired February 14, 2015 by the MODIS system on NASA's Aqua satellite (250m horizontal resolution), showing swirling patterns of ocean chlorophyll (NASA Earth Observatory)

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]de Marez, C. *et al.* On the 3D structure of eddies in the Arabian Sea. *Deep Sea Research Part I* (2019).

Numerical setup

We investigate the stability of a composite eddy[8], by running a high resolution hydrostatic primitive equation model initialized with a composite cyclone extracted in the Arabian Sea
→ **Contrary to previous stability studies we do not use analytical initial conditions**

We use the Coastal and Regional Ocean COmmunity model (CROCO)[9].
Horizontal advection terms for tracers and momentum are discretized with fifth-order upwind advection schemes (UP5); the horizontal viscosity and diffusivity are set to zero, the vertical advection is discretized with a Splines scheme; the vertical closure is done using a K-profile parameterization (KPP)

The model is integrated for 1 year 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).
The background stratification is the ambient stratification in the Arabian Sea.

Reference: [8]de Marez *et al.* Study of the stability of a large realistic cyclonic eddy. *Ocean Modelling* (2020);
[9]Shchepetkin *et al. Ocean Modelling* **9**, 347–404 (2005).

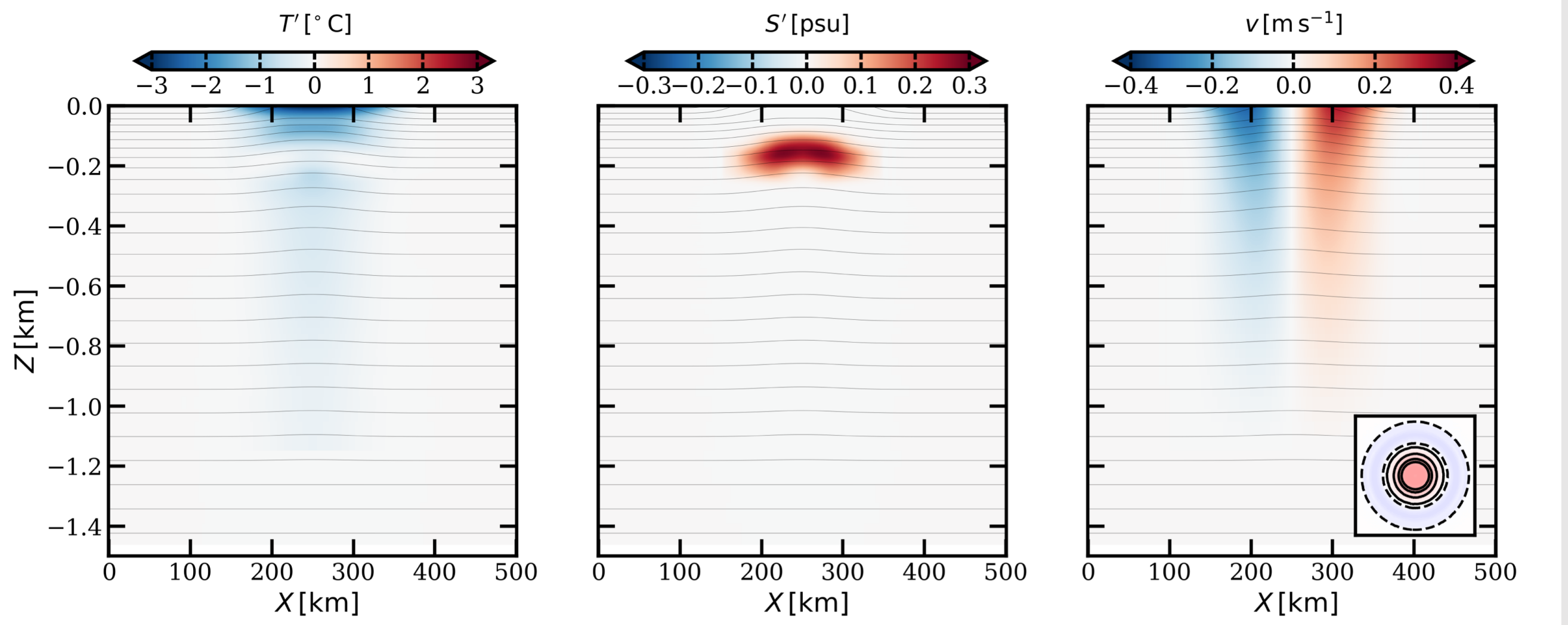

Fig. 2: Vertical sections at the center of the domain at initialization, showing the shape of the composite eddy. (left) Temperature anomaly, (middle) salinity anomaly and (right) meridional (south-north) velocity. Iso-density contours of the composite eddy are superposed in all panels. Insert in the right panel shows the -0.02, 0.02, 0.1, 0.2 and 0.25 dynamic Rossby number contours at the surface.

Overall course of the simulation

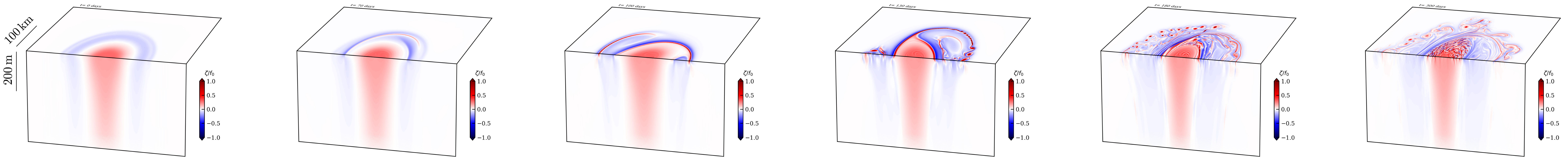

Fig. 3: Evolution of the composite eddy throughout the year of simulation: 3D snapshots of the normalized relative vorticity at t=0, 70, 100, 130, 180, and 300 days. Notice that the z-scale is very stretched to show the depth extension of the near-surface dynamics.

Primary instability

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 energy transfer terms indicates that the eddy is unstable with respect to a mixed barotropic/baroclinic instability.

