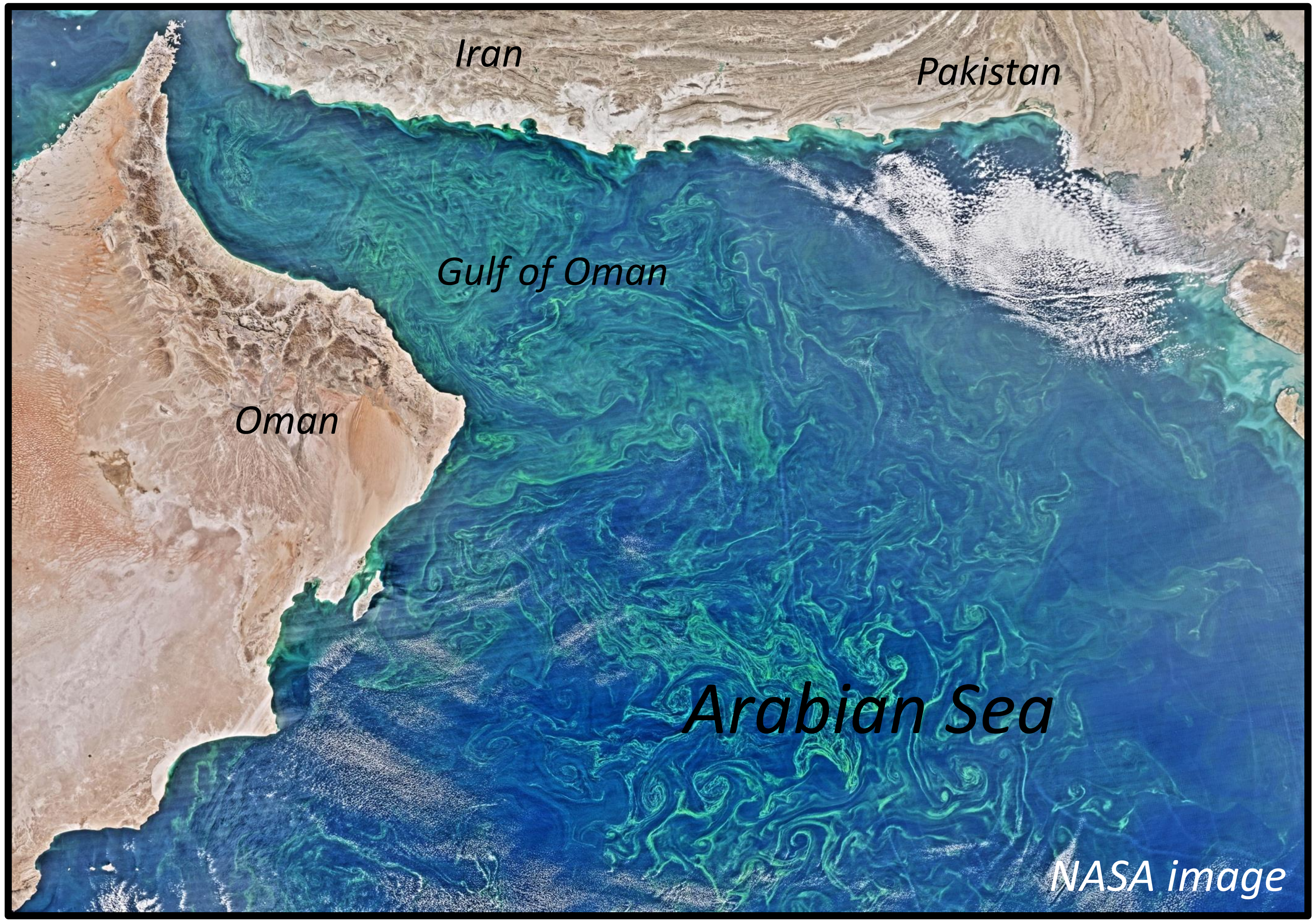
Dynamics of (sub)meso-scale structures in the Arabian Sea

Charly de Marez



PhD Thesis funded by DGA

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Thomas Meunier

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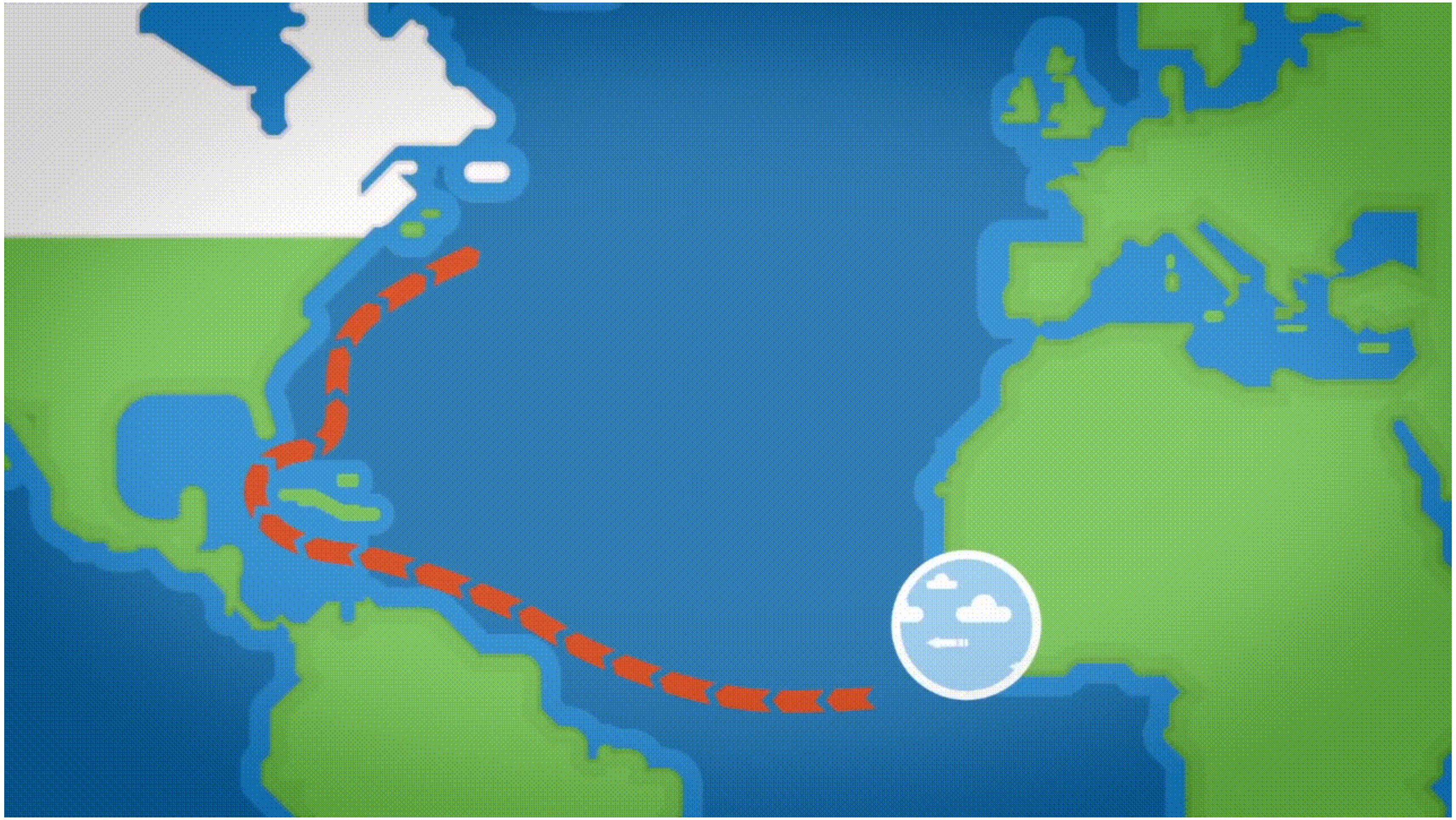
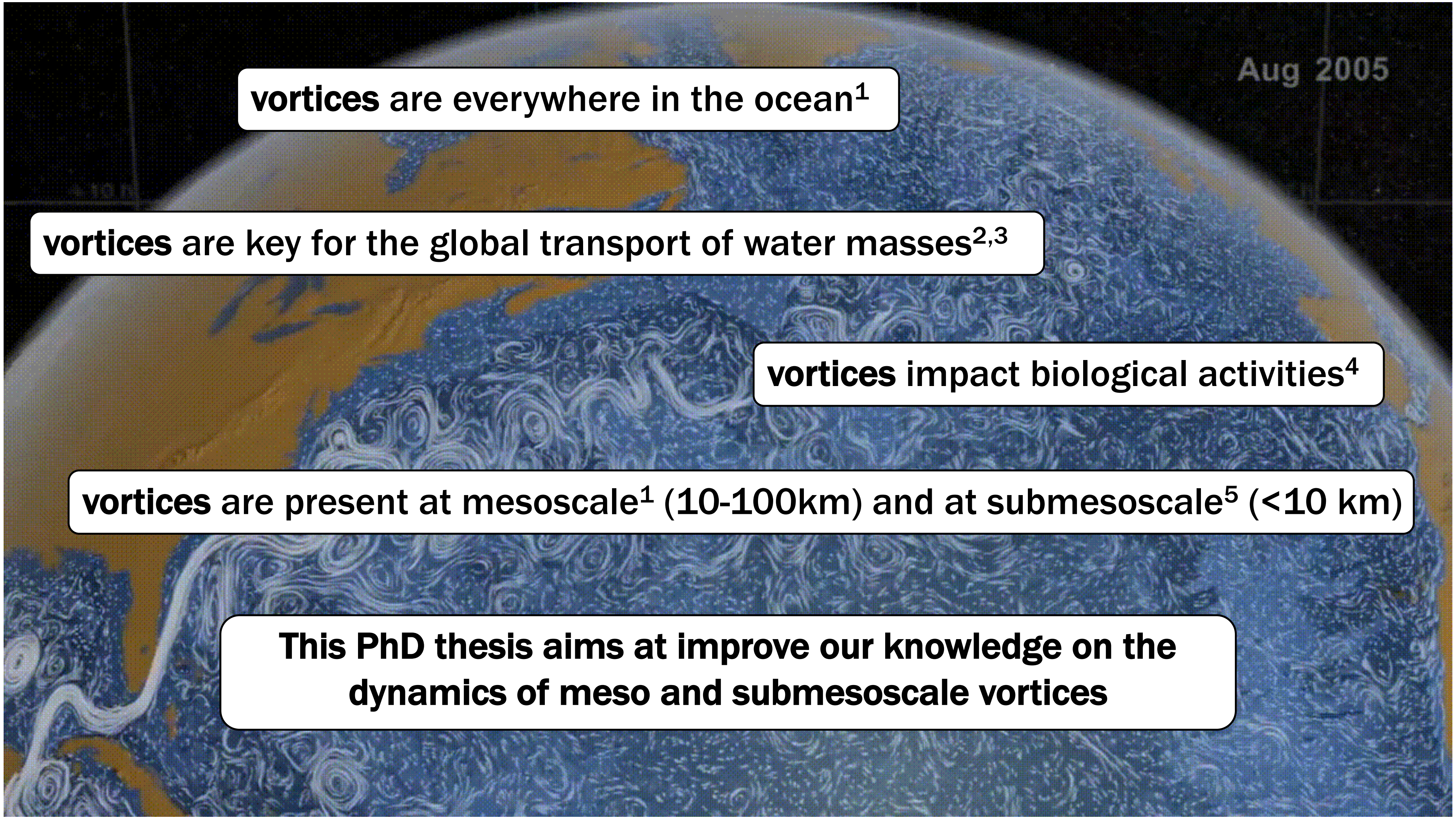


”The Gulf Stream explained” by Kurzgesagt (Youtube)



vortices are everywhere in the ocean[1]

vortices are key for the global transport of water masses[2,3]

vortices impact biological activities[4]

vortices are present at mesoscale[1] (10-100km) and at submesoscale[5] (<10 km)

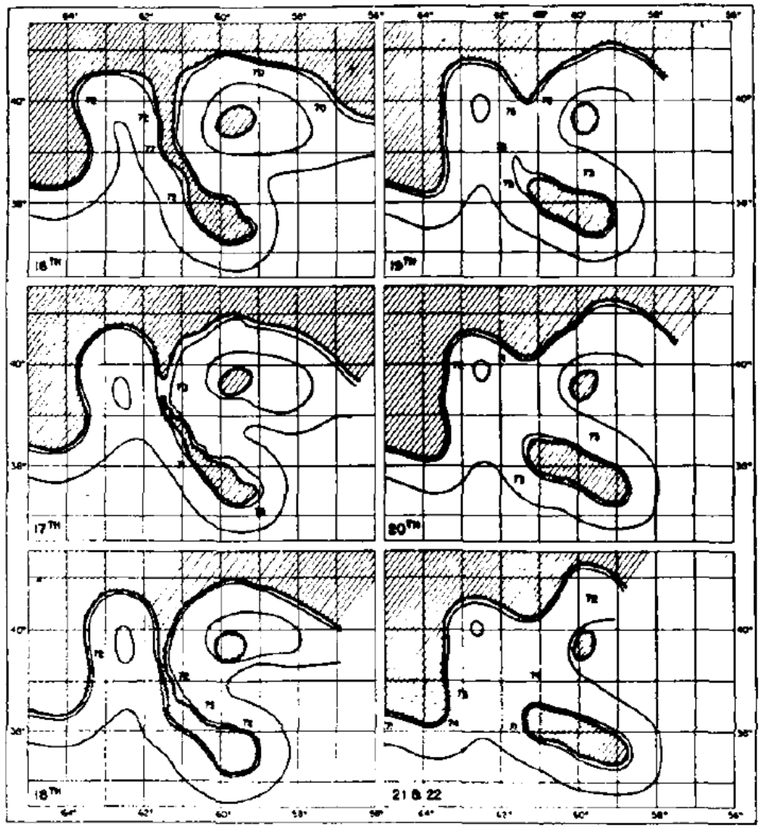
This PhD thesis aims at improve our knowledge on the dynamics of meso and submesoscale vortices

Surface currents in a high resolution simulation of the Earth's oceans (svs.gsfc.nasa.gov)

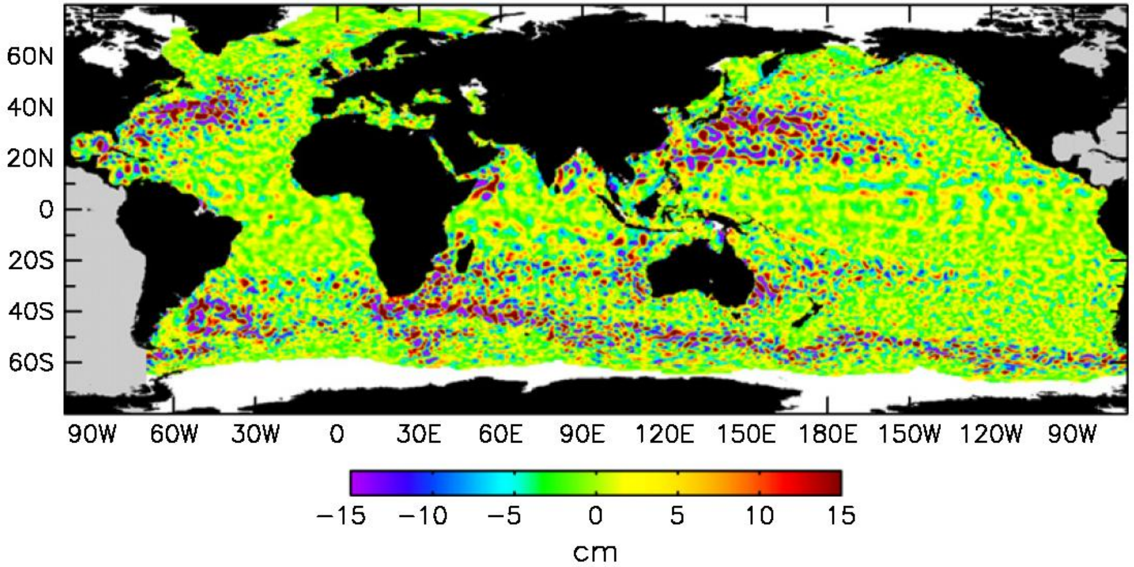
[1]Chelton 2011b; [2]Dong et al. 2014; [3]Zhang et al. 2014; [4]Chelton et al. 2014a; [5]McWilliams 2019

Context & Motivations

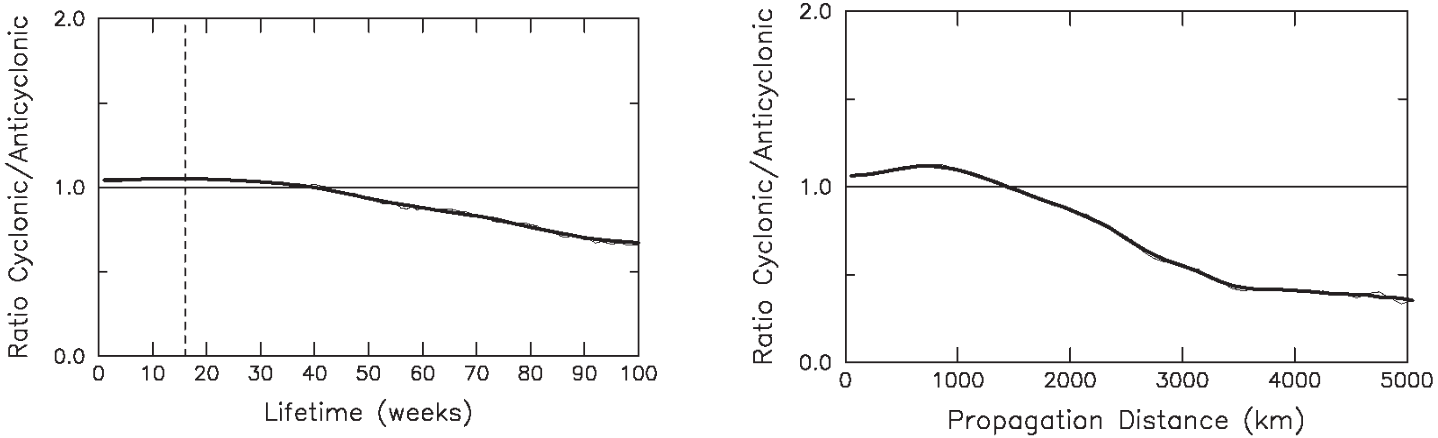
vortices



Observation of Edgar's formation in 1950[1]



Sea Surface Height on 28/08/1996[2]

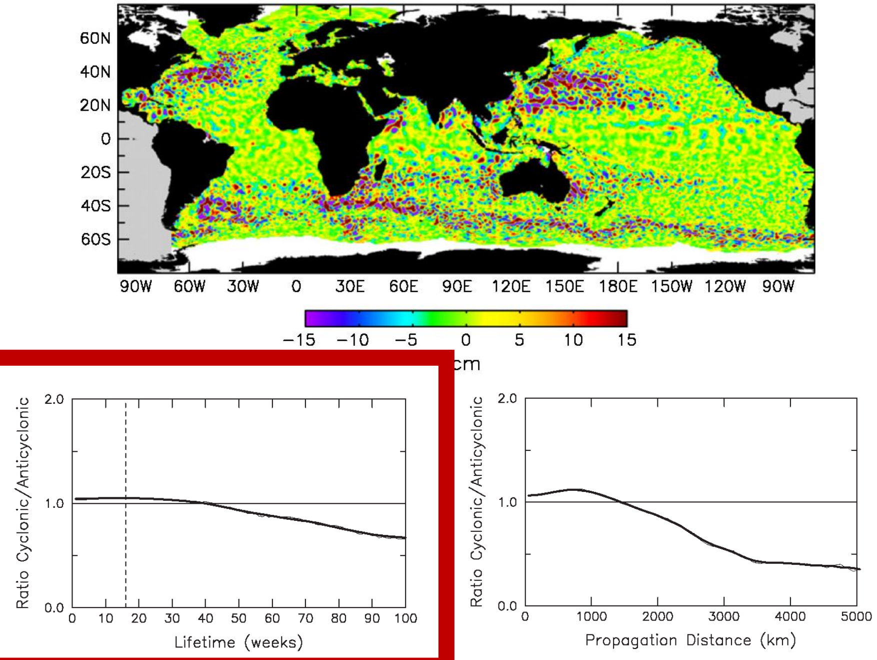


Lifetime (left) and propagation distance (right) of oceanic vortices from SSH observations[2]

[1]Fuglister & Worthington 1951; [2]Chelton 2011b

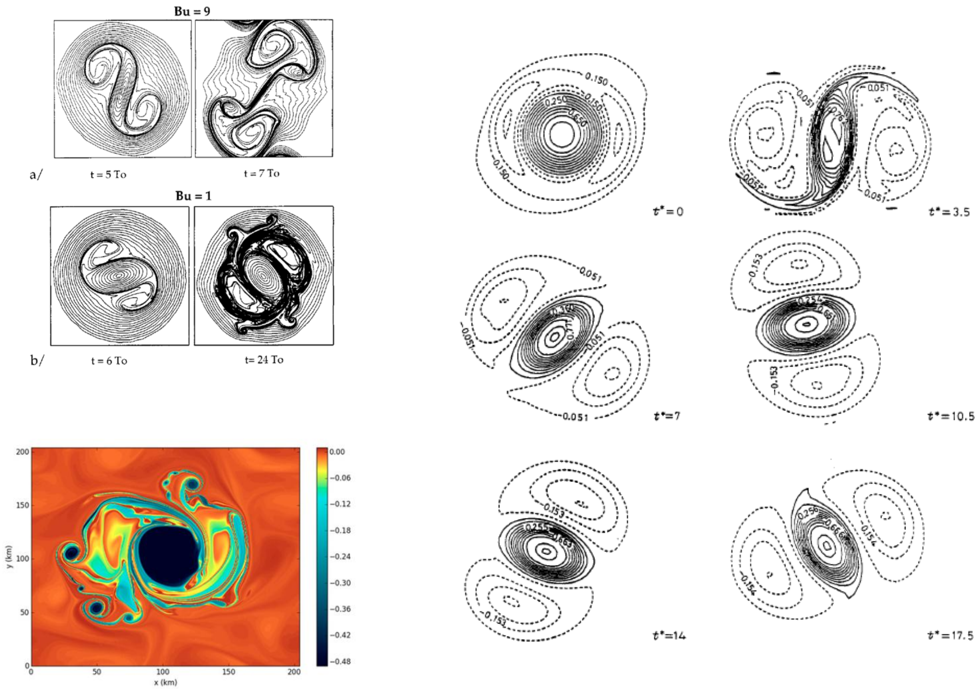
Context & Motivations

vortices lifetime stability



Sea Surface Height on 28/08/1996 (top), lifetime (left) and propagation distance (right) of oceanic vortices from SSH observations[1]

The stability of vortices determines their lifetime



Examples of vortex stability studies[2,3,4] *that use numerical models to investigate the evolution of vortices when isolated*

[1]*Chelton 2011b;* [2]*Carton et al. 1989;* [3]*Stegner et al. 1999;* [4]*Menesguen et al. 2018*

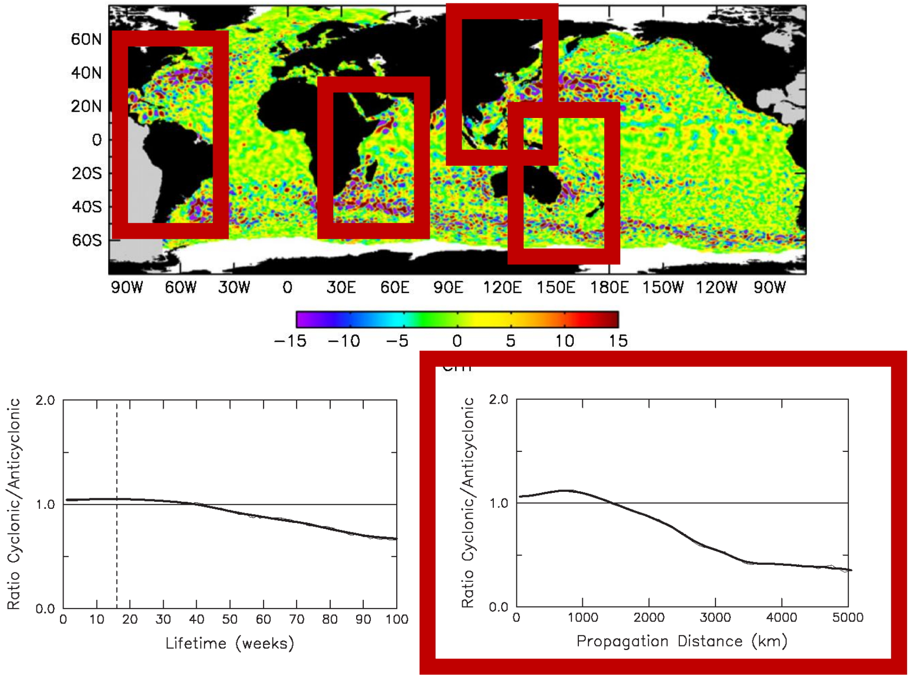
Context & Motivations

vortices

lifetime

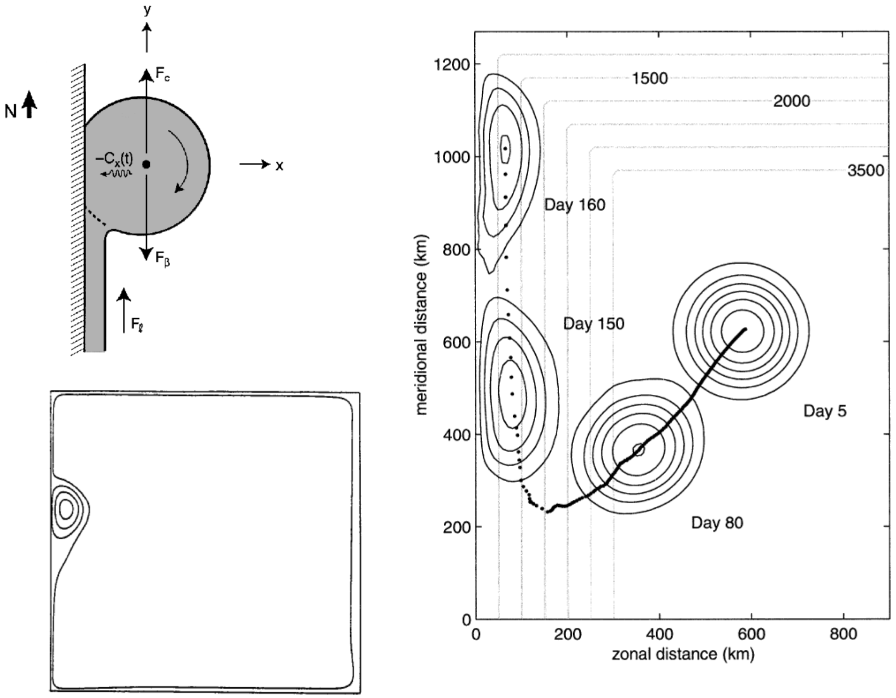
stability

Western boundary



Sea Surface Height on 28/08/1996 (top), lifetime (left) and propagation distance (right) of oceanic vortices from SSH observations[1]