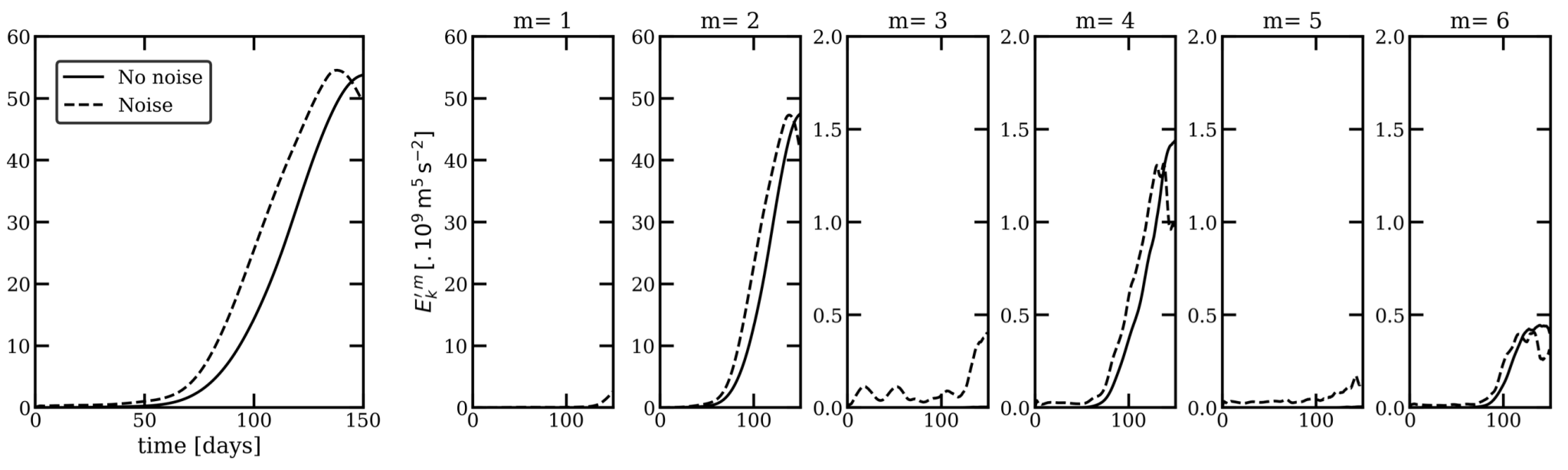

Fig. 4: Time evolution of the perturbation kinetic energy. The left panel shows the total kinetic energy while the panels on the right show the kinetic energy of the six first normal modes.

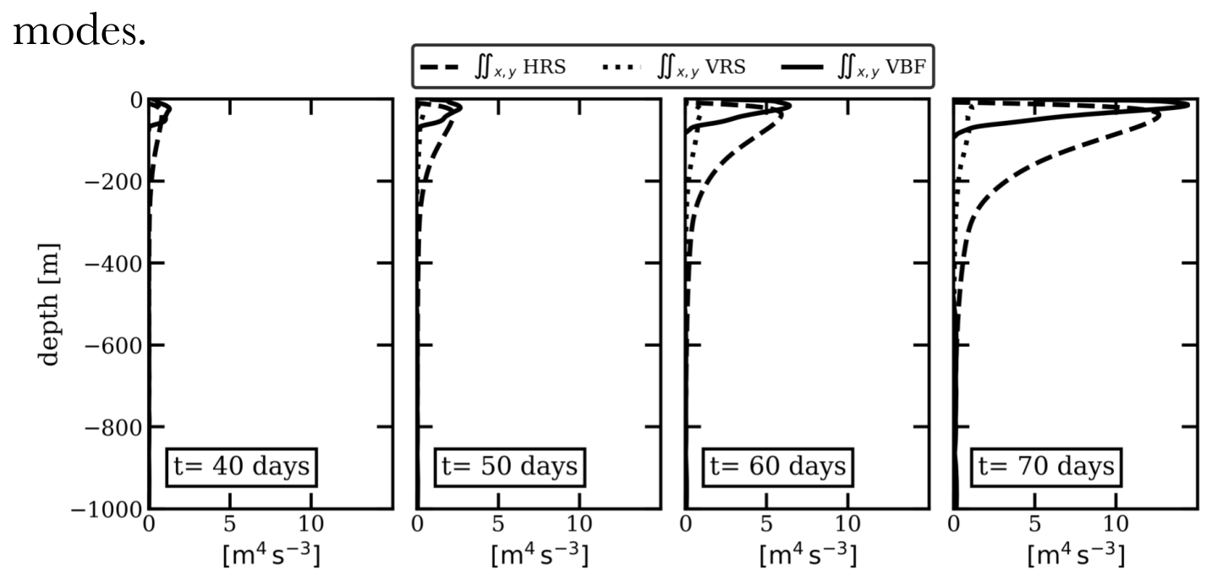

Fig. 5: Profiles of energy transfer terms integrated on the horizontal. HRS, VRS, and VBF stand for Horizontal Reynolds Stress, Vertical Reynolds Stress, and Vertical Buoyancy Flux.

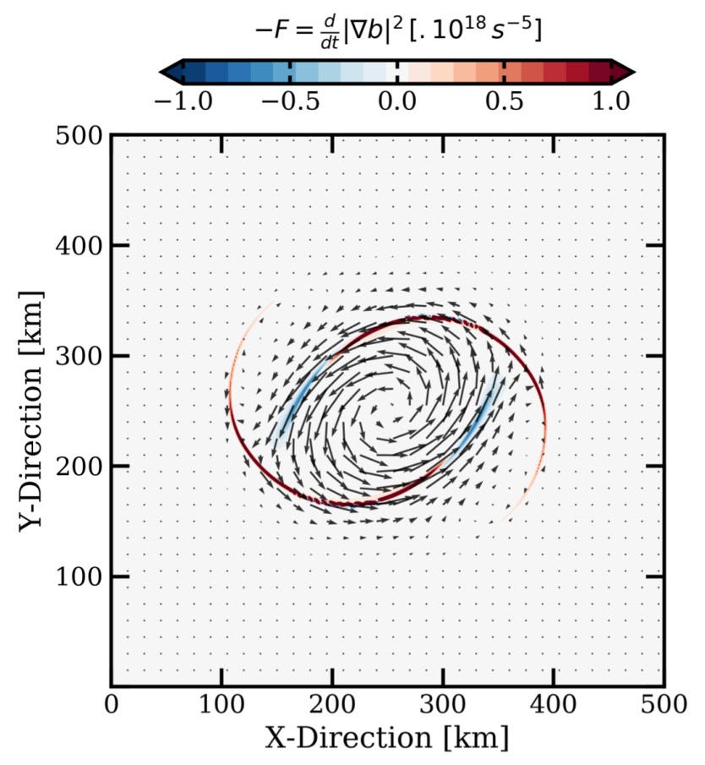

Fig. 6: Snapshot at t=100 days of Frontogenesis function at the surface. Black arrows indicate the surface horizontal velocity.

As the radial component of the velocity perturbation grows, spiral arms wrap around the eddy. 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 and in the spiral arms.

Secondary instabilities

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.