Vortices eventually end their journey on western boundaries because of the β-effect

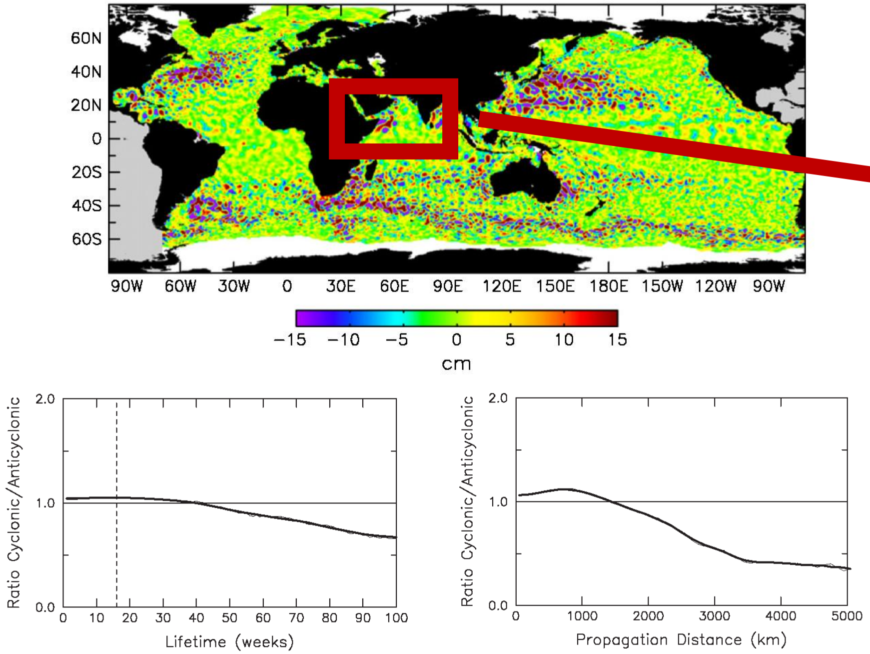


Examples of vortex-wall interaction on the β-plane studies[2,3,4]

[1]Chelton 2011b; [2]Shi & Nof 1993; [3]Nof 1999; [4]Sutyrin 2003

Context & Motivations

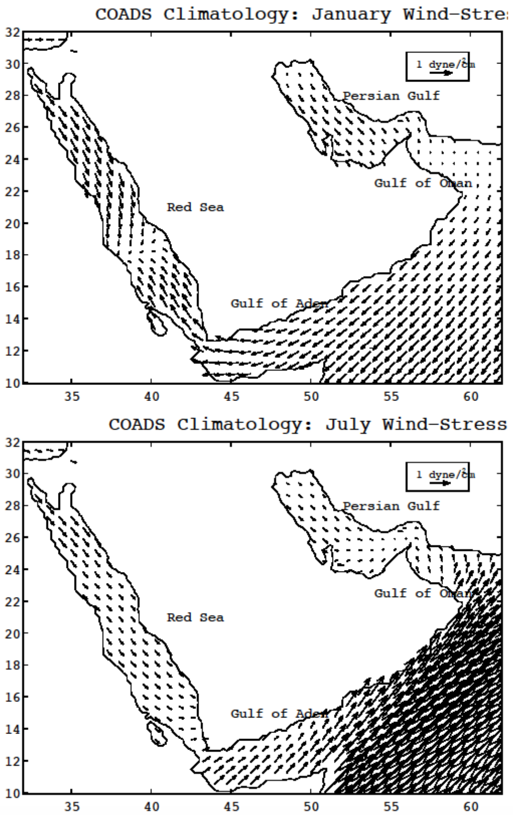
vortices lifetime stability Western boundary **Arabian Sea**



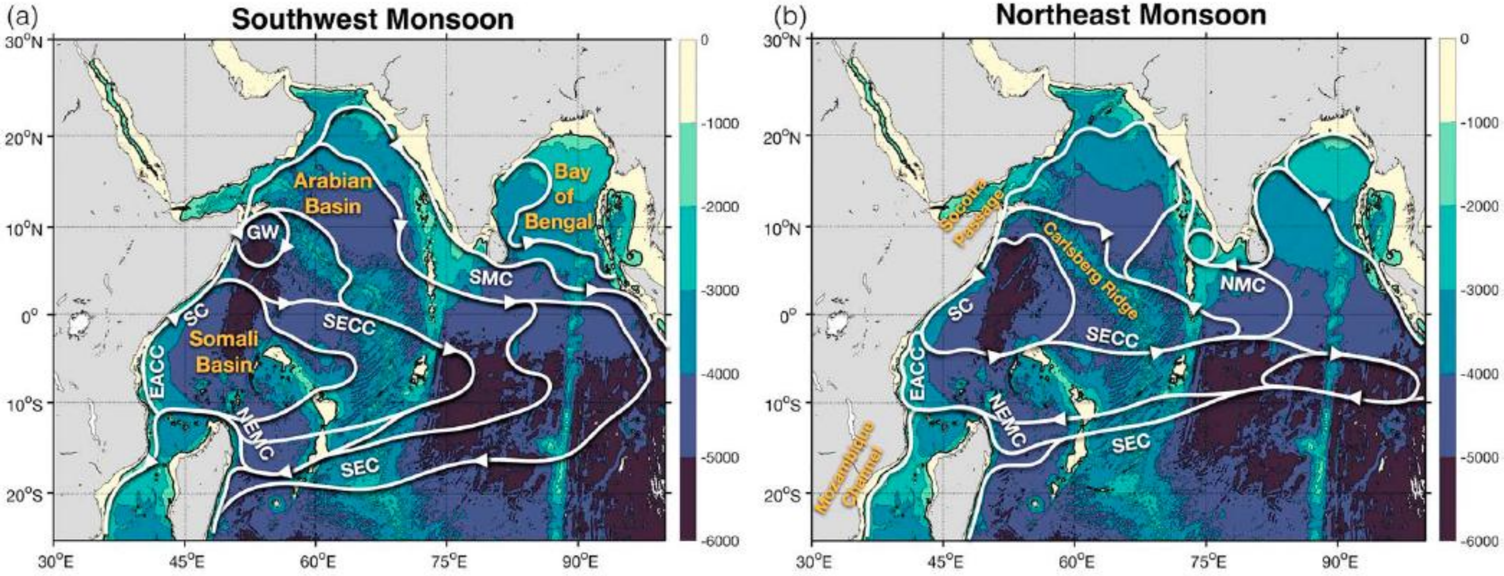
Sea Surface Height on 28/08/1996 (top), lifetime (left) and propagation distance (right) of oceanic vortices from SSH observations[1]

[1]*Chelton 2011b;* [2]*NASA Earth Observatory*

Context & Motivations



Monsoon wind regimes[1]



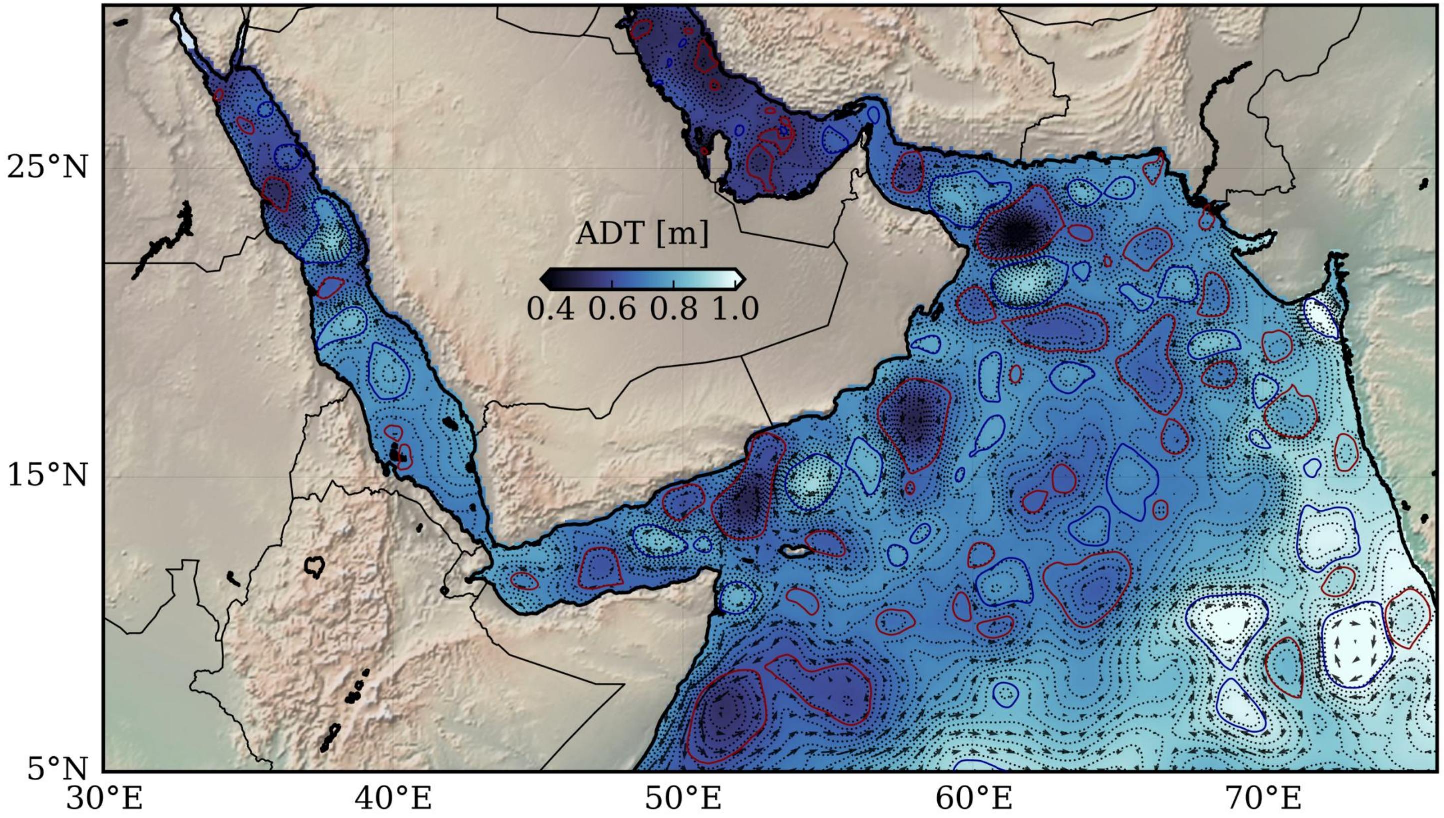
Basin-scale circulation of the Arabian Sea[2]

Instabilities of coastal currents and Rossby waves lead to the formation of mesoscale eddies in the whole Arabian Sea, throughout the year[3,4,5]

[1]*Arabian Marignal Seas and Gulfs, 1999 Report;* [2]*L'Hégaret et al. 2018;* [3]*Scharffenberg et al. 2010;* [4]*L'Hégaret et al. 2016;* [5]*Trott et al. 2018*

This PhD thesis

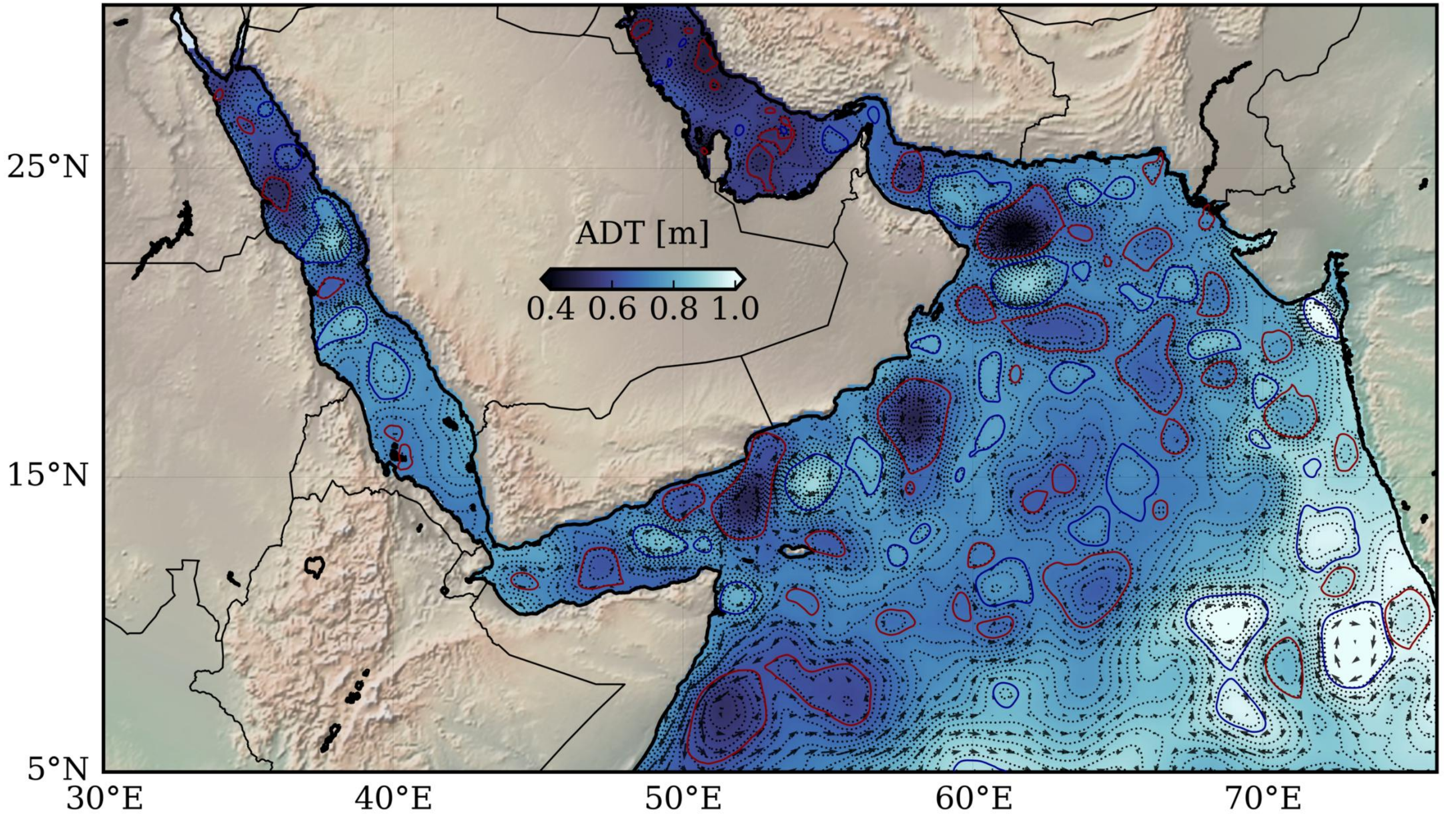
vortices lifetime stability Western boundary Arabian Sea



Altimetry on 18 February 2015; contours of cyclonic (red) and anticyclonic (blue) eddies detected from altimetry with a dedicated algorithm

This PhD thesis

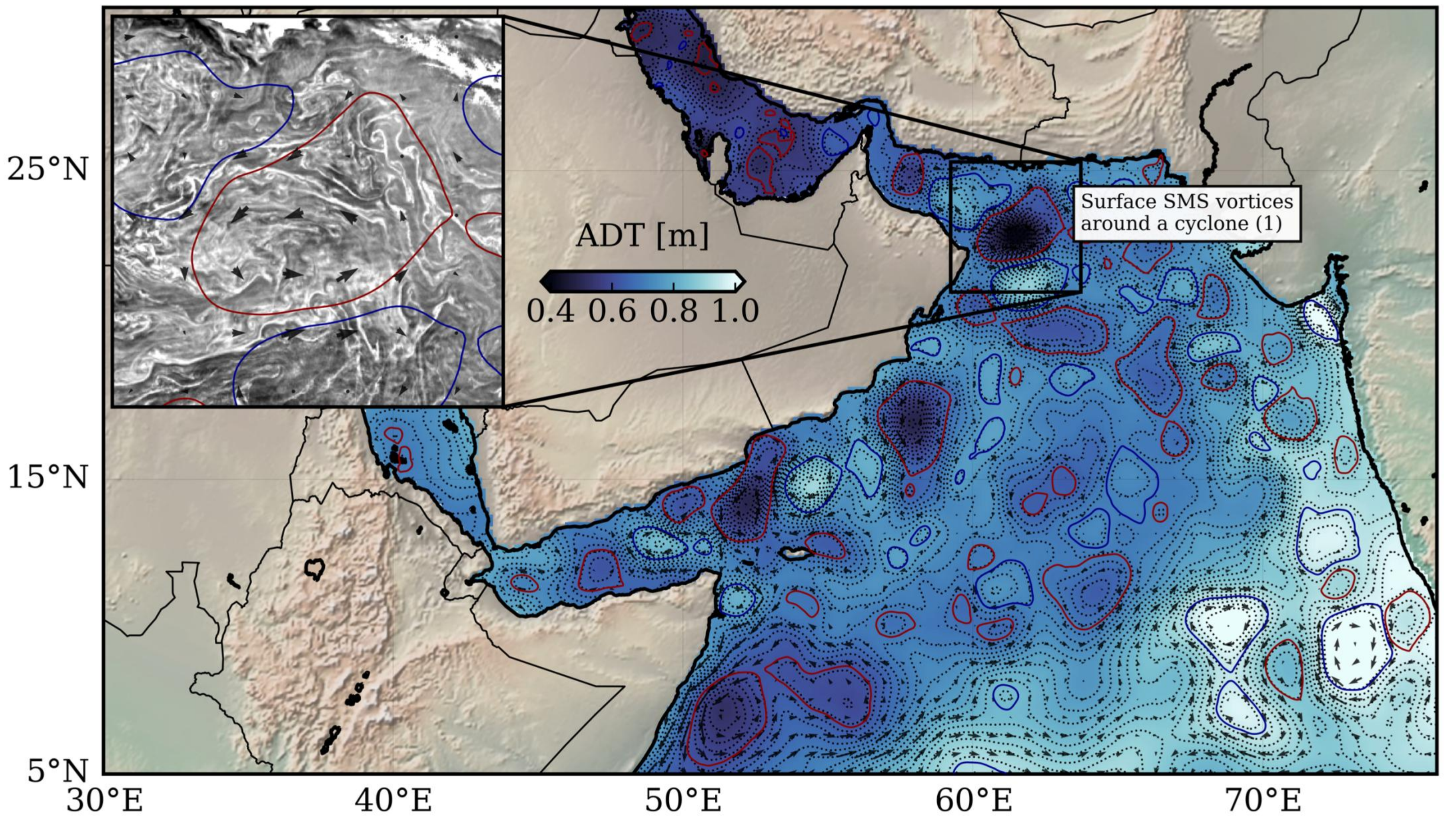
lifetime *stability* *Western boundary* *Arabian Sea*



Altimetry on 18 February 2015; contours of cyclonic (red) and anticyclonic (blue) eddies detected from altimetry with a dedicated algorithm

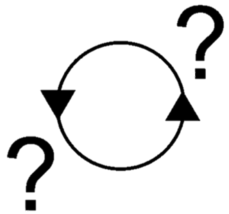
What is the 3D structure of the Arabian Sea eddies, as revealed by in situ data ?

This PhD thesis

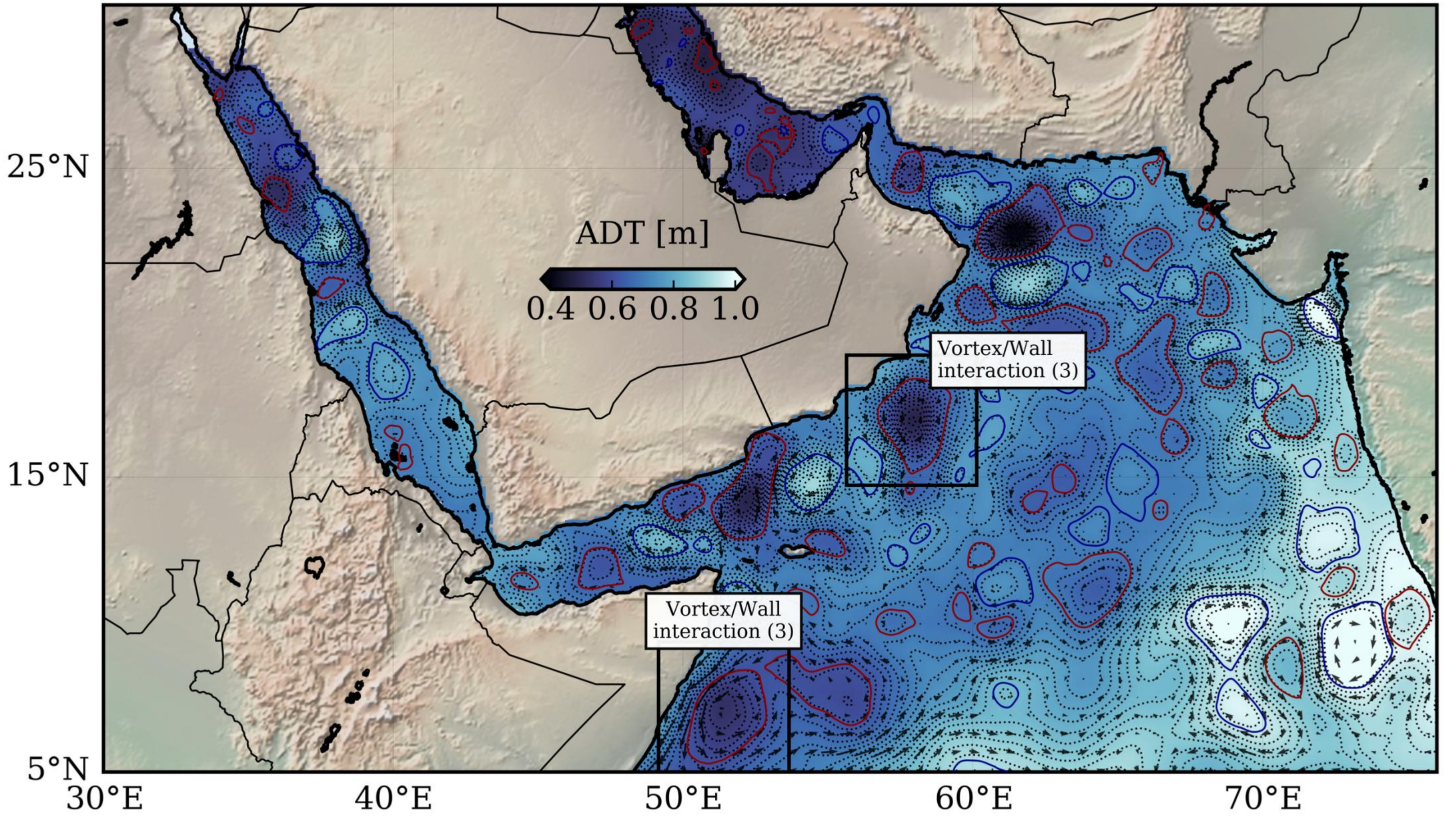


Altimetry on 18 February 2015; contours of cyclonic (red) and anticyclonic (blue) eddies detected from altimetry with a dedicated algorithm; insert shows true color image (NASA)

What are the stability characteristics of Arabian Sea eddies ? Can these latter explain the occurrence of surface Submesoscale features ?

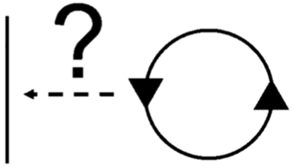


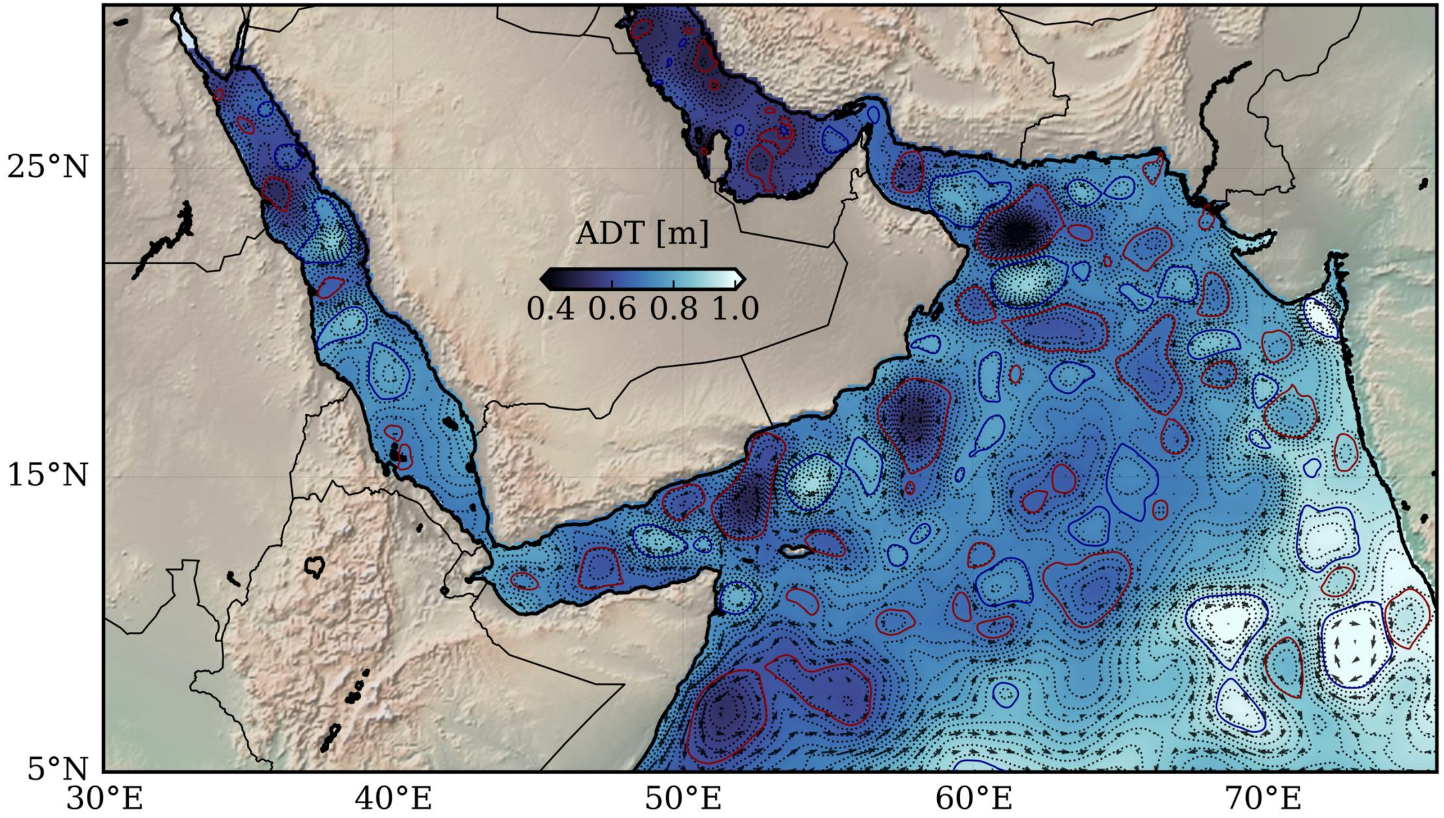
This PhD thesis



Altimetry on 18 February 2015; contours of cyclonic (red) and anticyclonic (blue) eddies detected from altimetry with a dedicated algorithm

What are the mechanisms involved in the interaction between mesoscale eddies and a western boundary ?





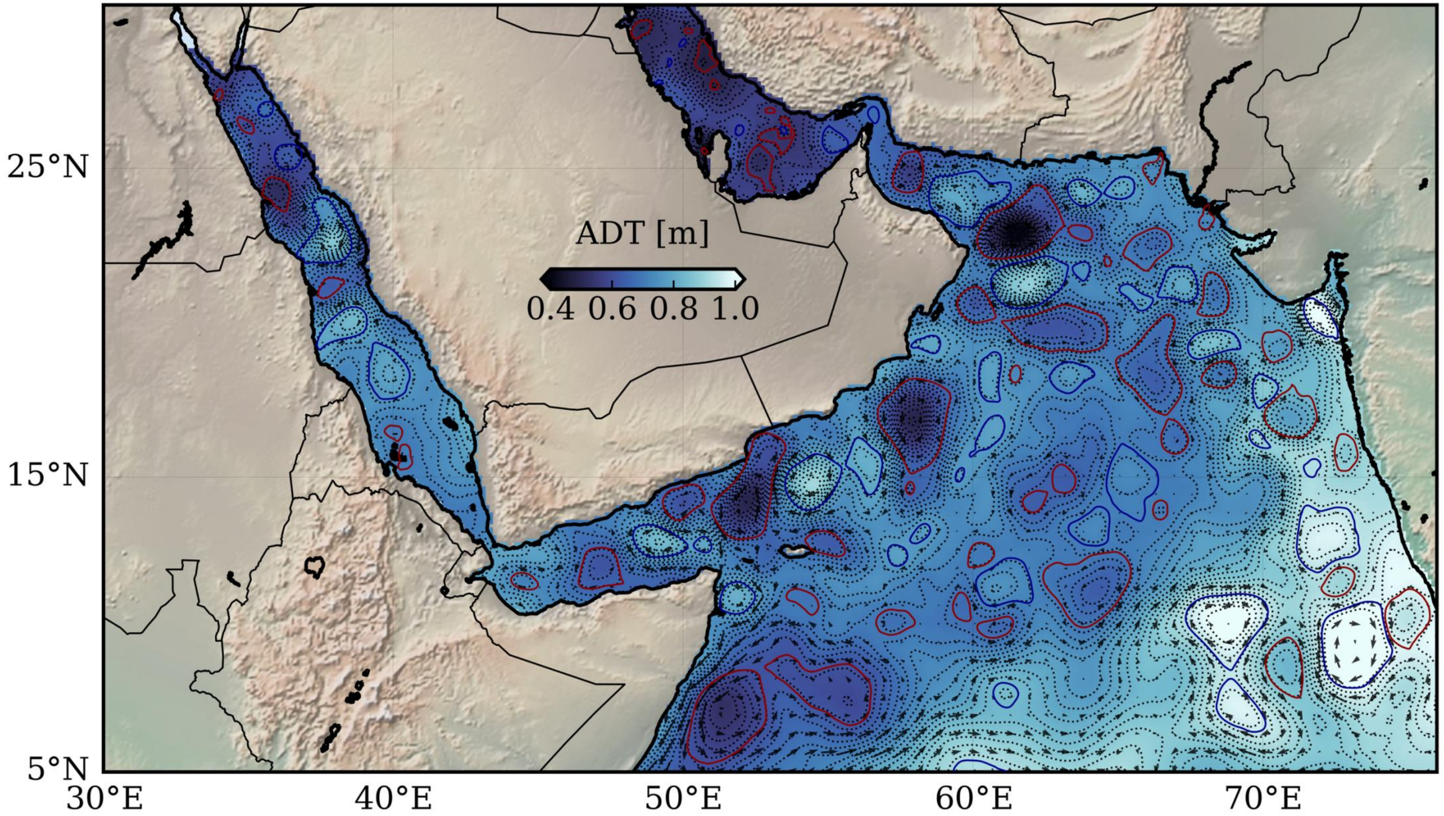
Altimetry on 18 February 2015; contours of cyclonic (red) and anticyclonic (blue) eddies detected from altimetry with a dedicated algorithm

1- What is the 3D structure of the Arabian Sea eddies, as revealed by in situ data ?[1]

2- What are the stability characteristics of Arabian Sea eddies ? Can these latter explain the occurrence of surface Submesoscale features ?[2]

3- What are the mechanisms involved in the interaction between mesoscale eddies and a western boundary ?[3,4]

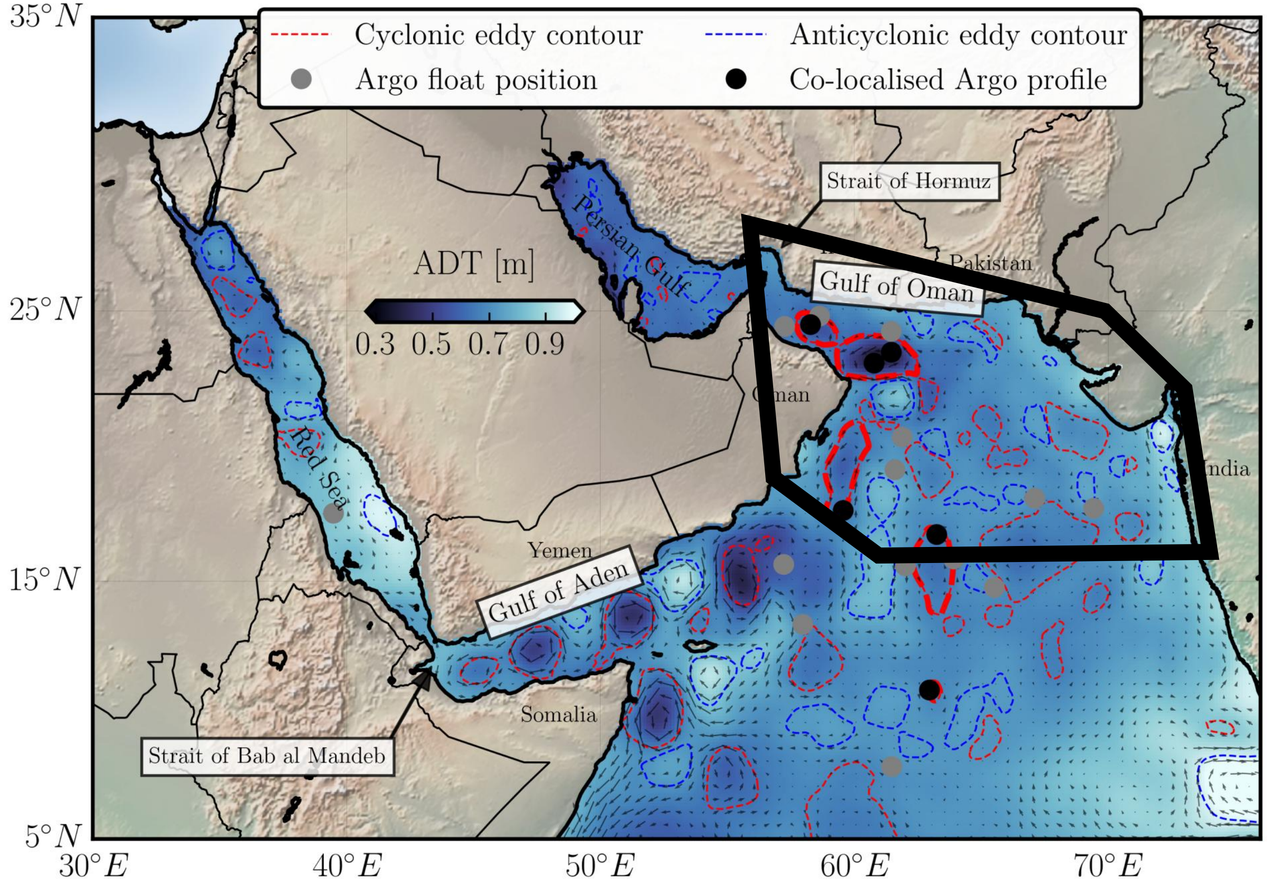
[1]de Marez et al. 2019, [2]de Marez et al. 2020a, [3]de Marez et al. 2020b, [4]de Marez et al. 2020c



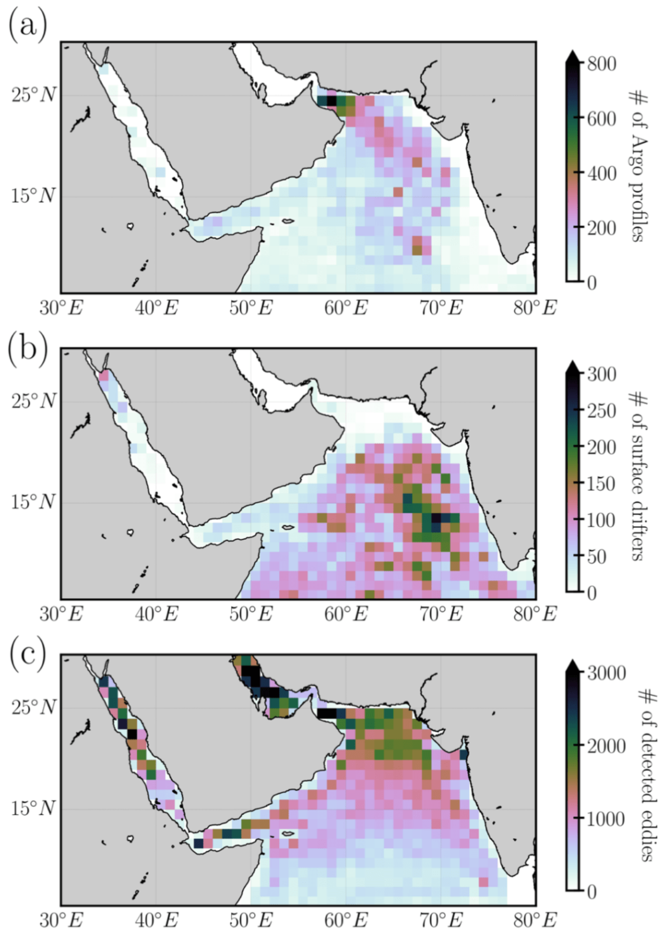
Altimetry on 18 February 2015; contours of cyclonic (red) and anticyclonic (blue) eddies detected from altimetry with a dedicated algorithm

1- What is the 3D structure of the Arabian Sea eddies, as revealed by in situ data ?[1]

[1]*de Marez et al. 2019*

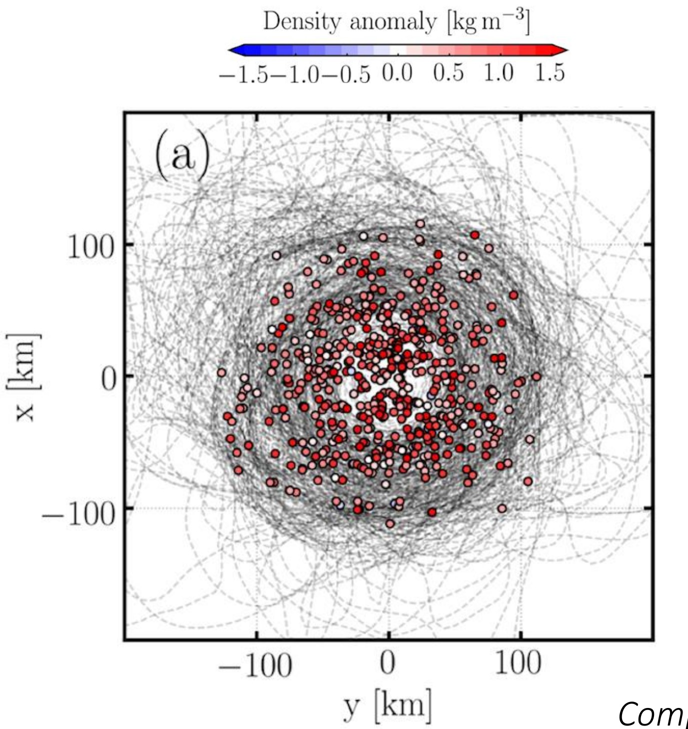


Snapshot of ADT from the altimetric product used for the detection of eddies. The contour of eddies from the eddy detection[1] (red and blue dashed lines), and the position of Argo Stations on the same date are superposed.

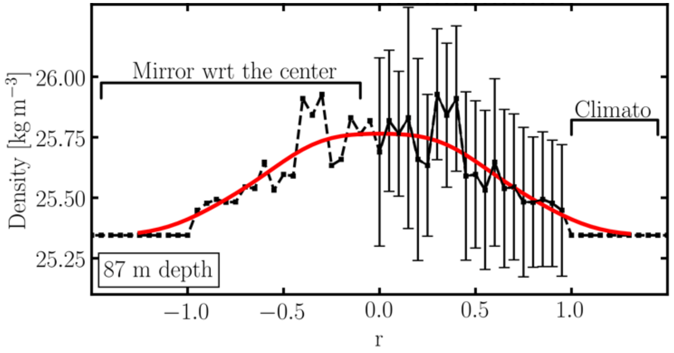


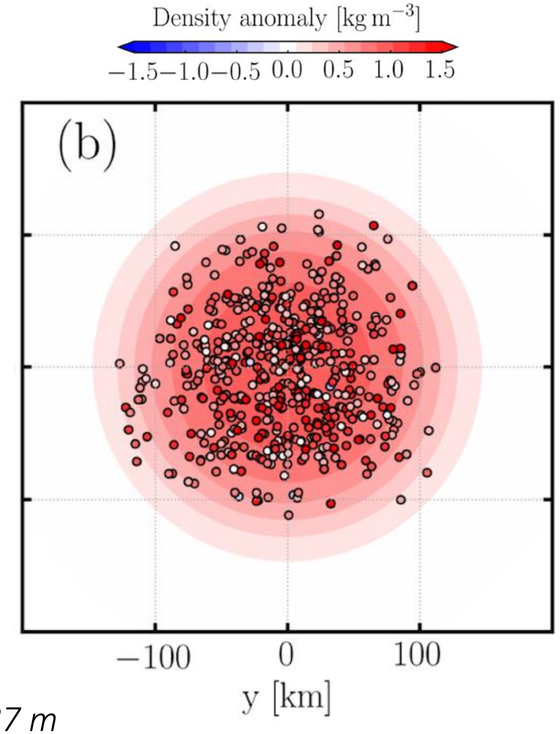
Distribution of the datasets used; (a) Argo profiles, (b) drifters data, (c) detected eddies.

[1]Le Vu et al. 2018



Composite approach[1]

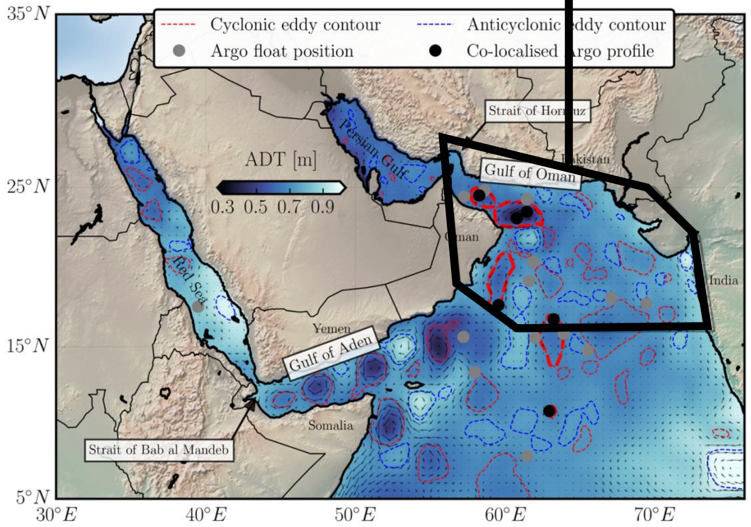




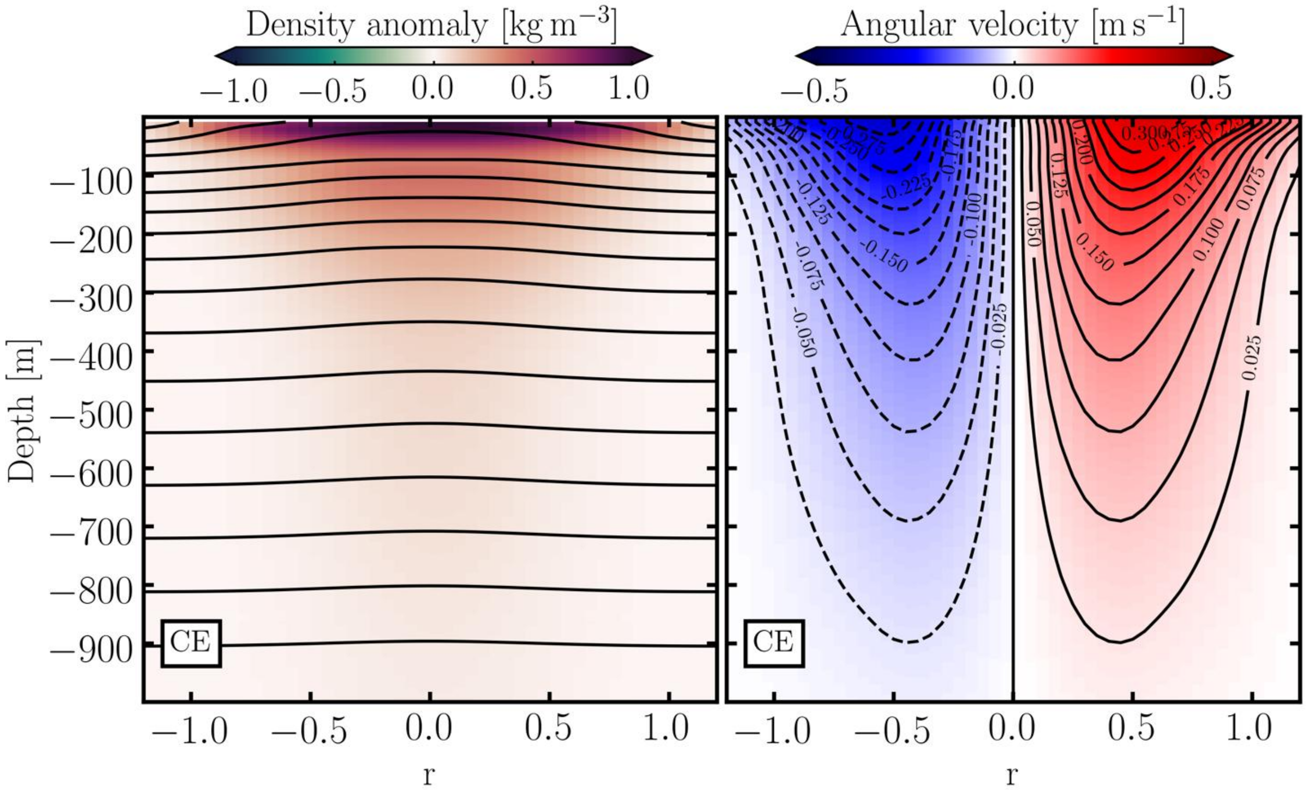
Composite calculation procedure showing the mean density anomaly at 87 m depth for surface cyclonic eddies in the northern Arabian Sea

[1]*Chaigneau et al. 2011*

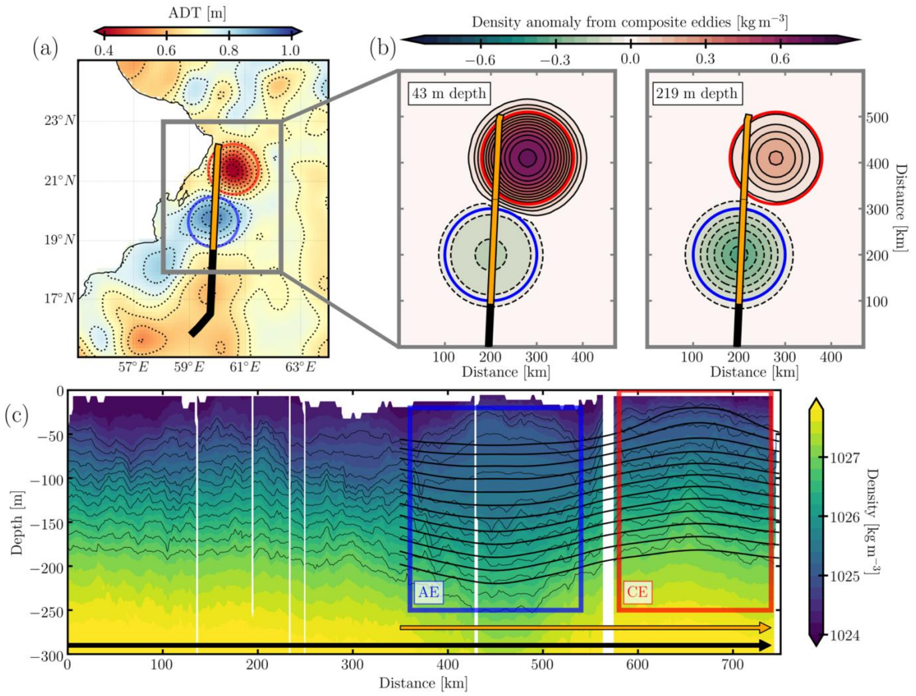
In this area, surface cyclonic eddies have this average shape