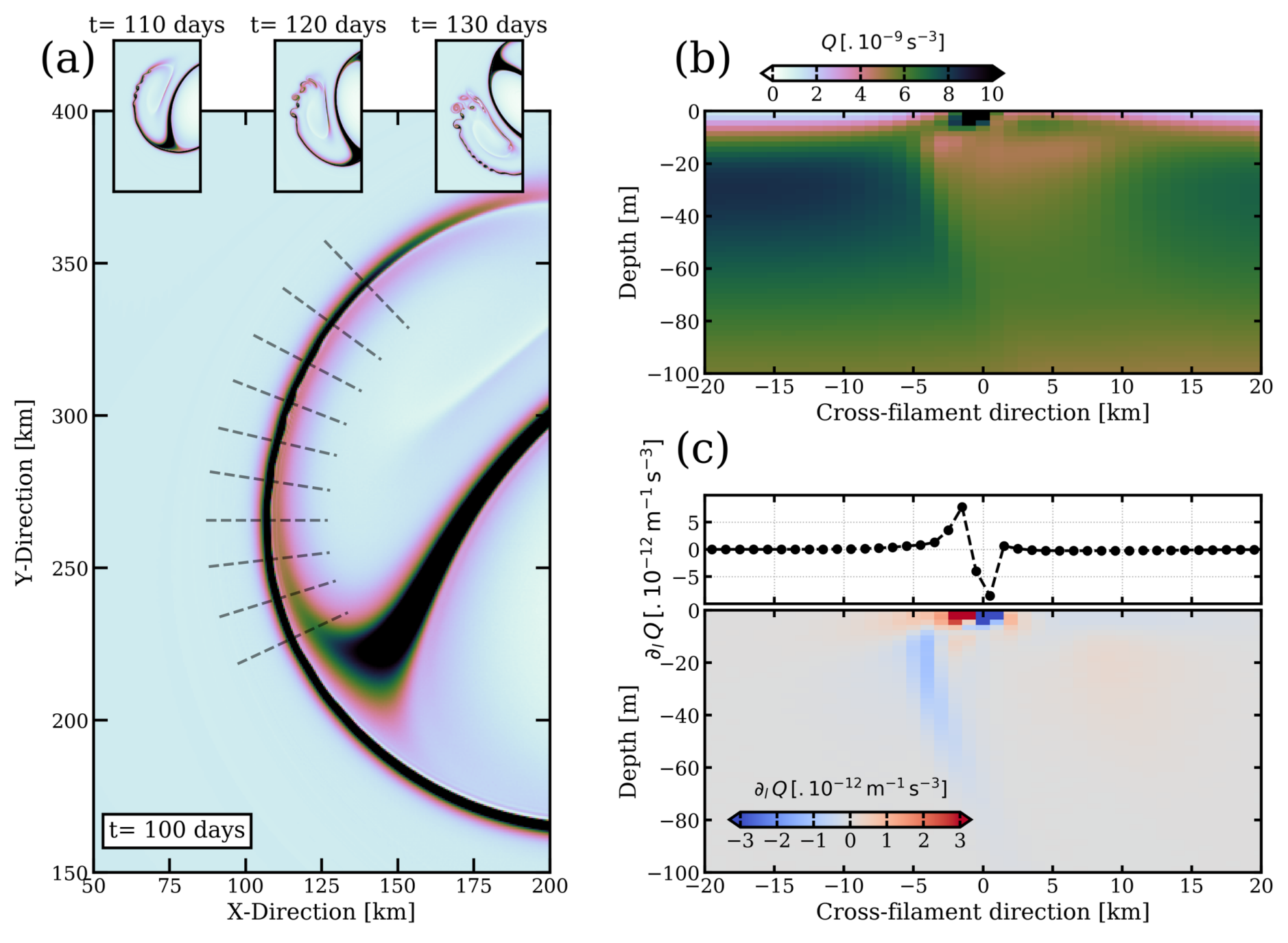

Fig. 7: (a) Snapshots of surface PV. The domain shown is the western part of the eddy. (b) Mean vertical section of PV computed using 10 sections perpendicular to the spiral arm at t= 100 days. (c) Derivative of the PV along the axis of the section, at the surface (top), and in the first 100 meters (bottom).