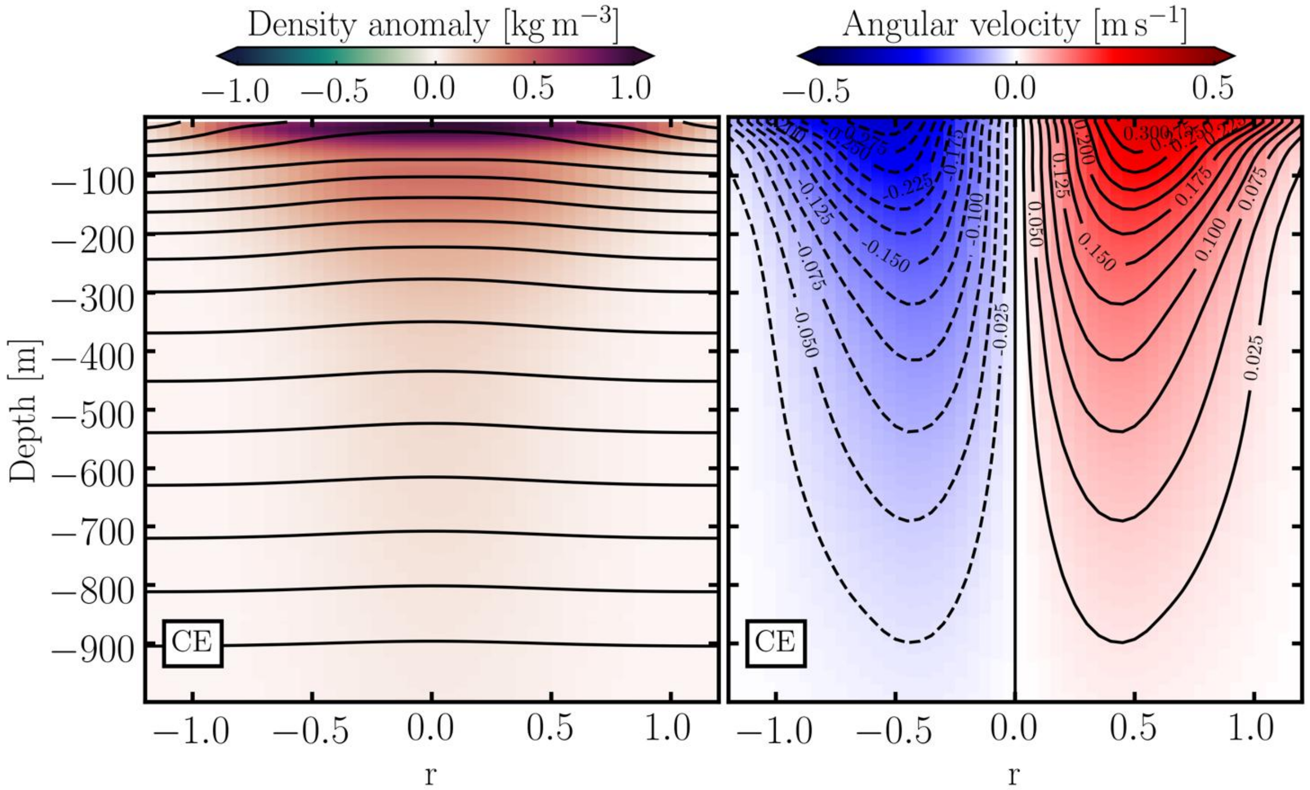
Snapshot of ADT from the altimetric product used for the detection of eddies. Black line shows the area of composite calculation



Composite density and azimuthal velocity structure of surface cyclonic eddies in the northern Arabian Sea

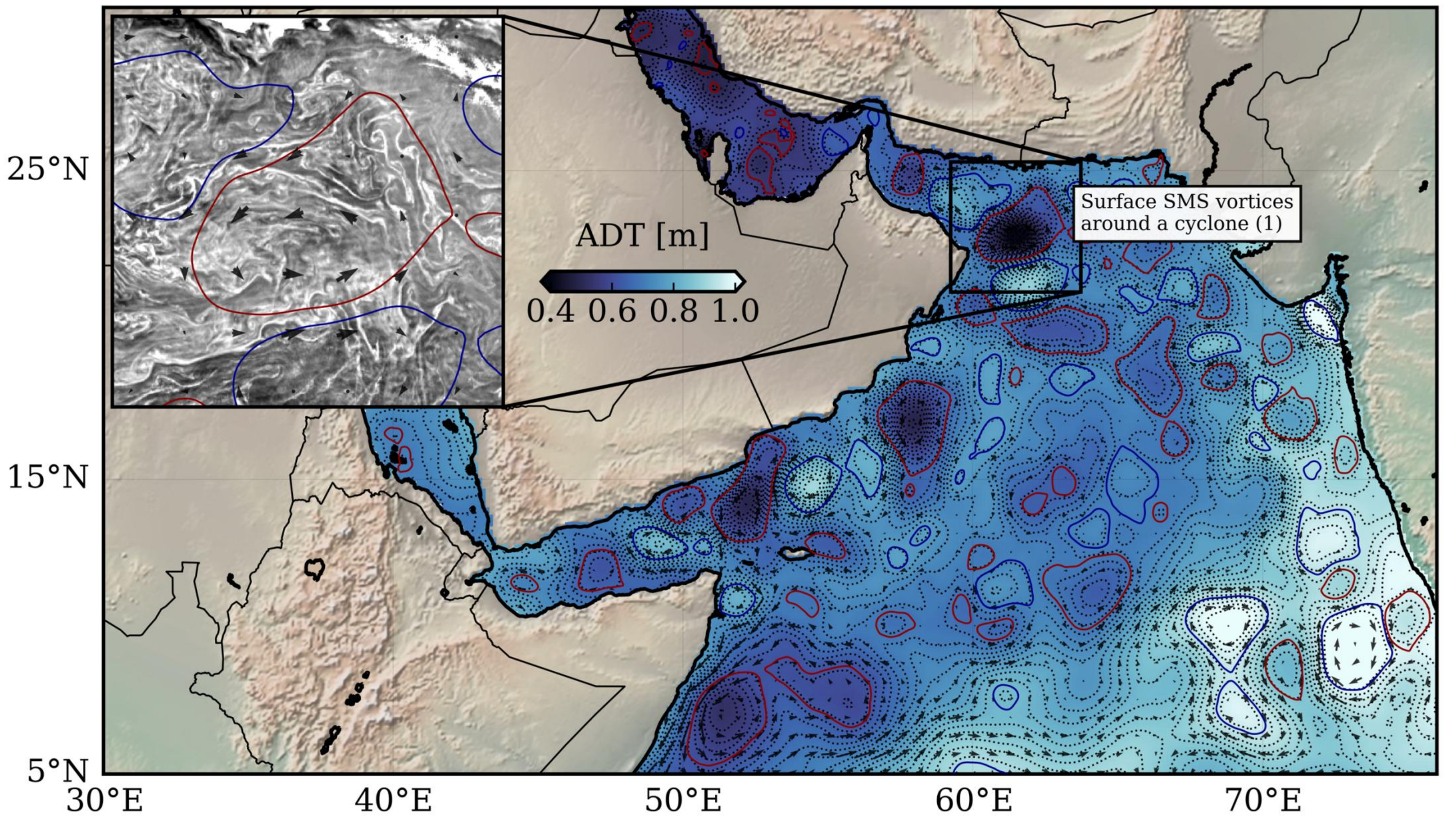


Comparison between the density anomaly of the composites and ship measurements (PHYSINDIEN 2011)



Composite density and azimuthal velocity structure of surface cyclonic eddies in the northern Arabian Sea

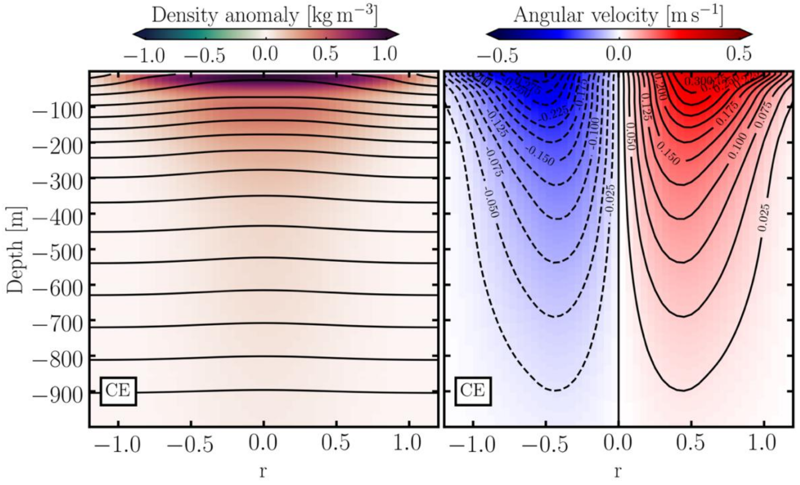
The cyclonic composite is representative of Arabian Sea eddies in this area



Altimetry on 18 February 2015; contours of cyclonic (red) and anticyclonic (blue) eddies detected from altimetry with a dedicated algorithm; insert shows true color image (NASA)

2- What are the stability characteristics of Arabian Sea eddies ? Can these latter explain the occurrence of surface Submesoscale features ?[1]

[1]*de Marez et al. 2020a*



Composite density and azimuthal velocity structure of surface cyclonic eddies in the northern Arabian Sea

CROCO
Coastal and Regional Ocean COmmunity model

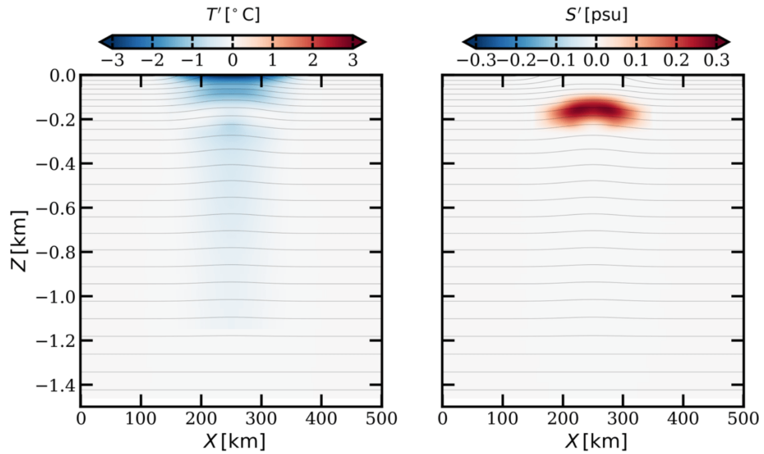
The composite is used as the initial condition of a high resolution primitive equation simulation[1]

Δx = 500 m

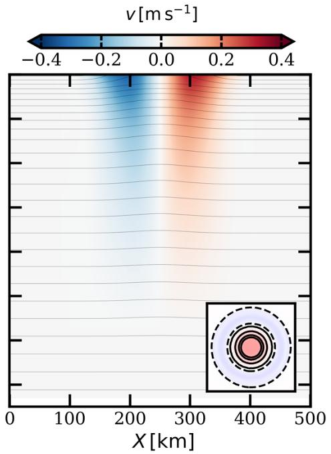
Δz = 2m

1 year spin-down simulation

no forcing

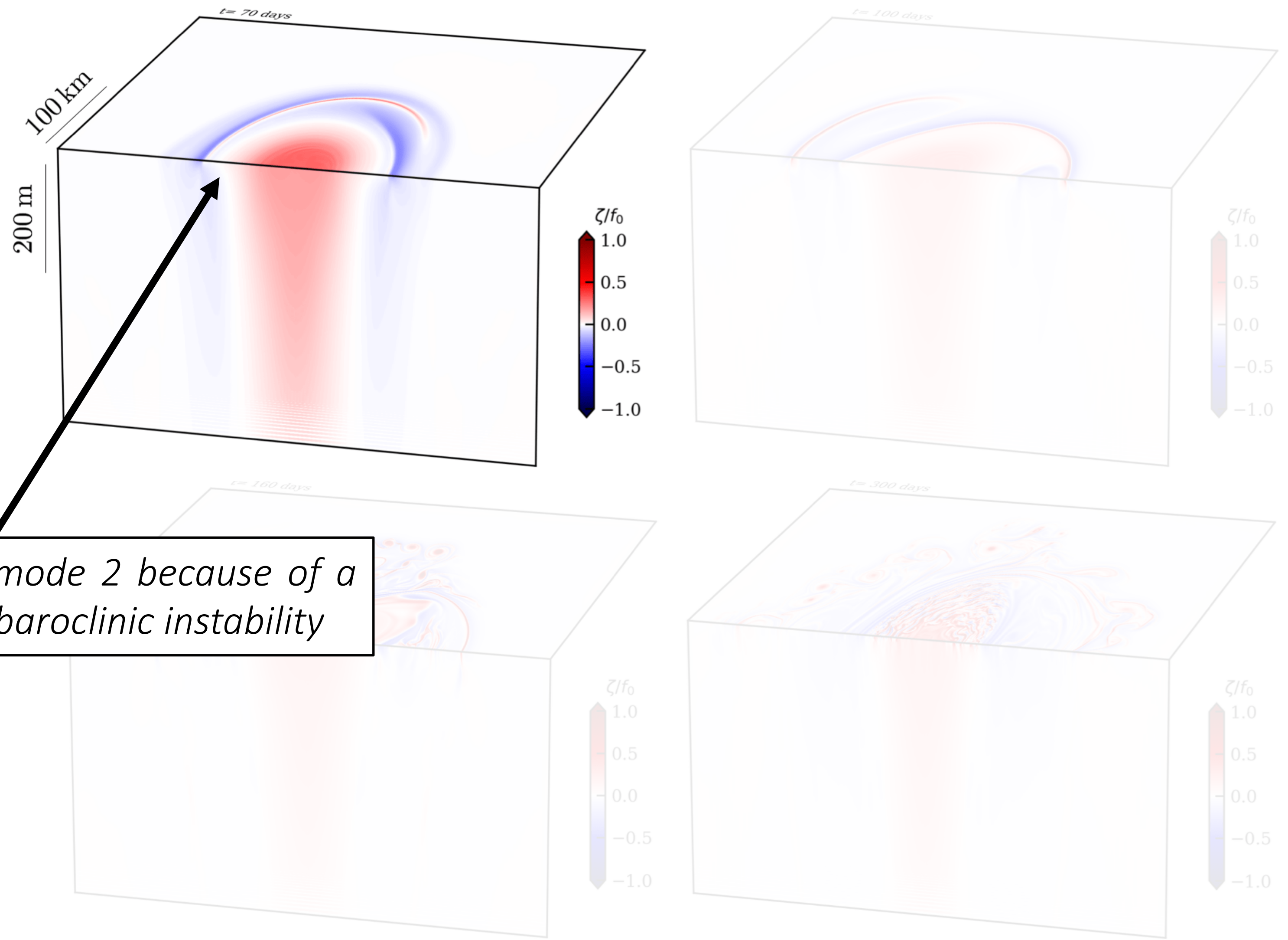


Temperature (left) and salinity (right) anomaly at model initialization, at the center of the domain



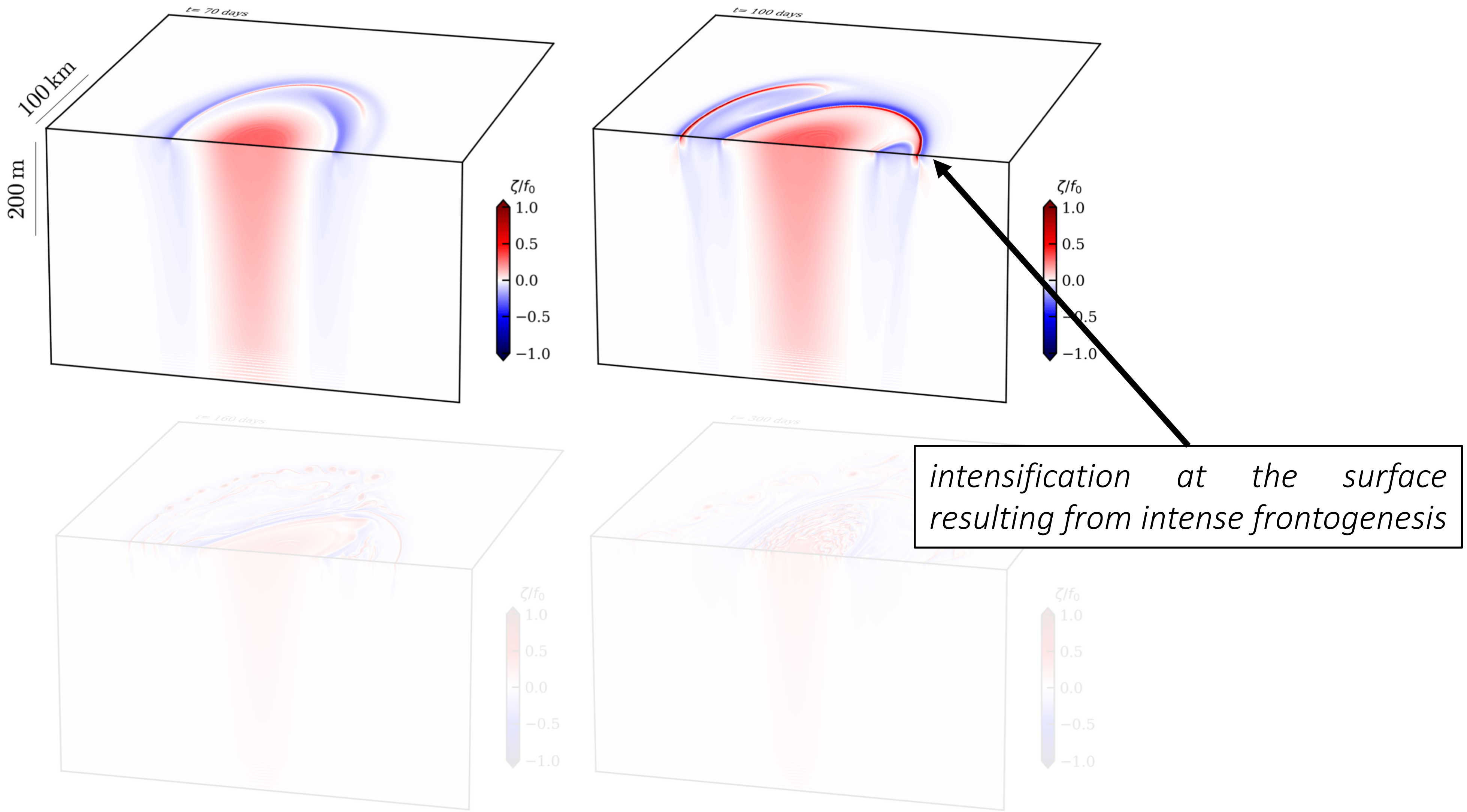
Meridional velocity at the center of the domain, and relative vorticity at the surface (insert)

[1] *Shchepetkin et al. 2005*

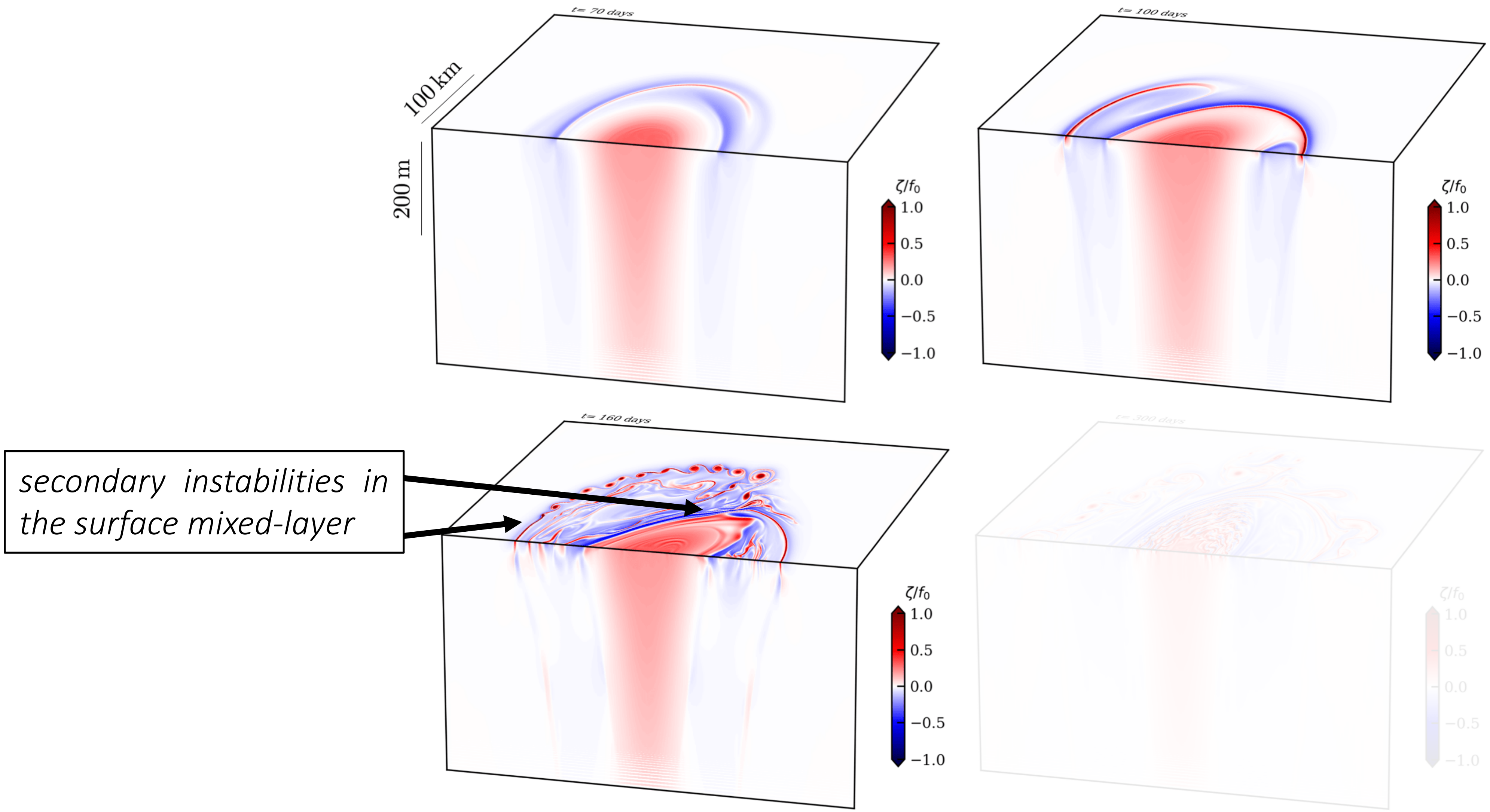


growth of azimuthal mode 2 because of a mixed barotropic and baroclinic instability

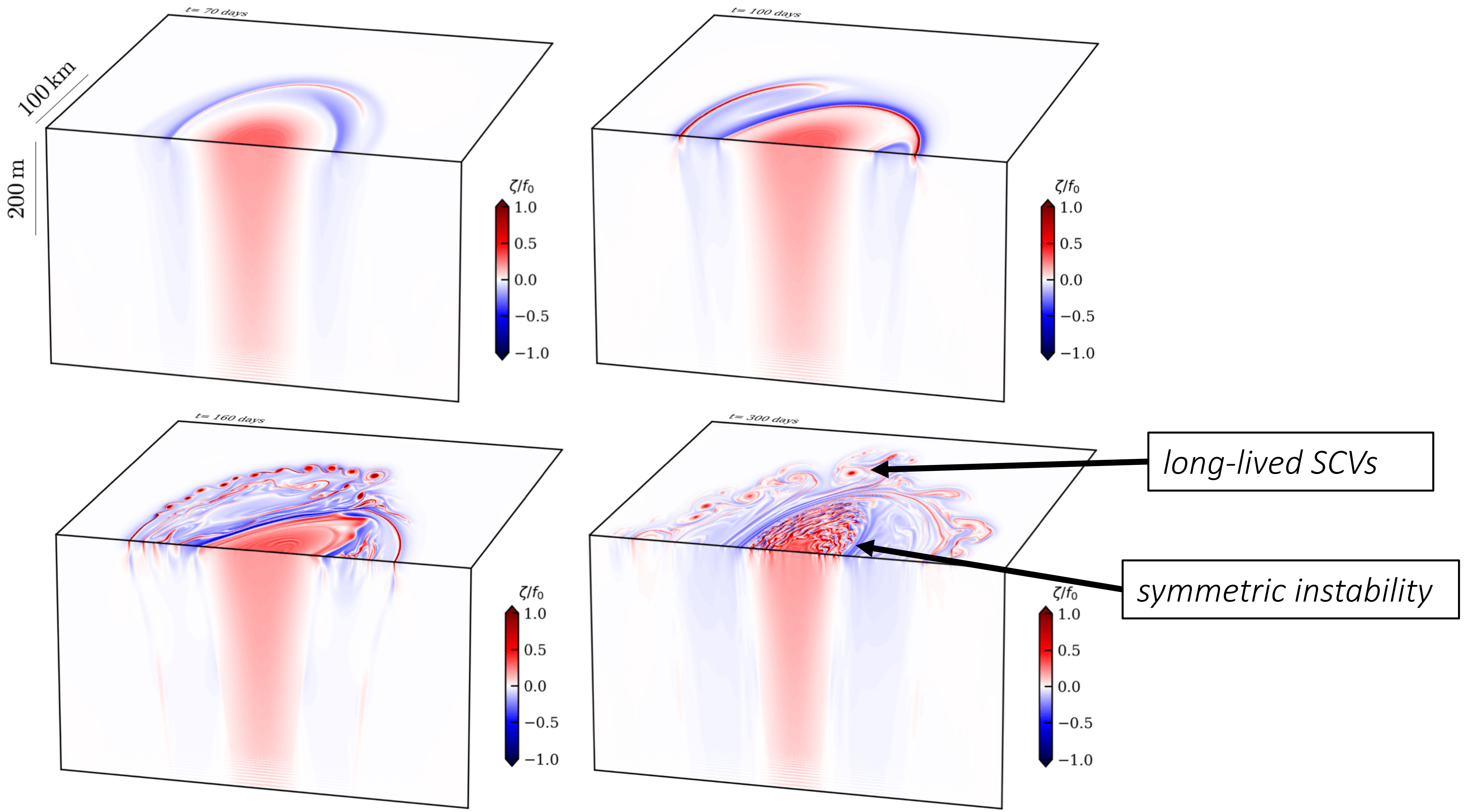
Relative vorticity normalized by the Coriolis frequency at t=70, 100, 160, and 300 days