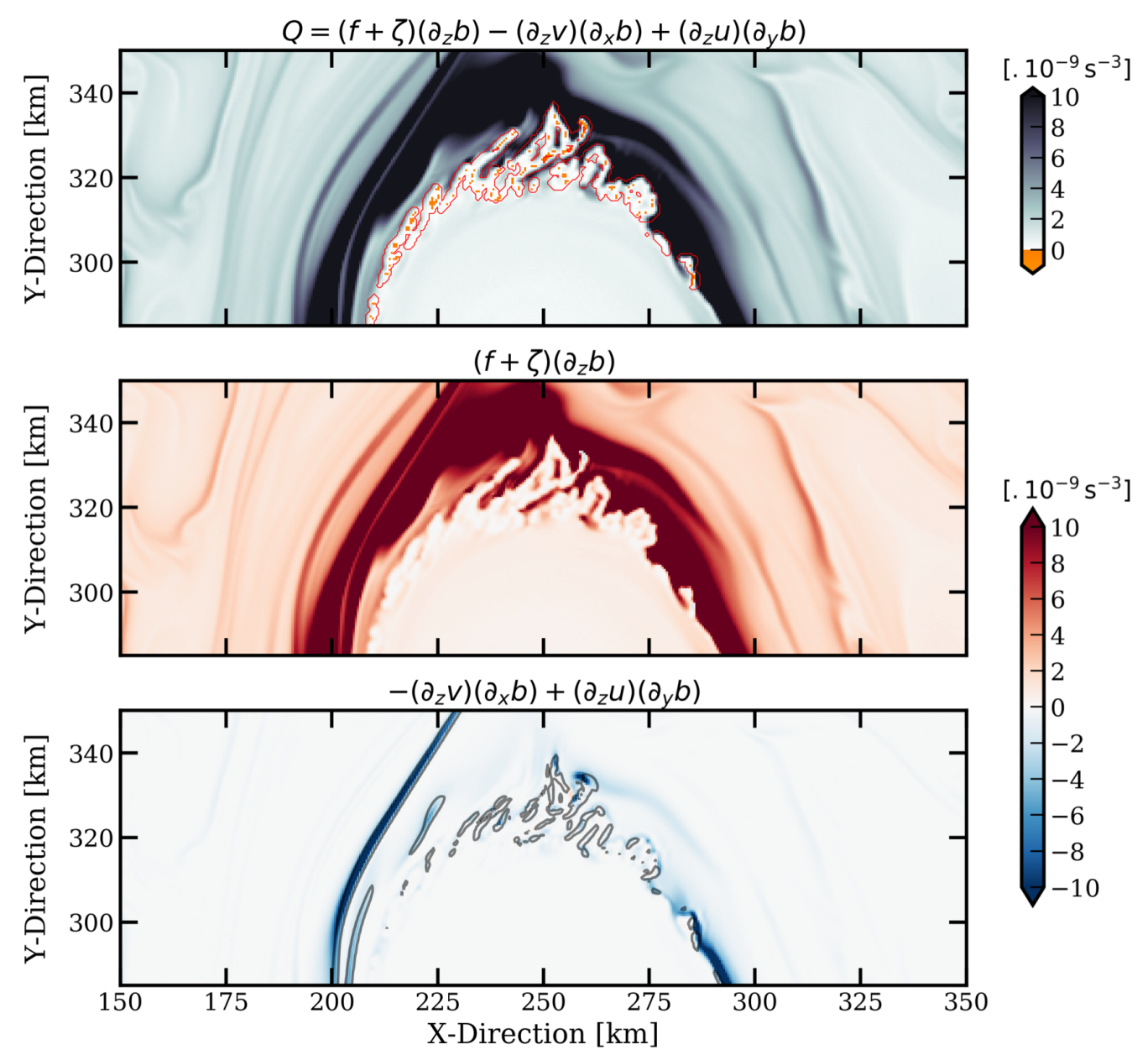

Fig. 8: Decomposition of the PV at t=180 days. (top) PV at the surface; the red dashed lines indicate places where the criterion for SI to occur $Ri < Ri_c$ is respected. (middle) First term of the PV. (bottom) Second and third terms of the PV; grey thin lines are contours of $-F = 10^{-18}\ s^{-5}$.

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.

Conclusion

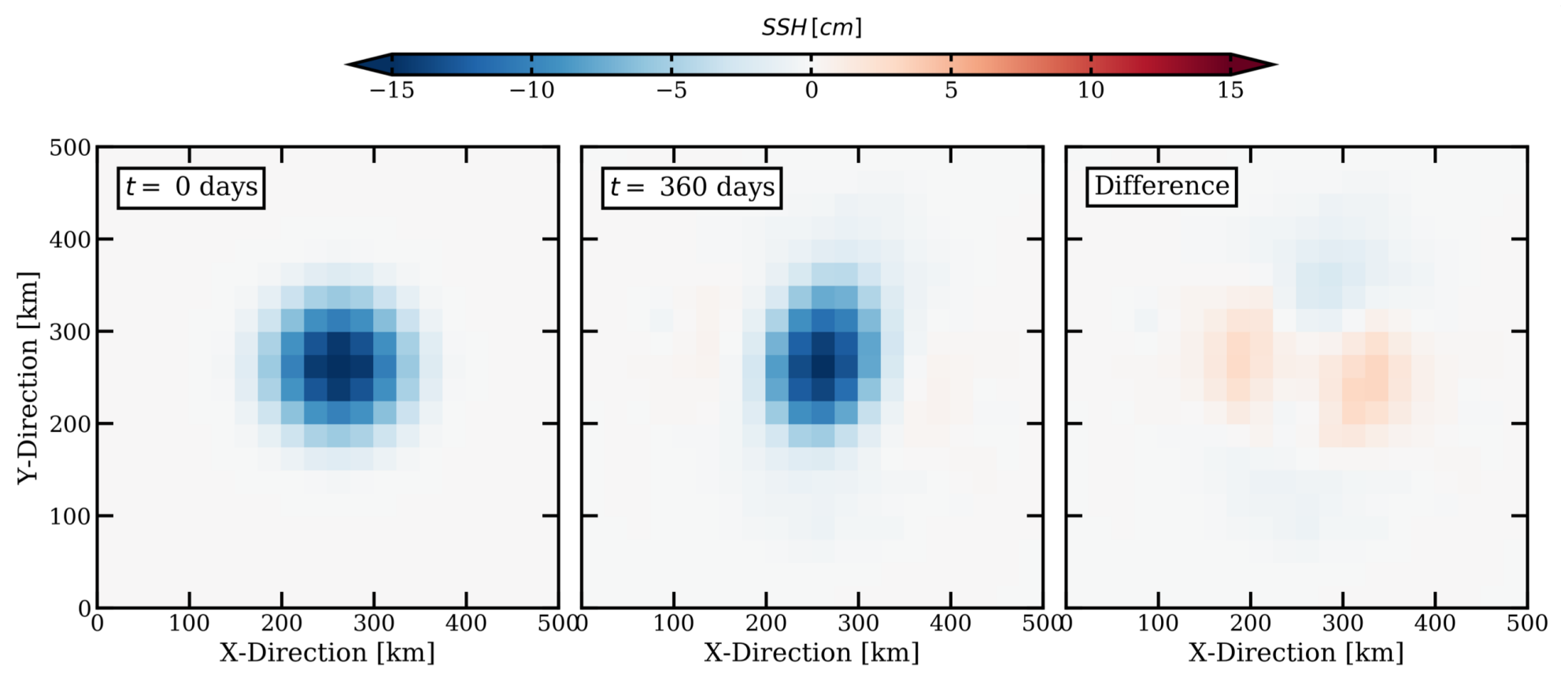

Fig. 9: SSH signature of the eddy at initialization (left), at the end of the simulation (t= 360 days) (middle), and the difference between the two. The resolution of the plot is downgraded to the same resolution as the altimetric product used to generate the composite eddy.

Despite the instabilities, the eddy is not destroyed and remains a large-scale coherent structure for the last 6 months of the simulation.

Looking at Sea Surface Height (SSH) and azimuthal averages of the eddy's final state , the composite eddy evolves little, and fairly represents the eddy observed in the altimetry which can live for several months[6]. The study of this simulation thus illustrates the numerous kinds of instabilities which may occur in large cyclonic eddies but can not be captured directly by altimetric or *in situ* data.

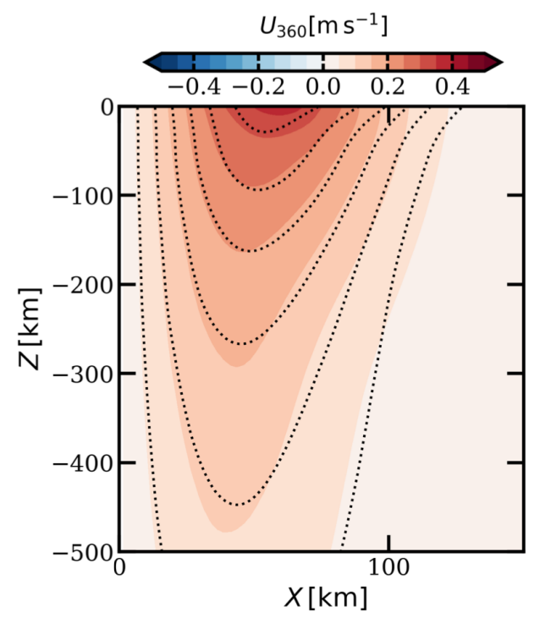

Fig. 10: Azimuthal averages of the final state azimuthal velocity (color contours), and same contours for the initial state (black dashed contours).