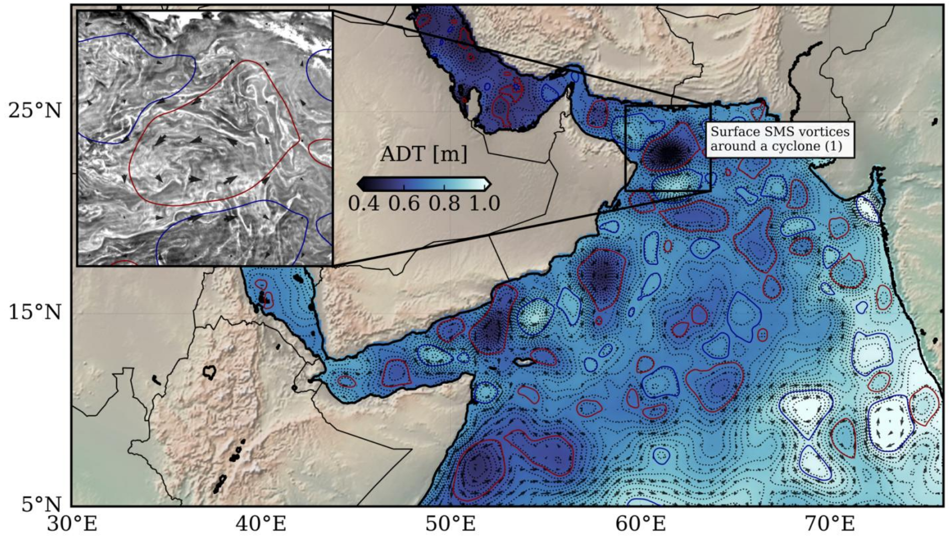
Relative vorticity normalized by the Coriolis frequency at t=70, 100, 160, and 300 days



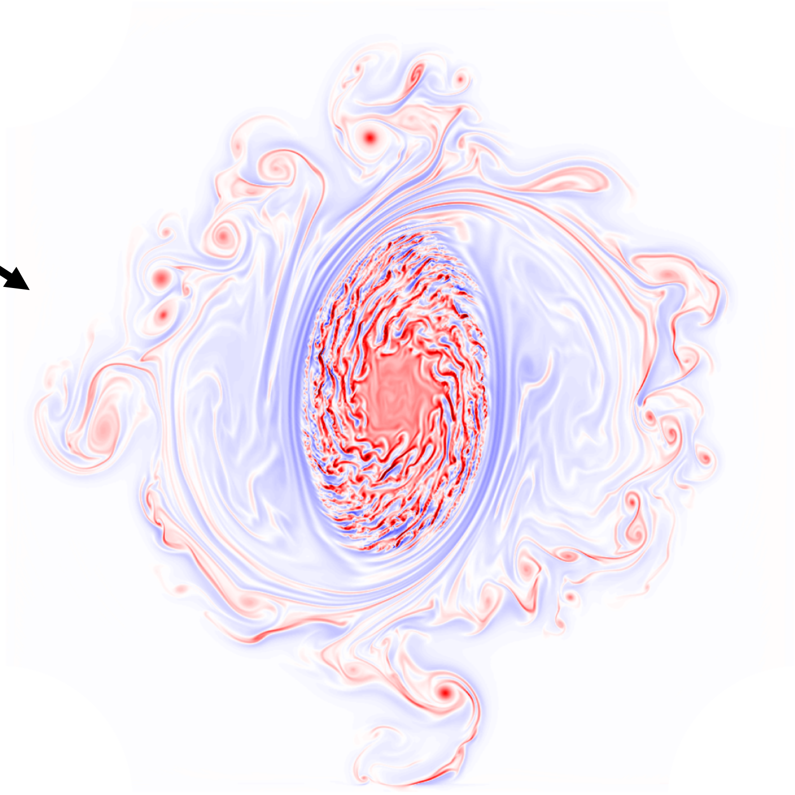
Relative vorticity normalized by the Coriolis frequency at t=70, 100, 160, and 300 days



Relative vorticity normalized by the Coriolis frequency at t=70, 100, 160, and 300 days

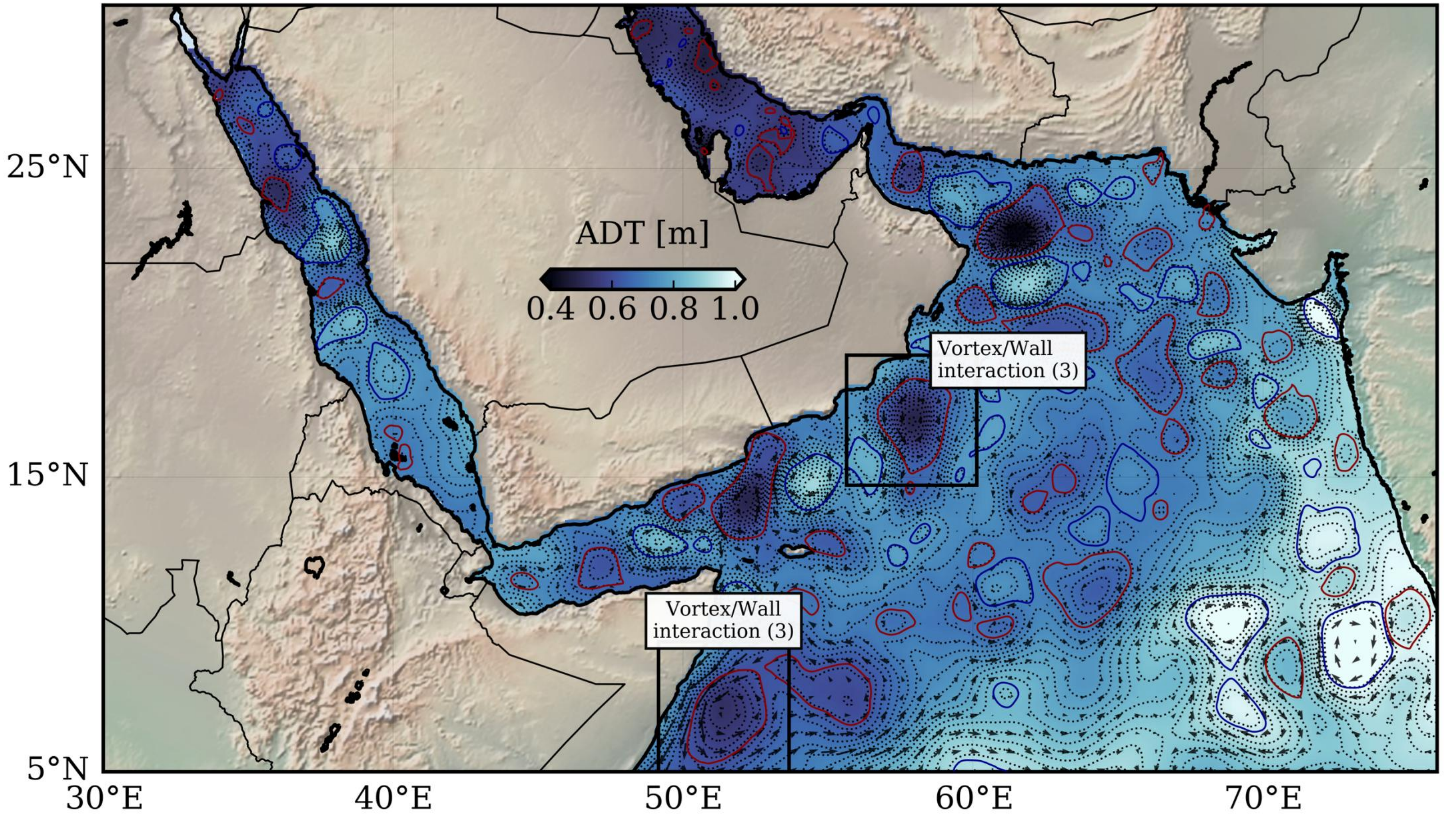


Altimetry on 18 February 2015; contours of cyclonic (red) and anticyclonic (blue) eddies detected from altimetry with a dedicated algorithm; insert shows true color image (NASA)



Surface relative vorticity at t=360 days

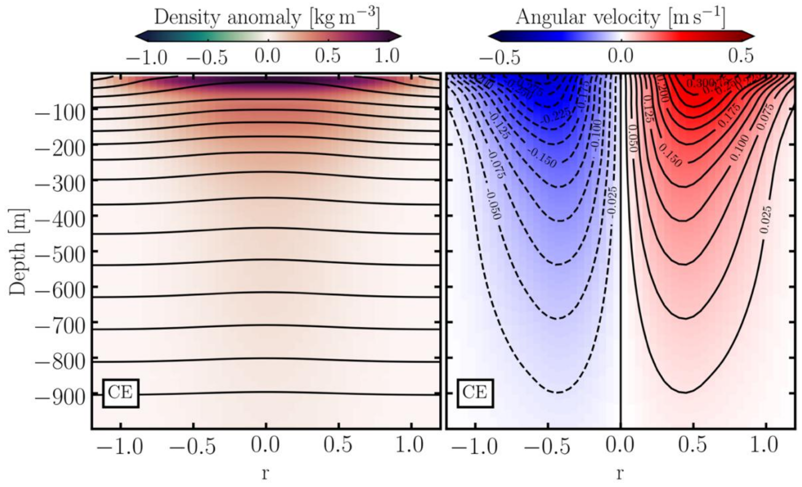
Vortex stability properties show that Arabian Sea eddies can remain coherent for several years and spontaneously generate Submesoscale dynamics



Altimetry on 18 February 2015; contours of cyclonic (red) and anticyclonic (blue) eddies detected from altimetry with a dedicated algorithm

3- What are the mechanisms involved in the interaction between mesoscale eddies and a western boundary ?[1,2]

[1]*de Marez et al. 2020b*, [2]*de Marez et al. 2020c*



Composite density and azimuthal velocity structure of surface cyclonic eddies in the northern Arabian Sea

CROCO
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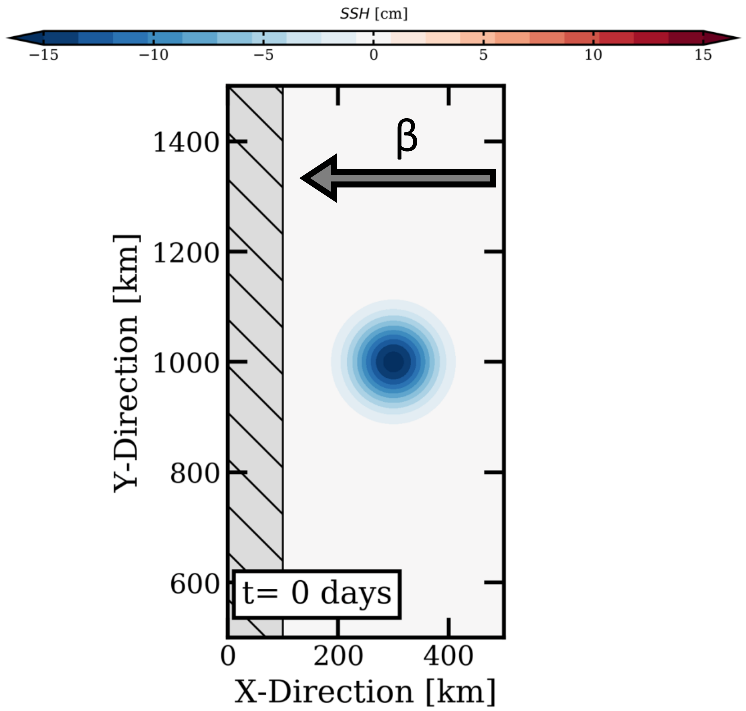
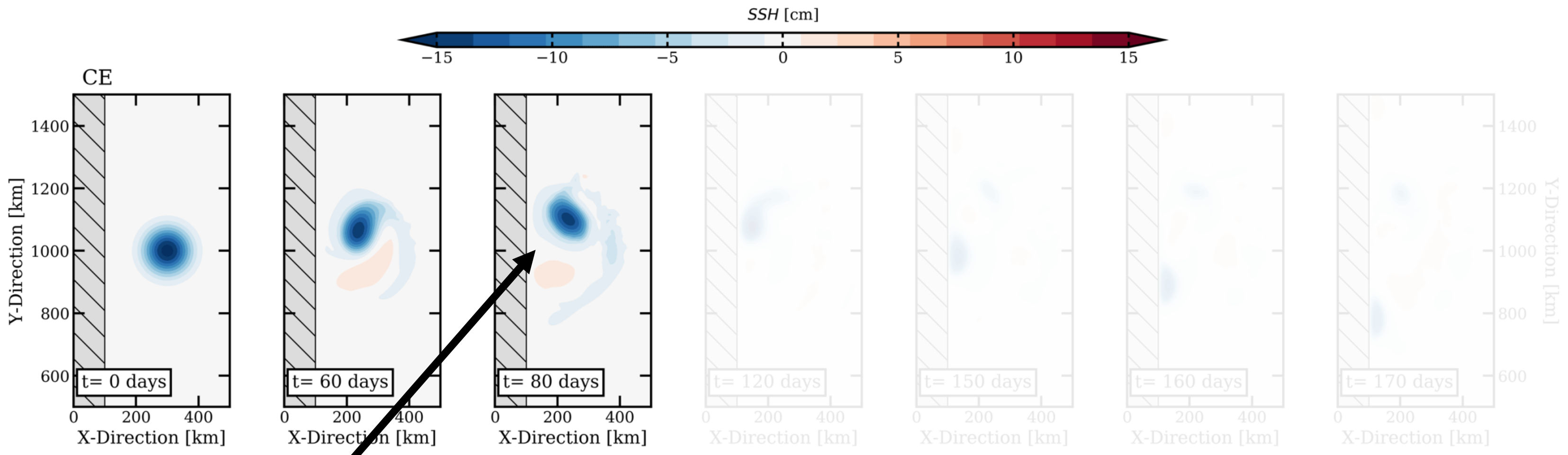
The composite is used as the initial condition of a primitive equation simulation[1] on the β-plane with a western boundary (free-slip)

Δx = 5 km
Δz = 10m
1 year spin-down simulation
no forcing



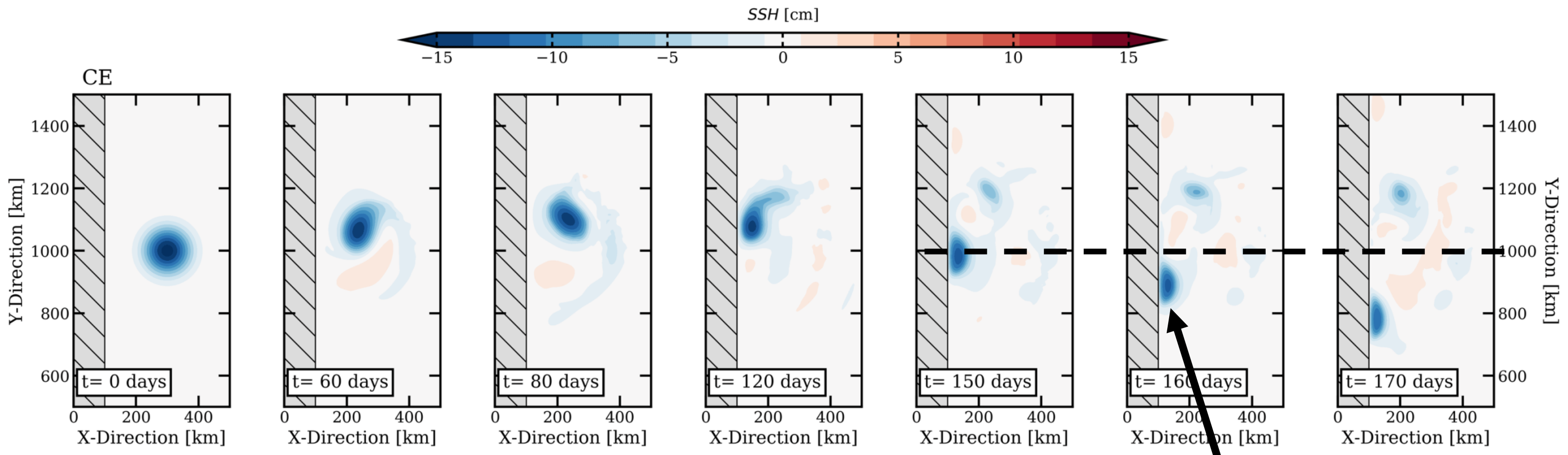
Sea Surface Height at simulation initialization

[1]*Shchepetkin et al. 2005*



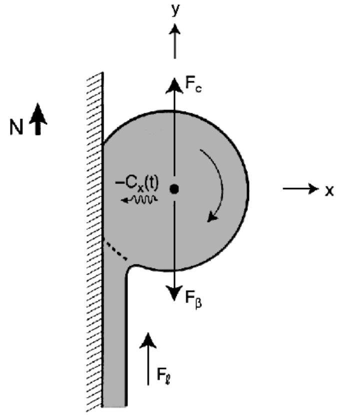
Time evolution of the Sea Surface Height in the simulation

drift of the cyclone due to β-effect



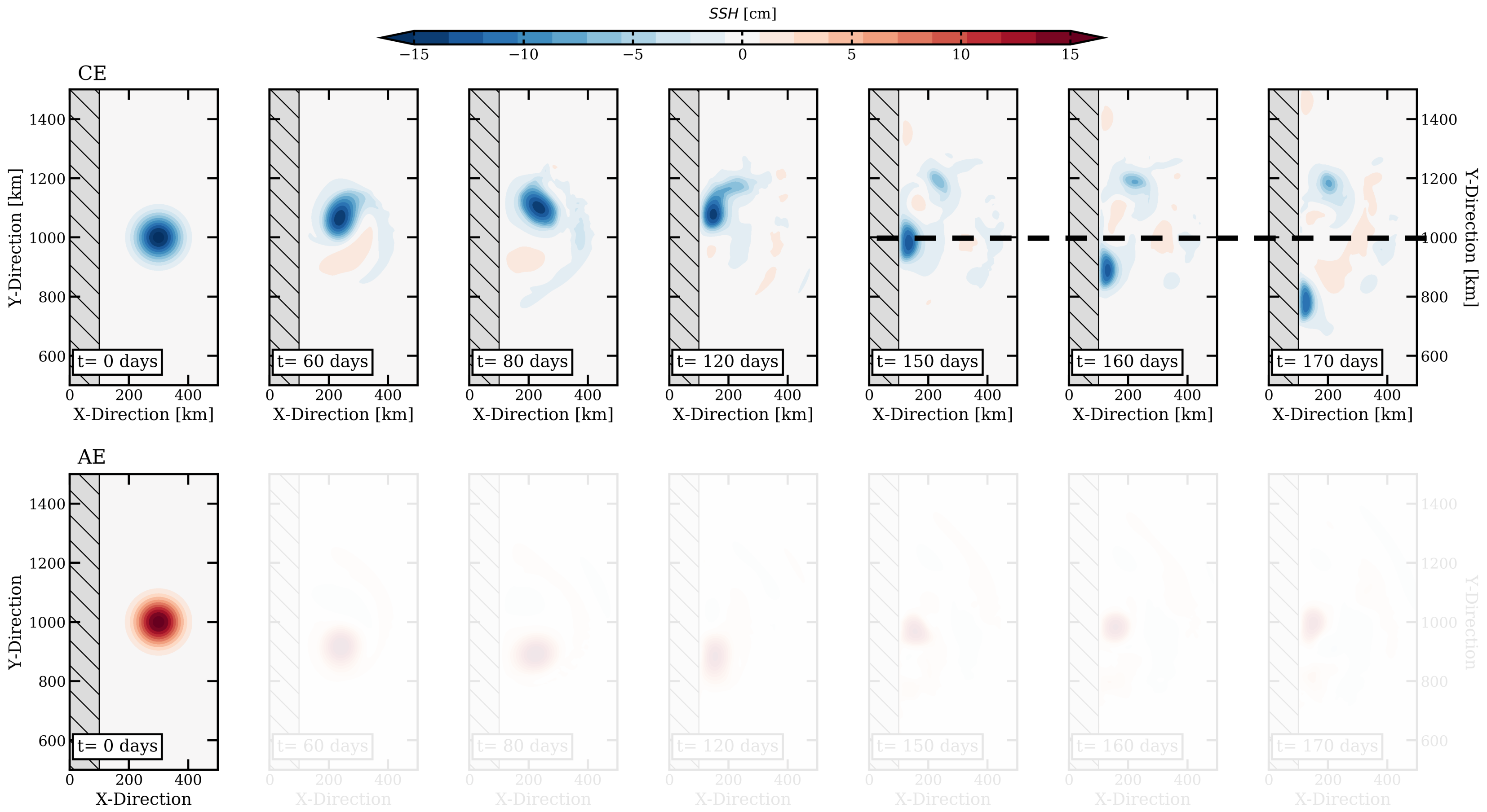
Time evolution of the Sea Surface Height in the simulation

coupling with the wall, and steady southward drift of the cyclone as a "wodon"[1,2,3]



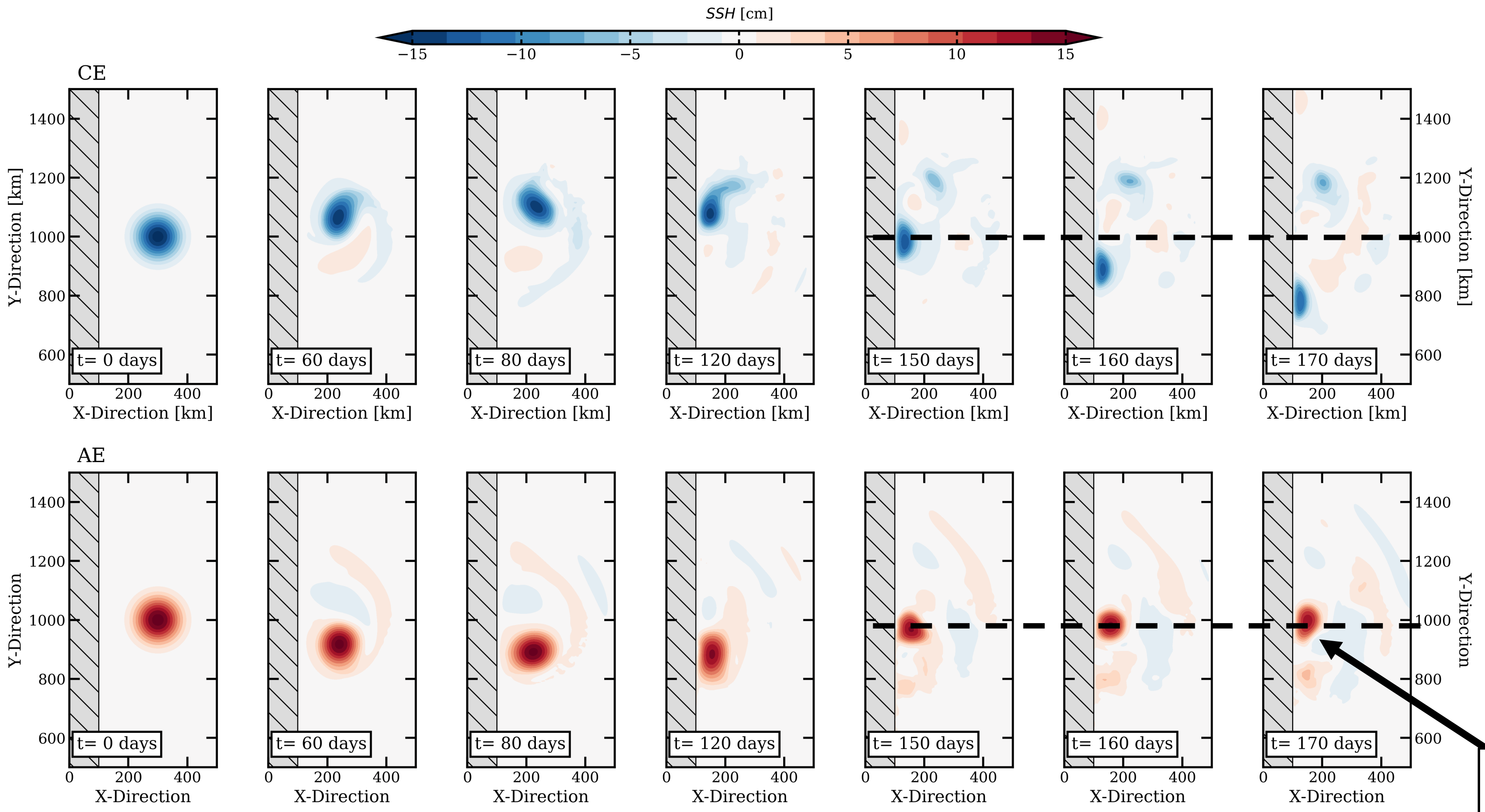
Wodon explanation for an anticyclone[1]

[1]Shi & Nof 1993; [2]Nof 1999; [3]Sutyrin 2003



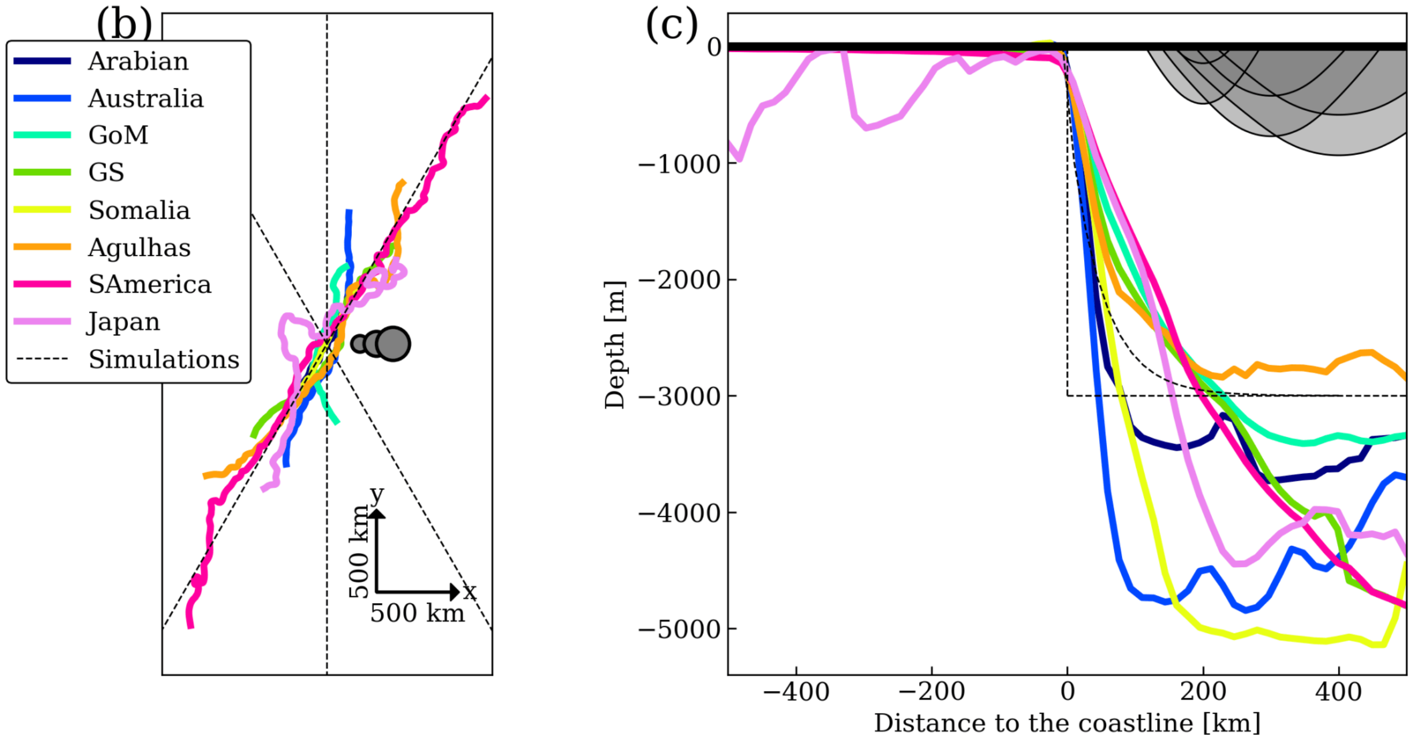
we take the opposite of the composite density anomaly, to test the same situation with an anticyclone

Time evolution of the Sea Surface Height in the simulation with the original cyclonic composite (top), and the density-inverted anticyclonic composite (bottom)



Time evolution of the Sea Surface Height in the simulation with the original cyclonic composite (top), and the density-inverted anticyclonic composite (bottom)

NO steady wodon formation → CE/AE asymmetry in the vortex-wall interaction



Scheme of simulation initializations; dashed lines show the coast considered in simulations, and gray contours show the different vortex size/intensity used.

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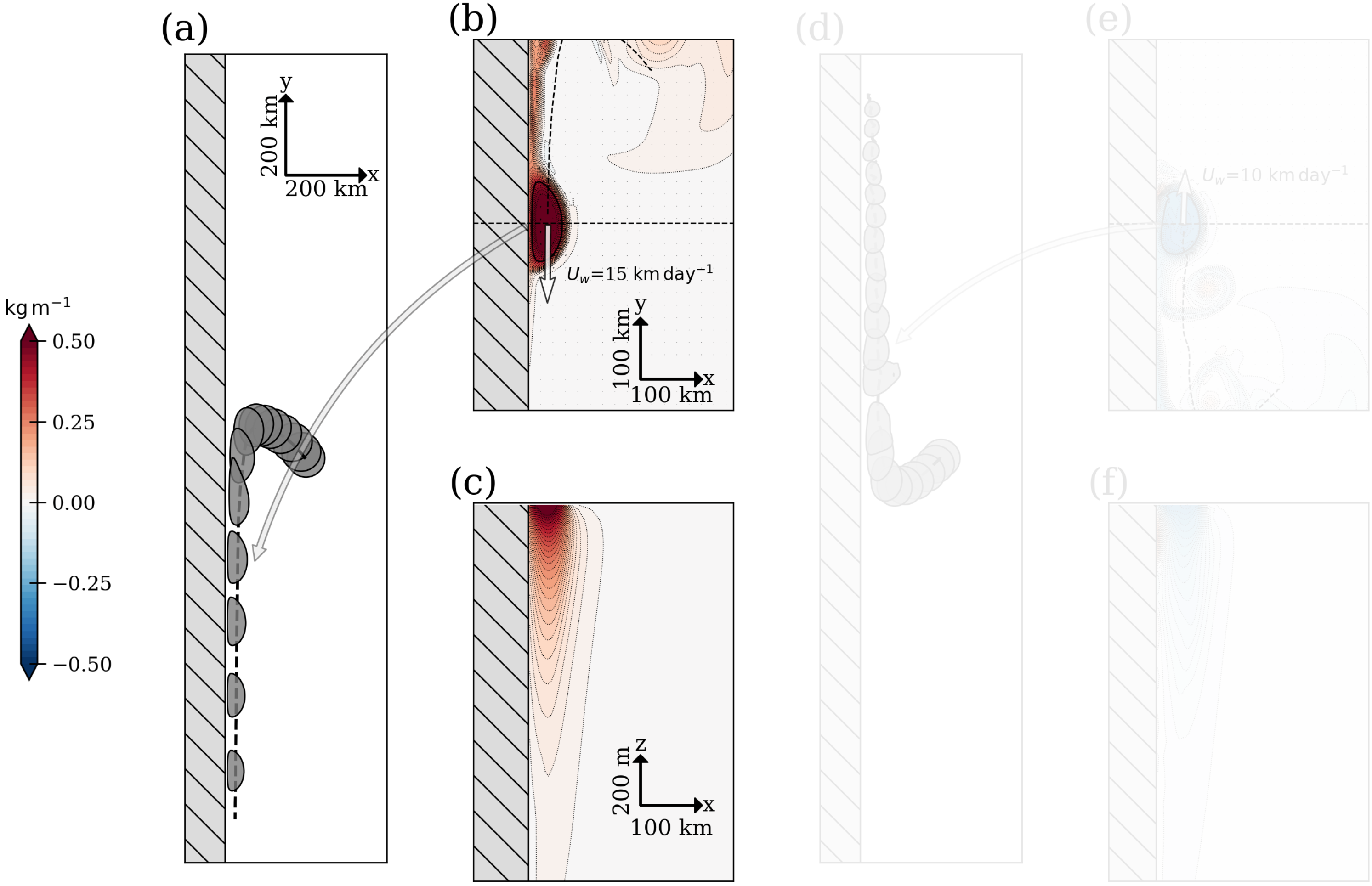
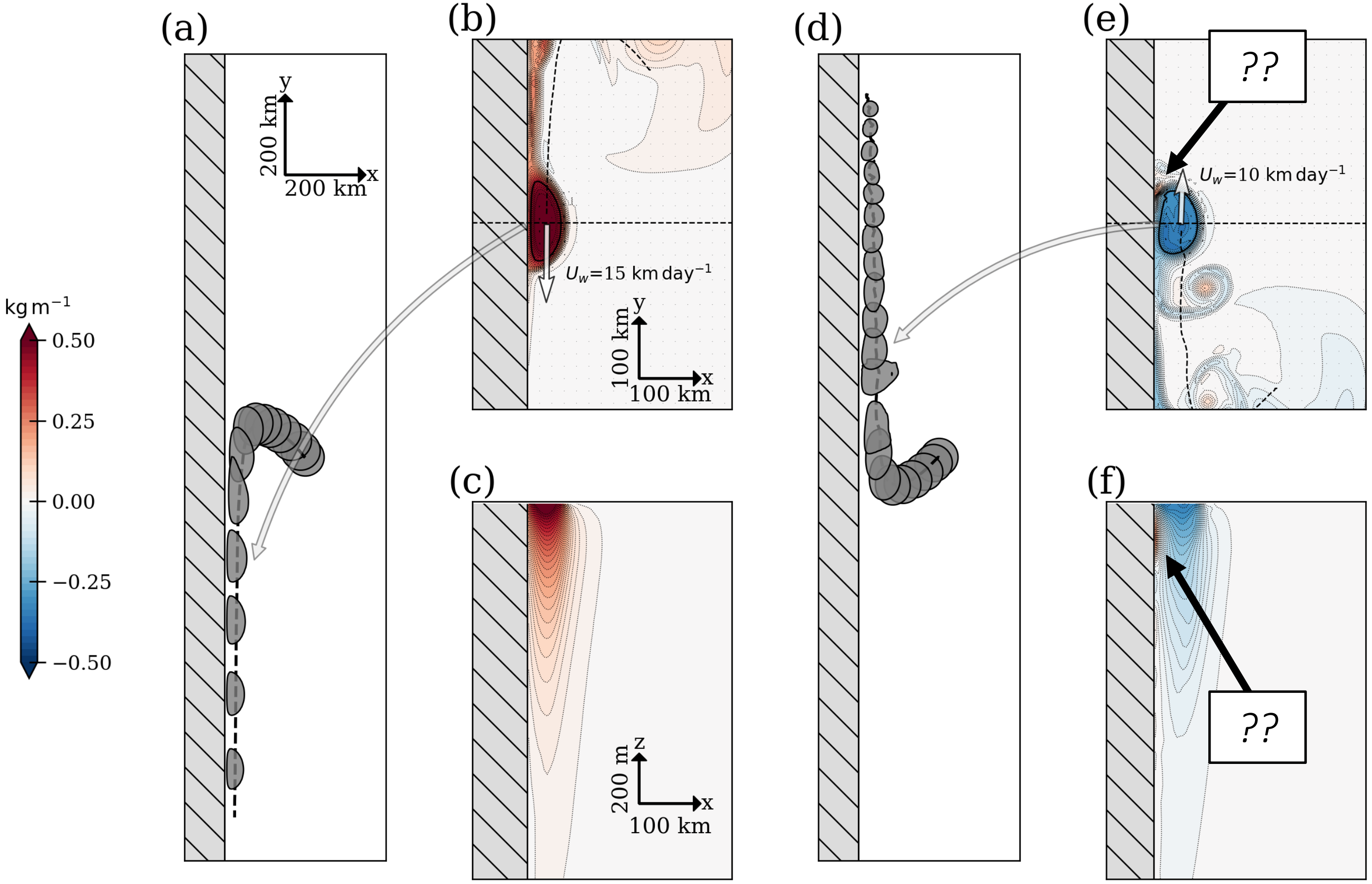
the process is studied in a large parameter space with analytical shaped vortices

Δx = 5 km
Δz = 10m
1 year spin-down simulation
no forcing



Density anomaly in the simulation of a cyclone with R=50 km, V_0= 0.5 m s^{-1}, and a straight wall

Cyclones eventually form a stable wodon when they encounter the wall

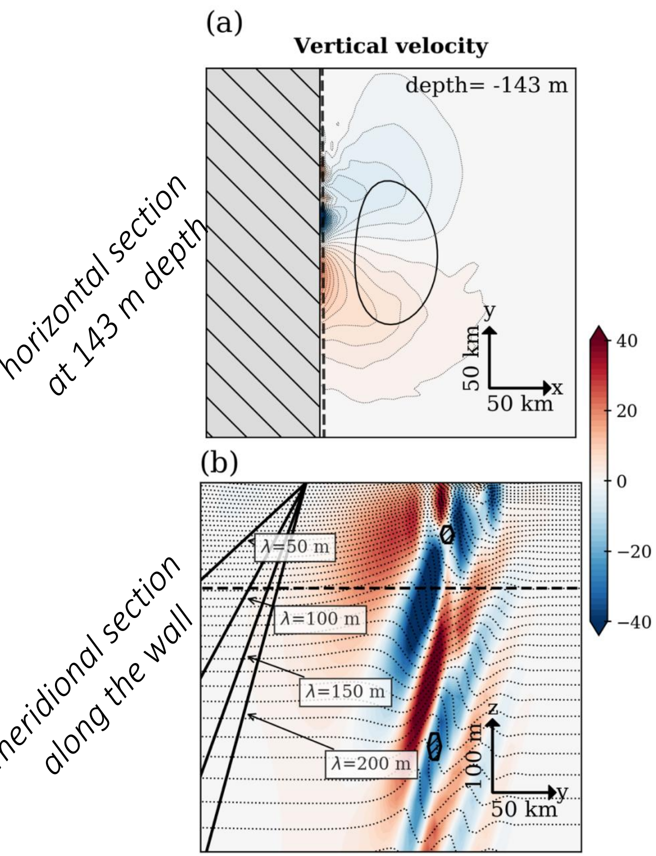


Density anomaly in the simulation of a cyclone with R=50 km, V_0= 0.5 m s^{-1}, and a straight wall

Density anomaly in the simulation of an anticyclone with R=50 km, V_0= 0.5 m s^{-1}, and a straight wall

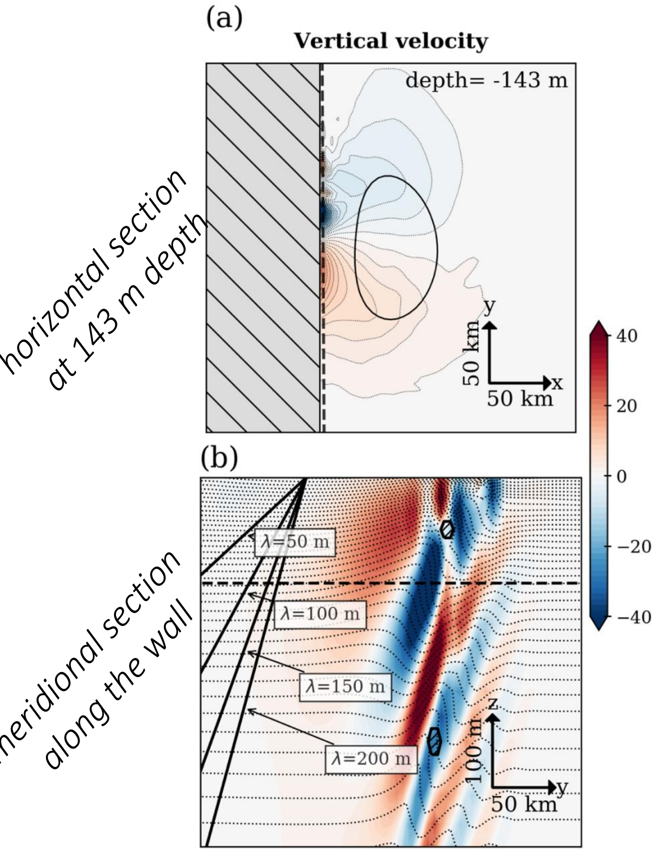
Cyclones eventually form a stable wodon when they encounter the wall

Anticyclonic wodons are not stable, their drift velocity is weaker (or null), and patches of density anomaly are seen along the wall



Vertical velocity at t= 64 days

Kelvin waves are generated along the boundary during the eddy adjustment



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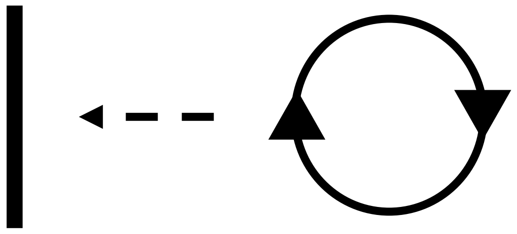
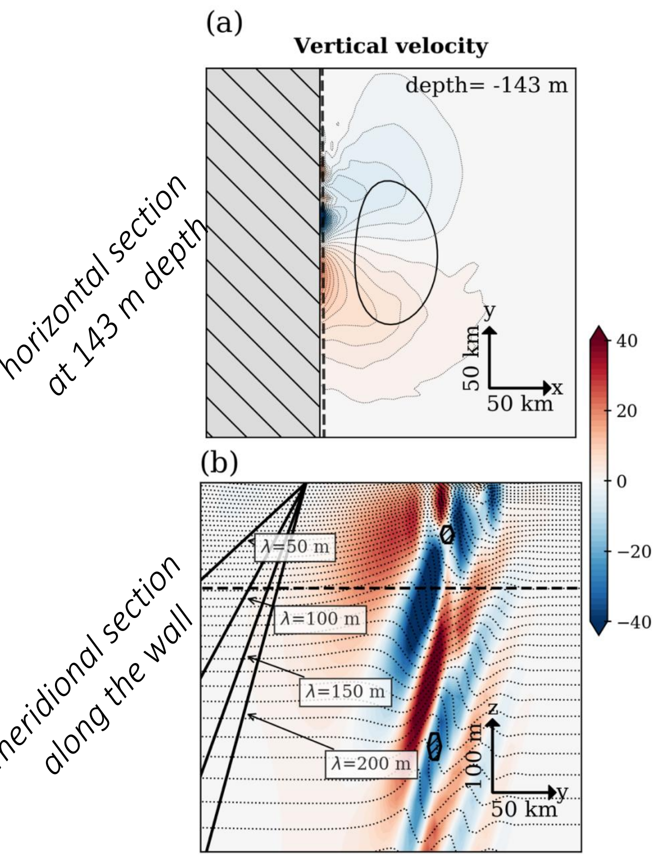


1°/ The eddy drifts toward the wall



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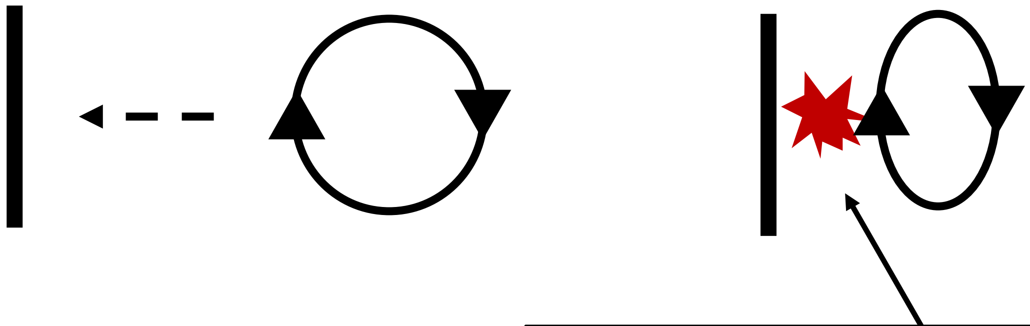
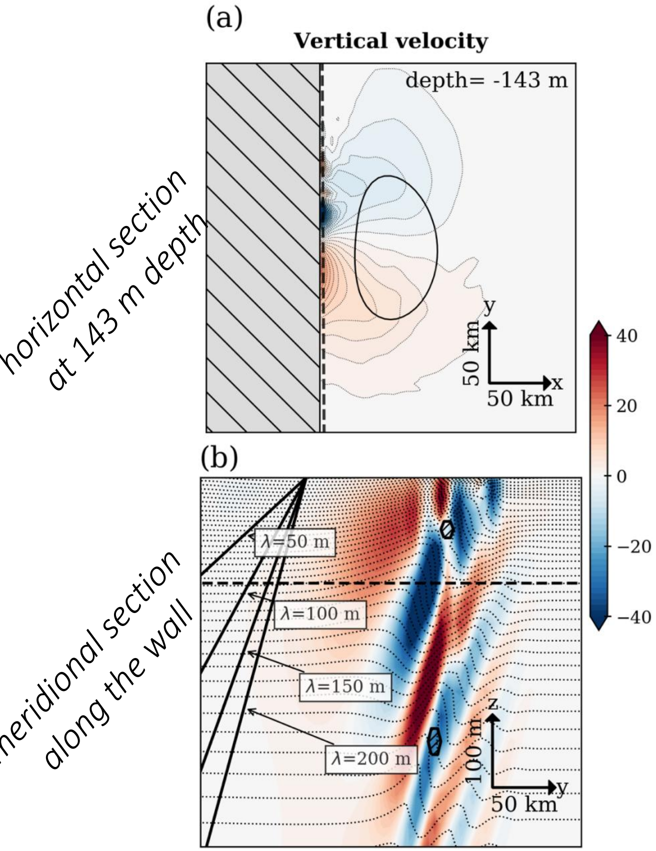
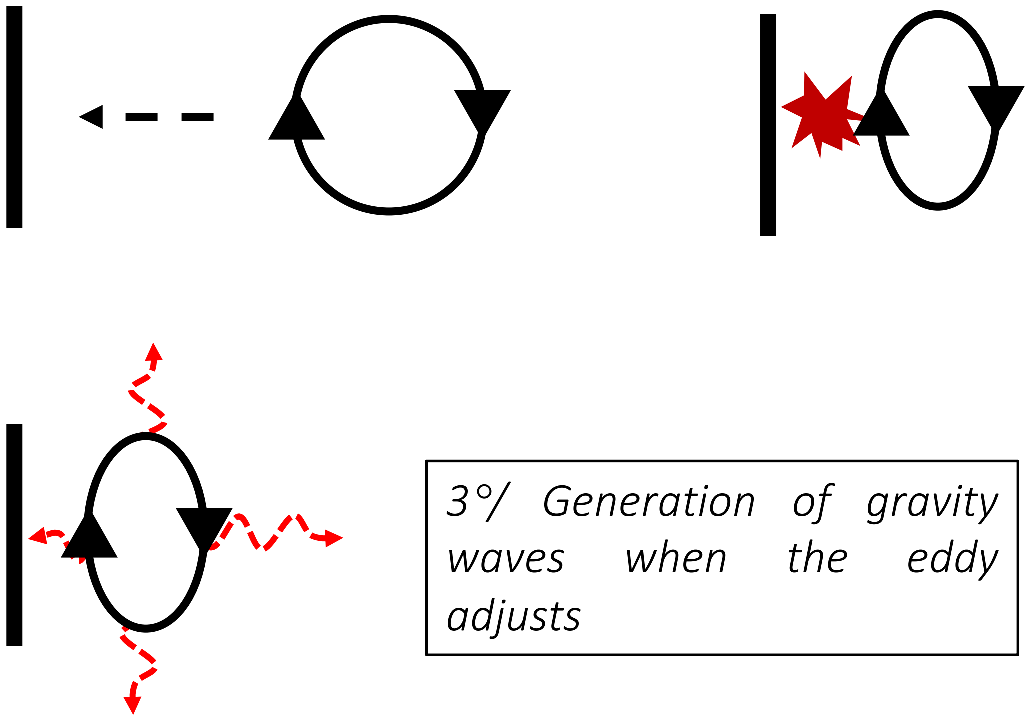


2°/ Collision between the eddy and the wall, and deformation of the eddy

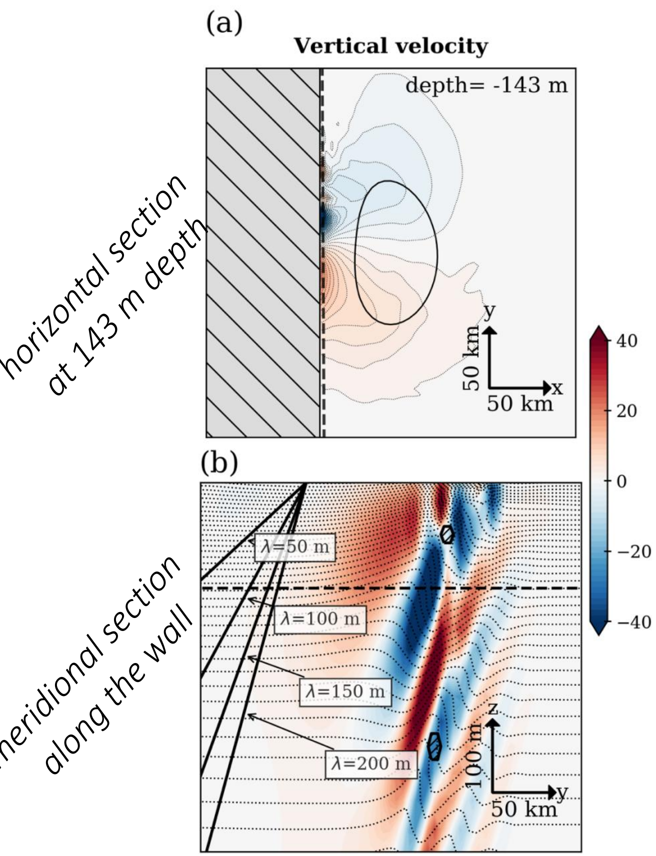


Vertical velocity at t= 64 days

Kelvin waves are generated along the boundary during the eddy adjustment

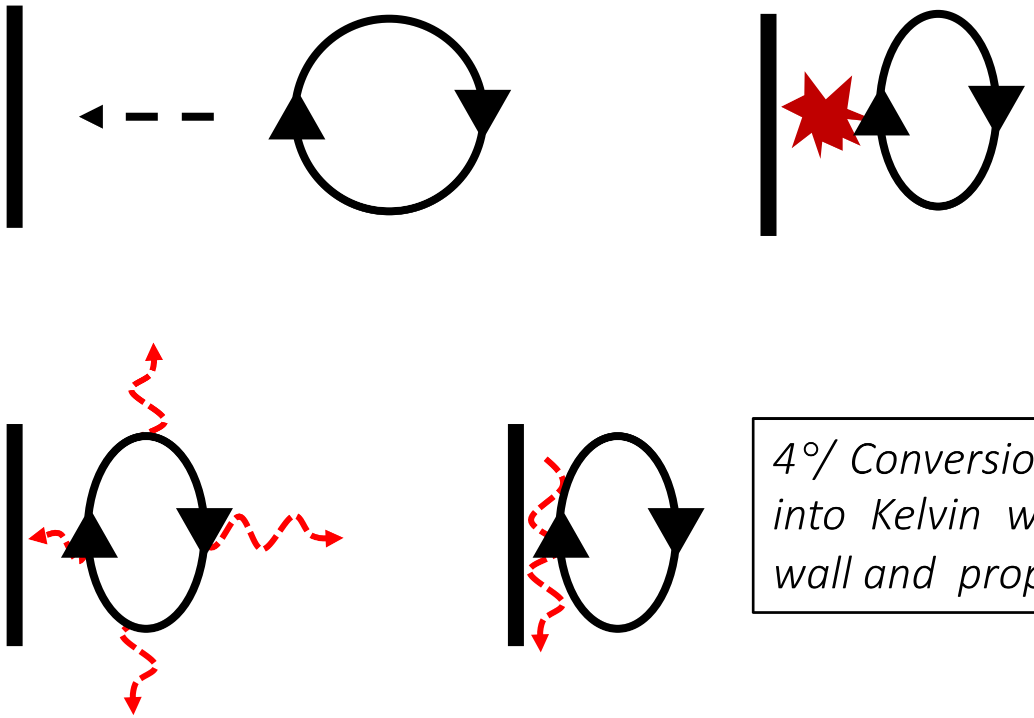


3°/ Generation of gravity waves when the eddy adjusts

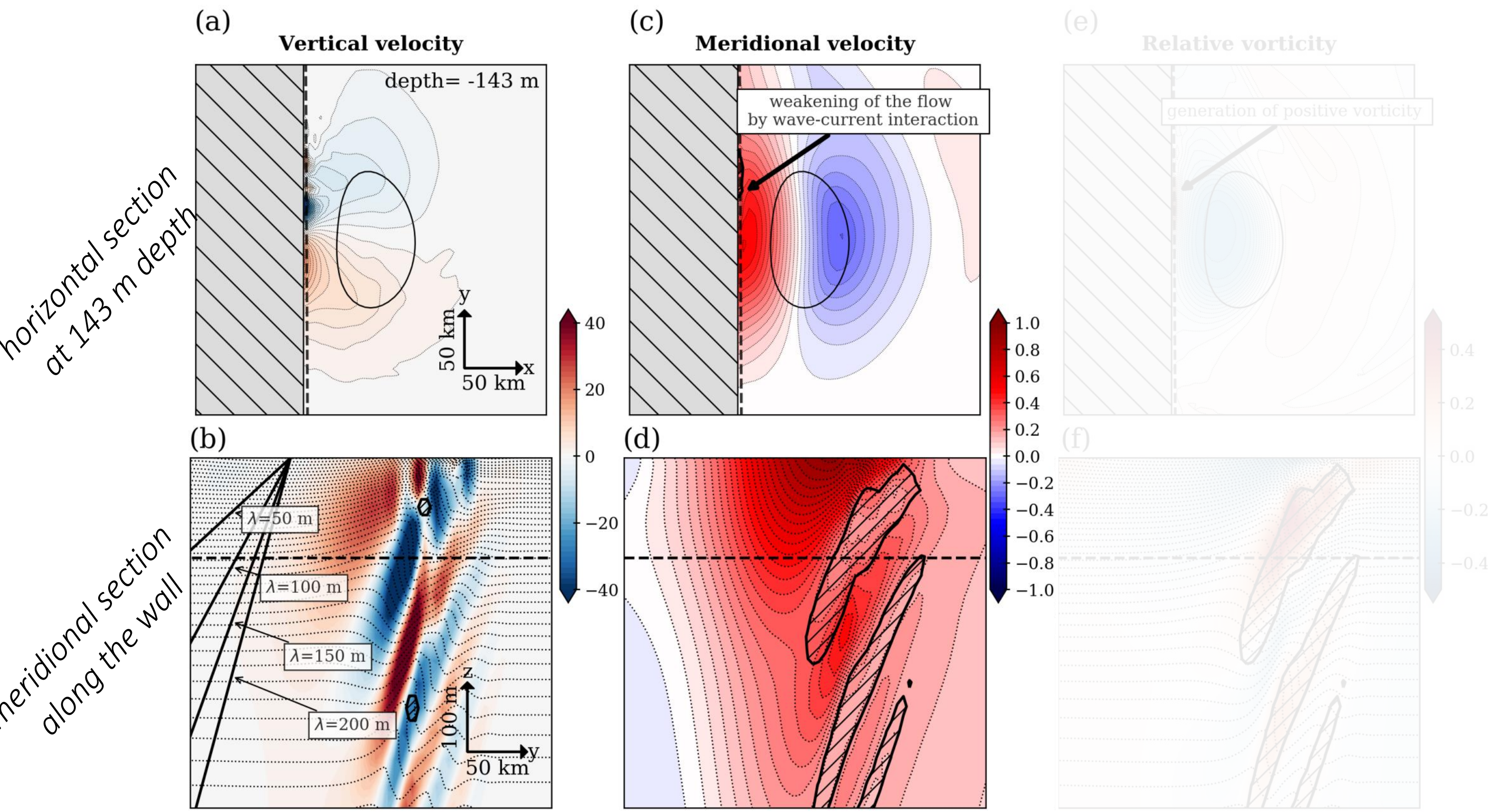


Vertical velocity at t= 64 days

Kelvin waves are generated along the boundary during the eddy adjustment



4% Conversion of the radiated energy into Kelvin waves trapped along the wall and propagating southward

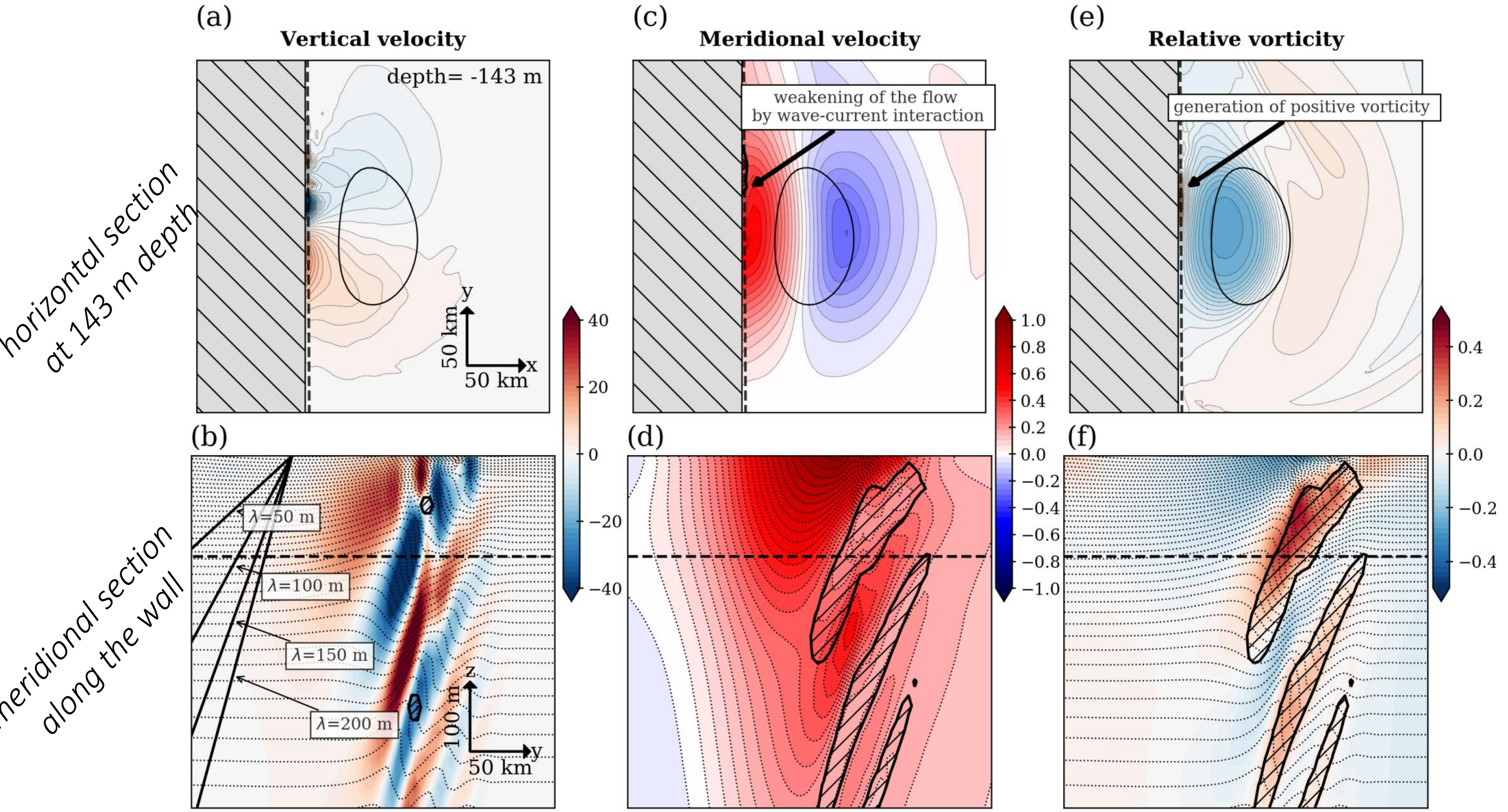


Vertical velocity at t= 64 days

Meridional velocity and Eliassen-Palm flux divergence (hatched areas)

Kelvin waves are arrested by the anticyclonic flow (their phase velocity is comparable with the meridional velocity of the eddy)

The waves act by weakening the mean current (as revealed by the EP flux div) where nonlinear processes occur

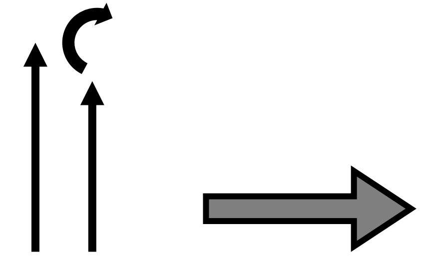


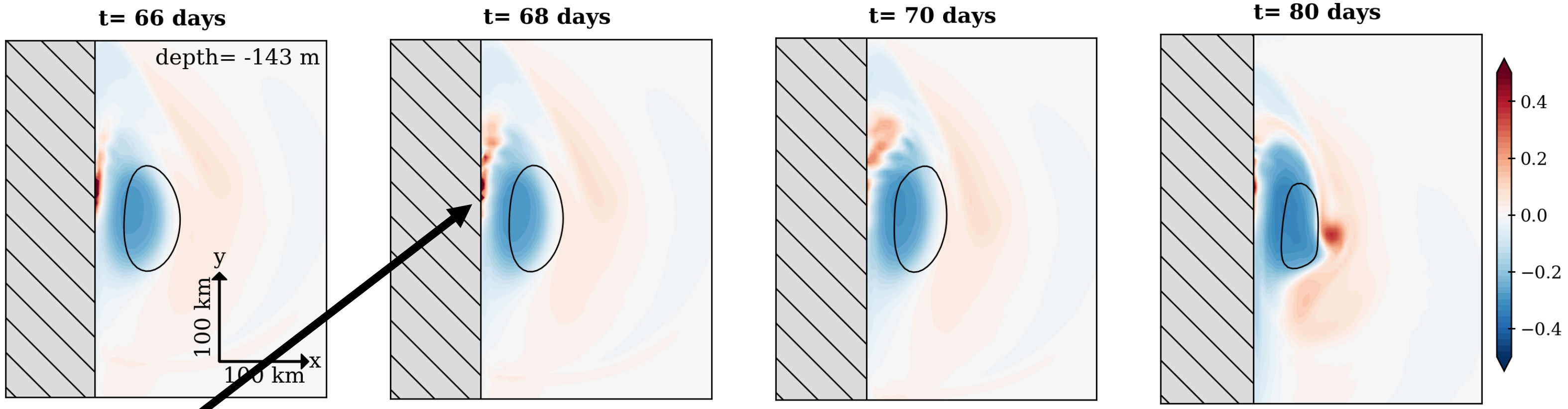
Vertical velocity at t= 64 days

Meridional velocity and Eliassen-Palm flux divergence (hatched areas)

Relative vorticity and Eliassen-Palm flux divergence (hatched areas)

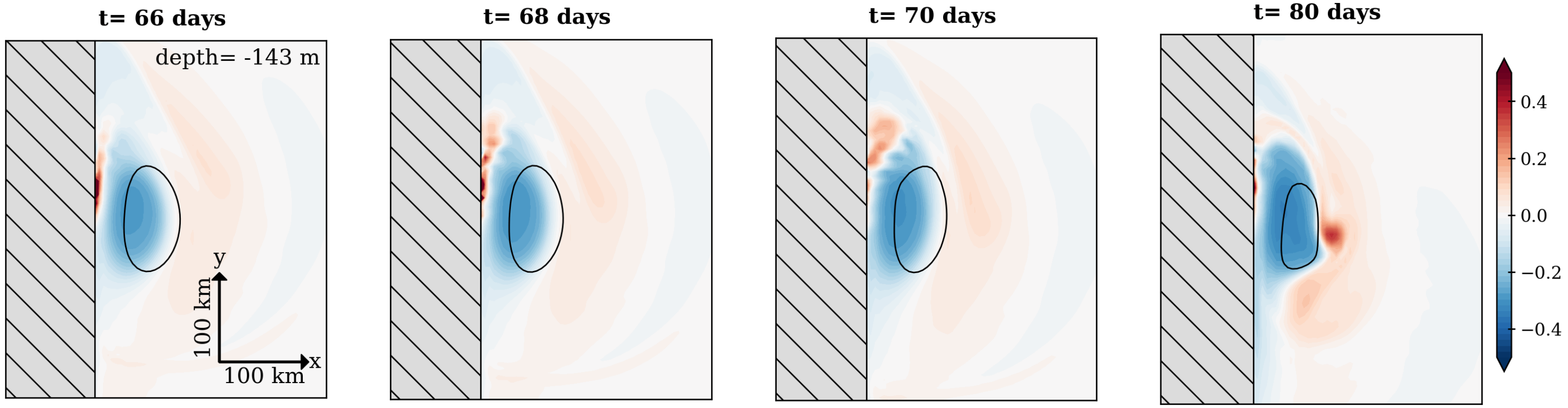
The weakening of the current generates patches of positive relative vorticity





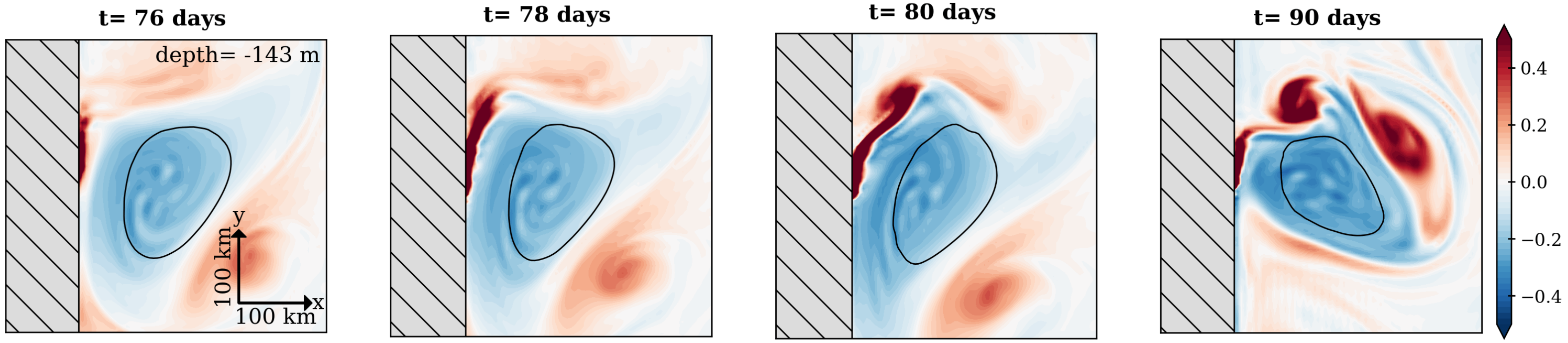
Relative vorticity at 143 m depth (the domain follows the drift of the eddy)

Generation of cyclonic vorticity that prevents the wodon to drift steadily by dipolar coupling

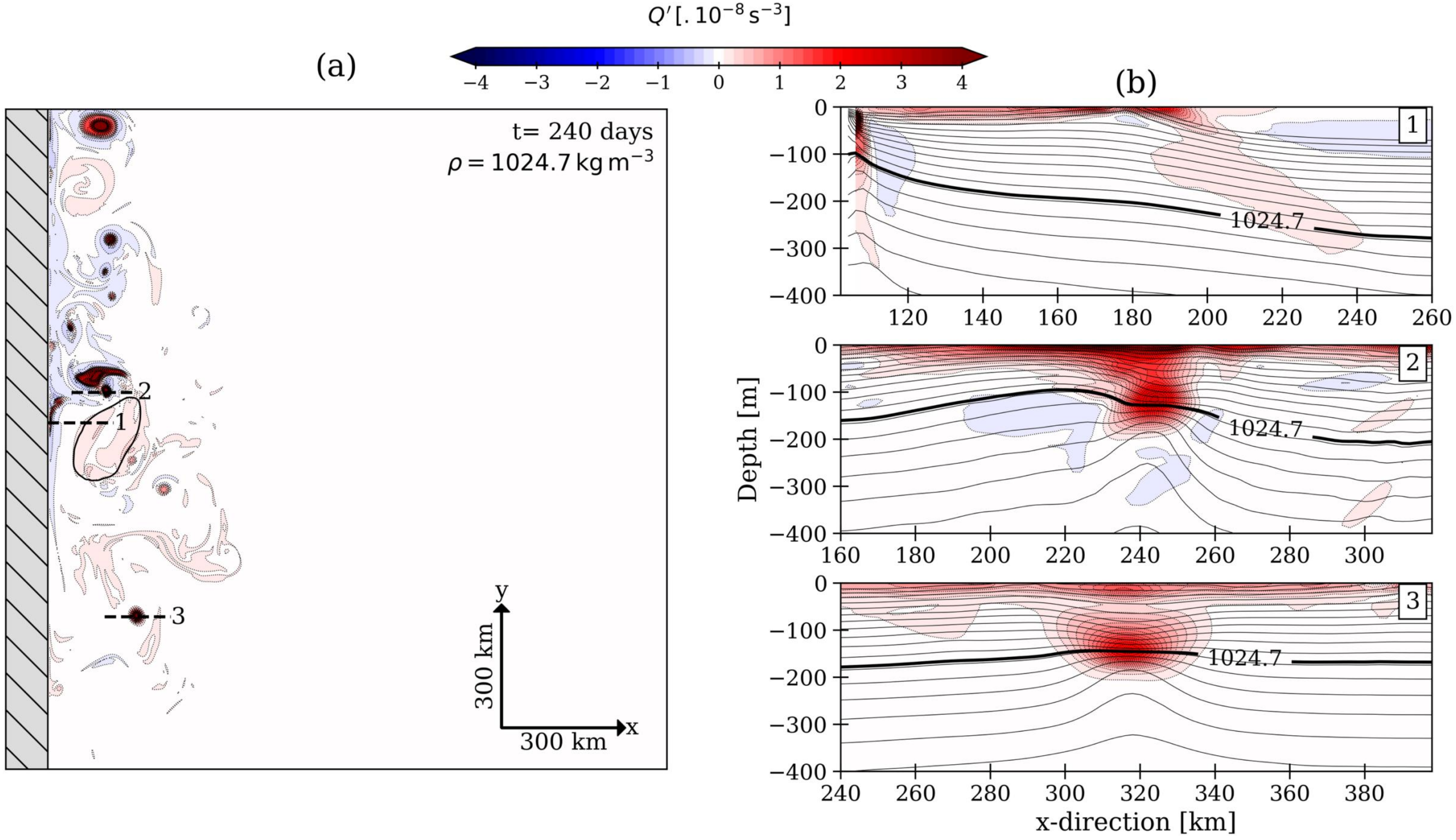


Relative vorticity at 143 m depth (the domain follows the drift of the eddy)

The effect is enhanced for larger anticyclones

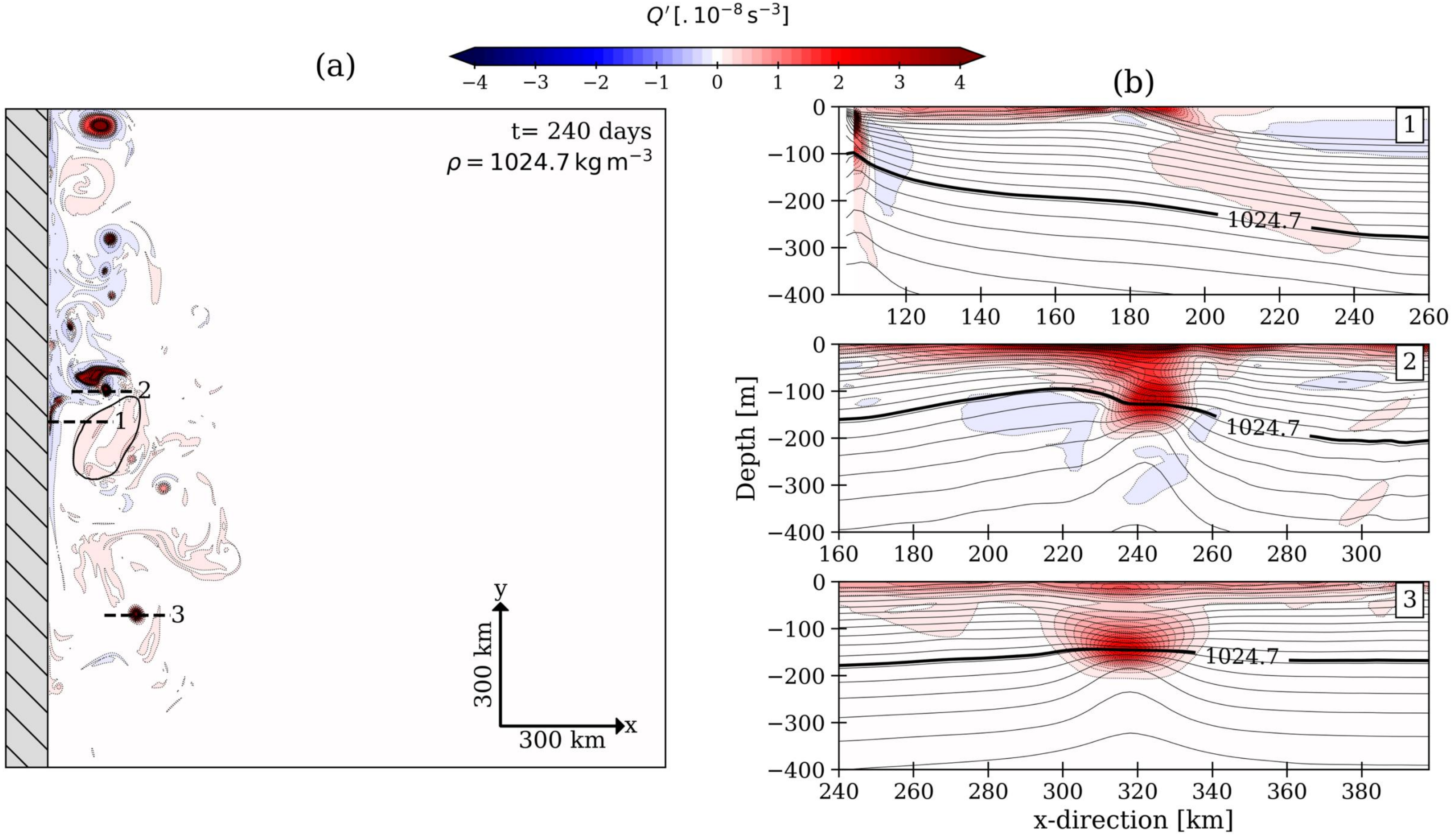


Relative vorticity at 143 m depth in a simulation with a larger anticyclone (R=100 km)



The process is efficient in generating long-lived Submesoscale coherent vortices

PV anomaly on (a) an isopycnal, and on (b) particular vertical sections in the simulation with a large anticyclone at t= 240 days. This simulation has larger horizontal and vertical resolutions (Δx = 2 km and Δz = 5m)



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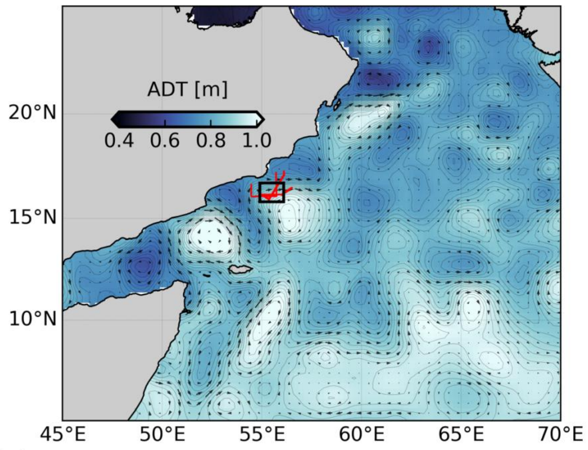
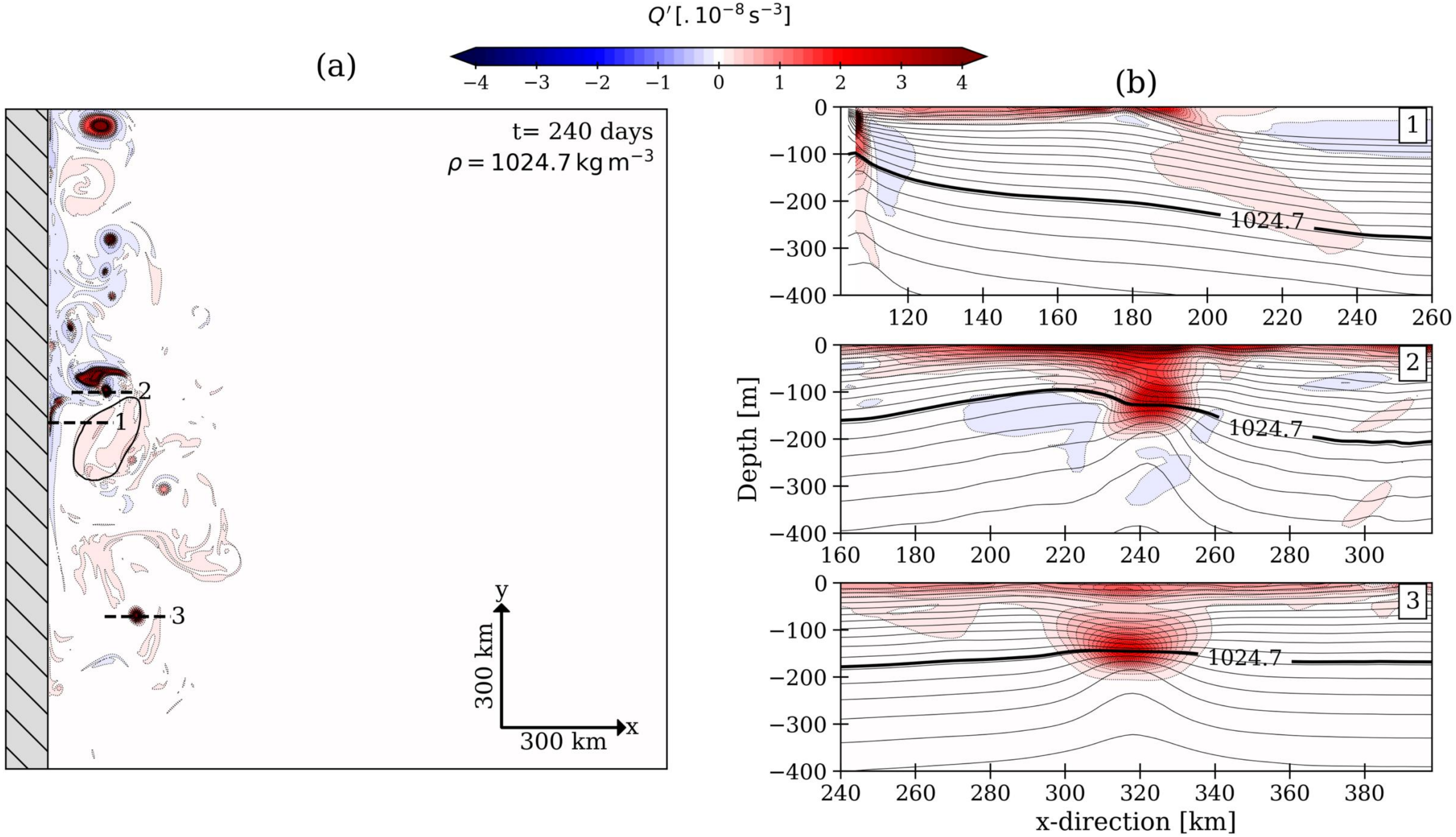


PHYSINDIEN 2019 measurements on May 2019

Evidence of this process in observations ?



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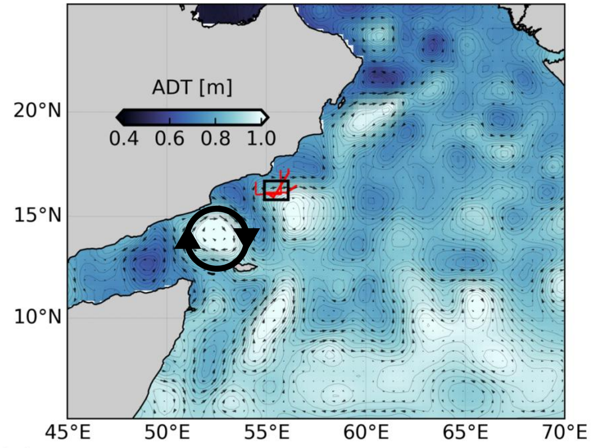
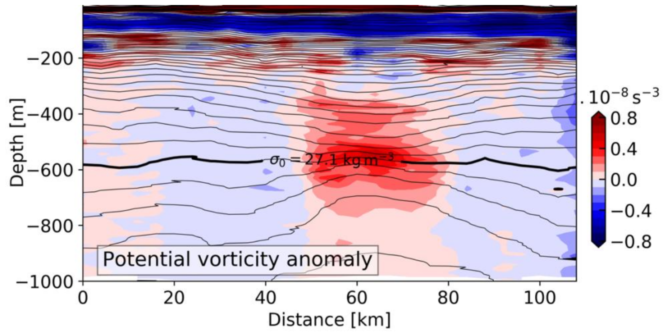
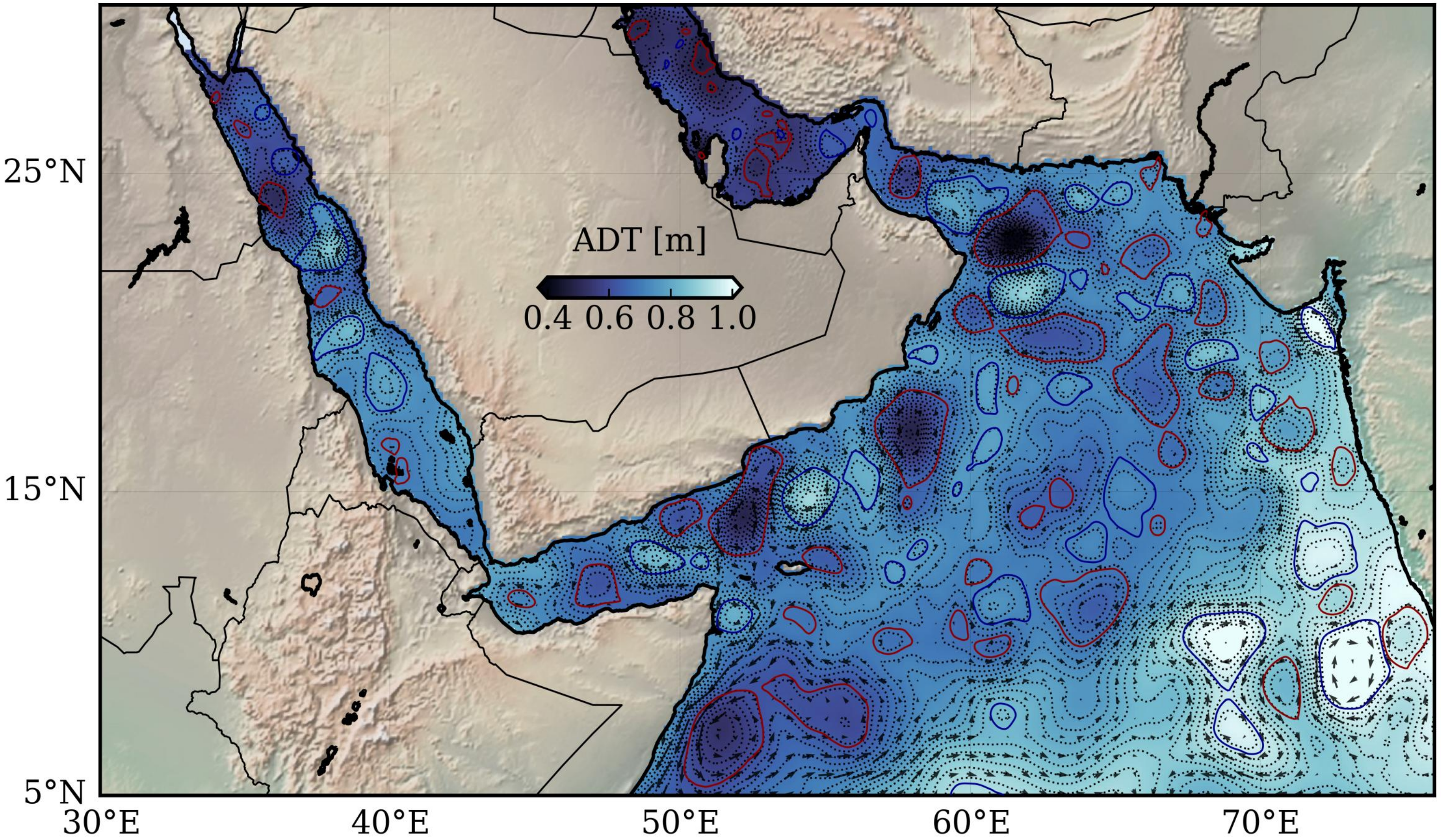


PHYSINDIEN 2019 measurements on May 2019



Vertical section of PV anomaly crossing a submesoscale coherent cyclonic vortex during the PHYSINDIEN 2019 experiment



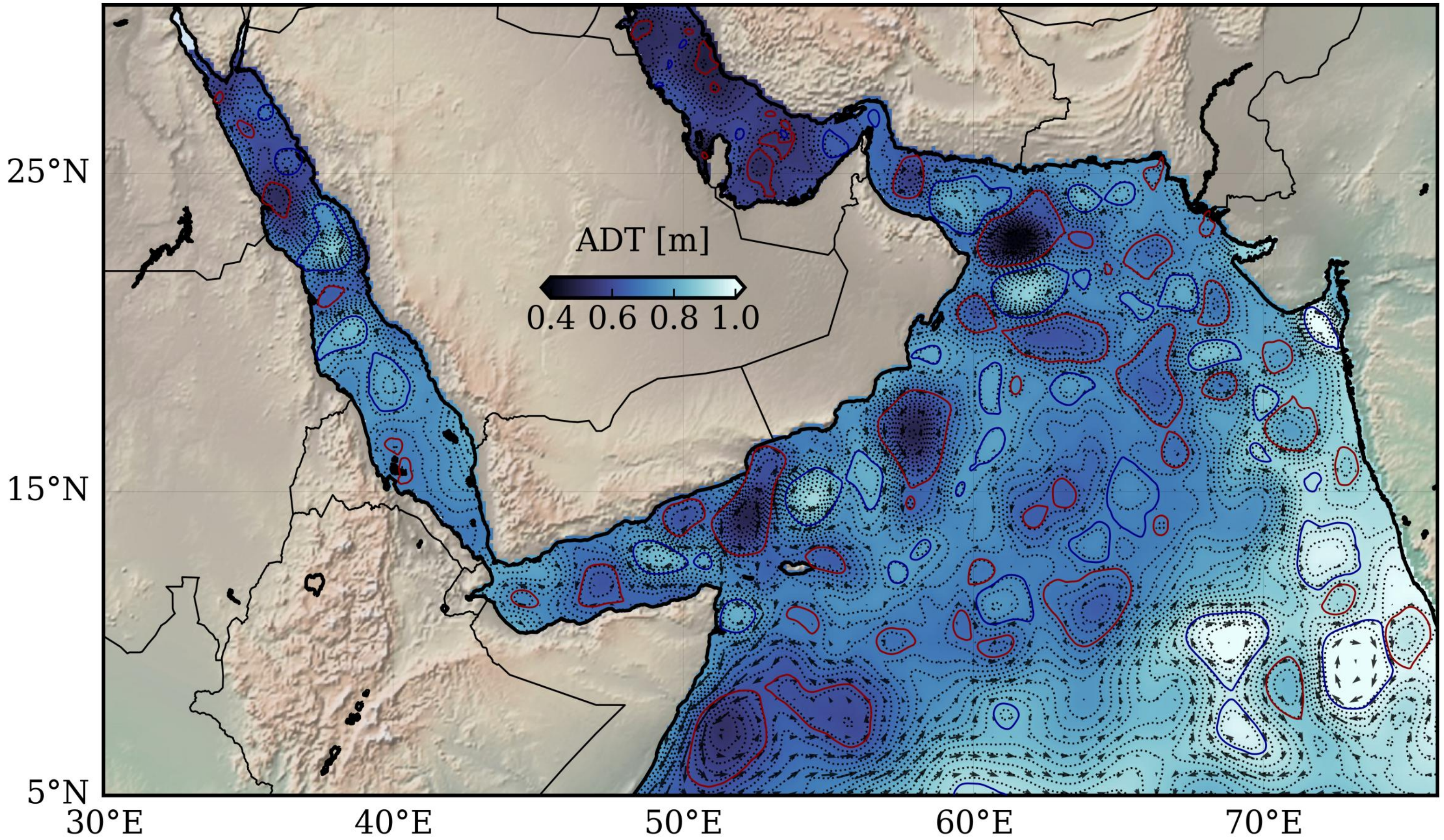
Altimetry on 18 February 2015; contours of cyclonic (red) and anticyclonic (blue) eddies detected from altimetry with a dedicated algorithm

1- What is the 3D structure of the Arabian Sea eddies, as revealed by in situ data ?[1]

2- What are the stability characteristics of Arabian Sea eddies ? Can these latter explain the occurrence of surface Submesoscale features ?[2]

3- What are the mechanisms involved in the interaction between mesoscale eddies and a western boundary ?[3,4]

[1]de Marez et al. 2019, [2]de Marez et al. 2020a, [3]de Marez et al. 2020b, [4]de Marez et al. 2020c



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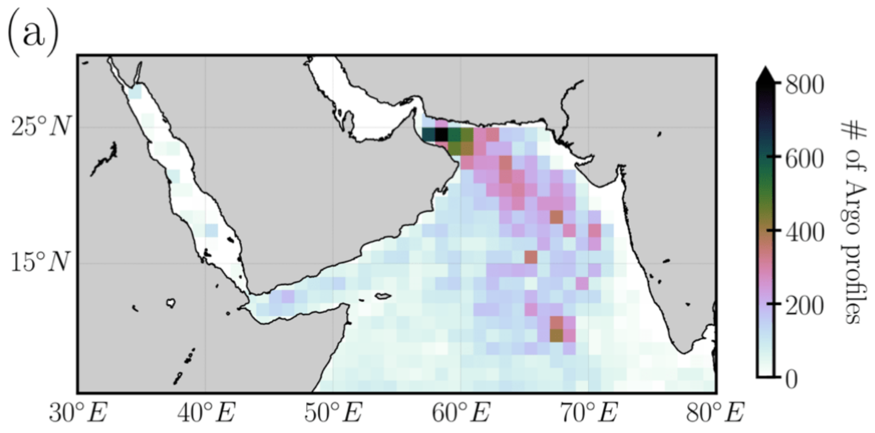
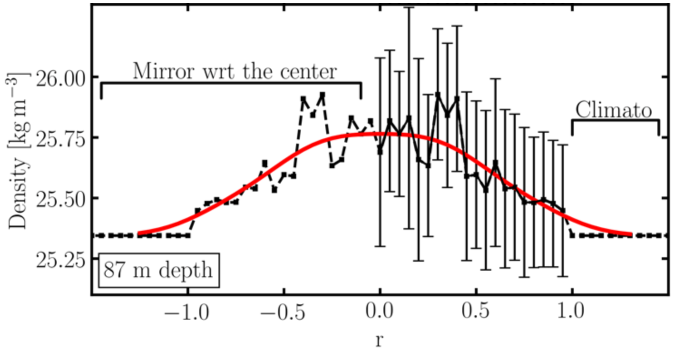


Distribution of Argo profiles used to determine the 3D shape of eddies



Smoothing procedure of the density of the composite cyclone representing the northern Arabian Sea

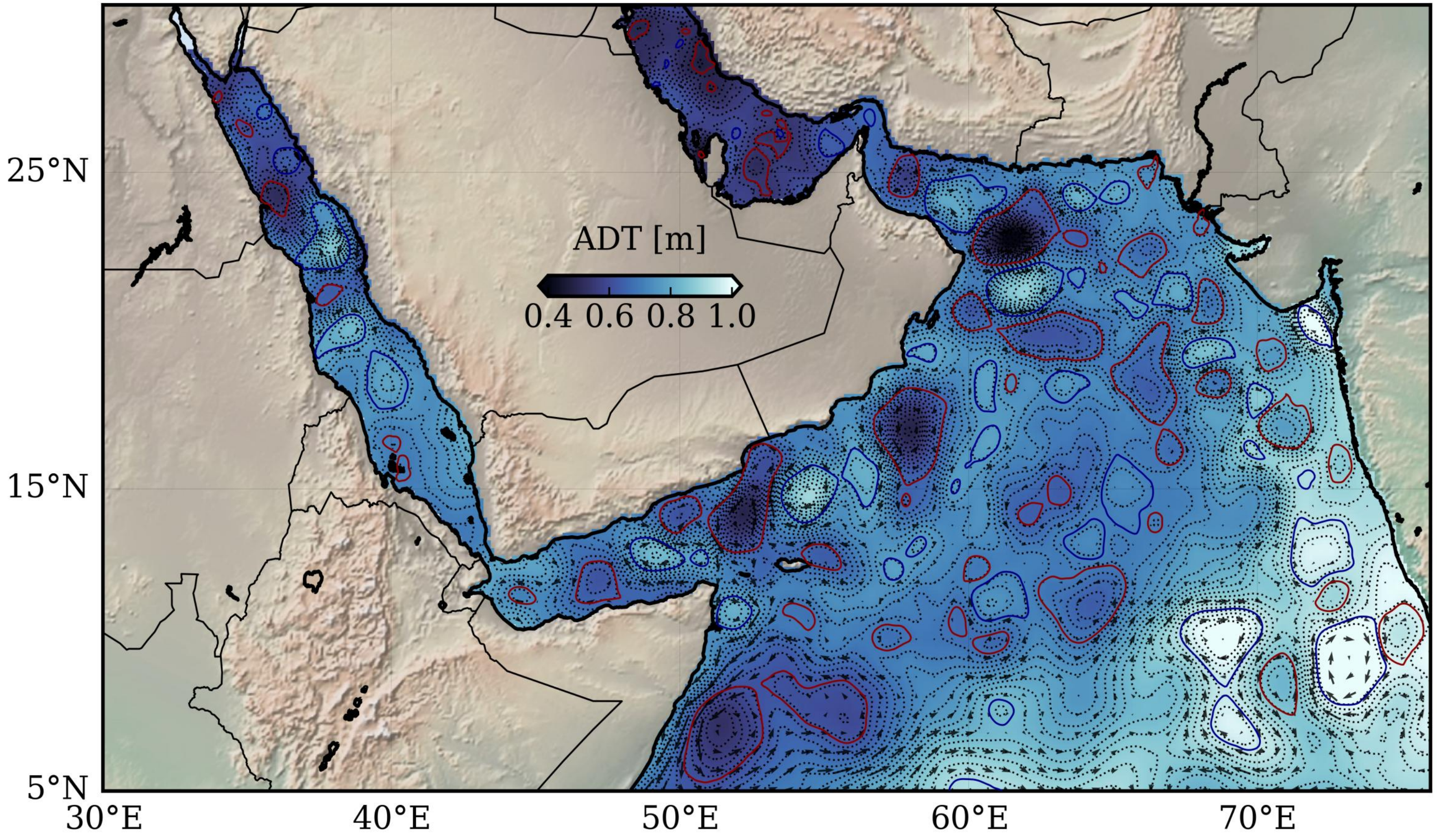
Lack of vertical profiles in regions of interest: Gulf of Aden, marginal seas, Gulf of Somalia…

→ Upcoming missions will allow to better sample the shape of mesoscale eddies in the Arabian Sea

Using a composite method forgets extreme values and misses the "real" shape of particular eddies

→ If enough profiles were available, better average solely the data in particular eddies[1,2,3]

[1]*Zhang et al. 2016,* [2]*Ioannou et al. 2017,2020,* [3]*Ayouche 2021*



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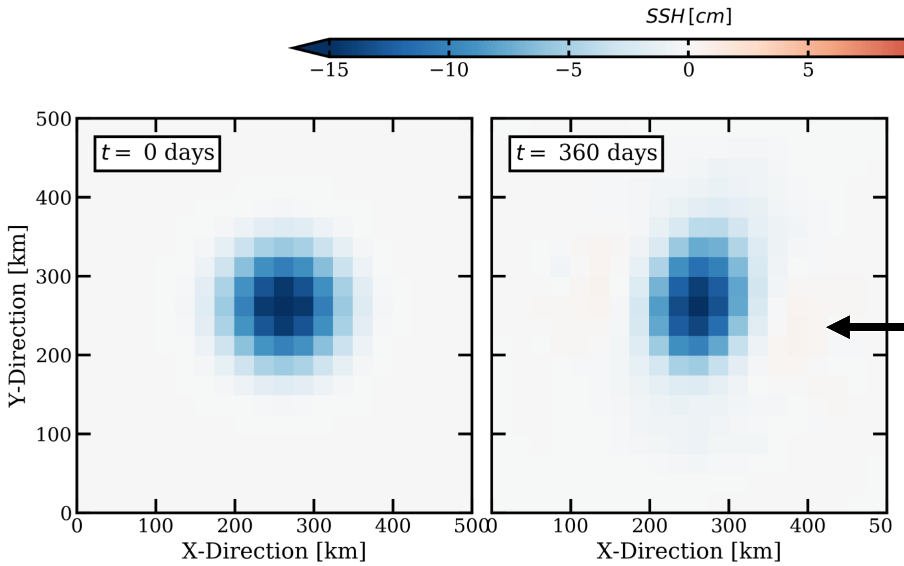
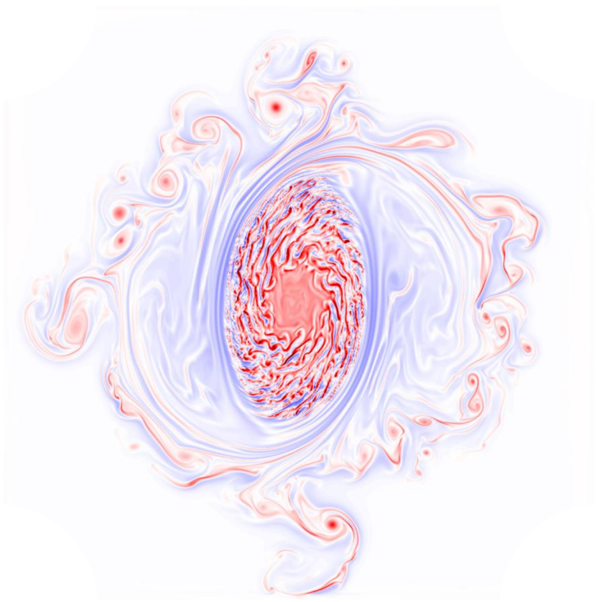
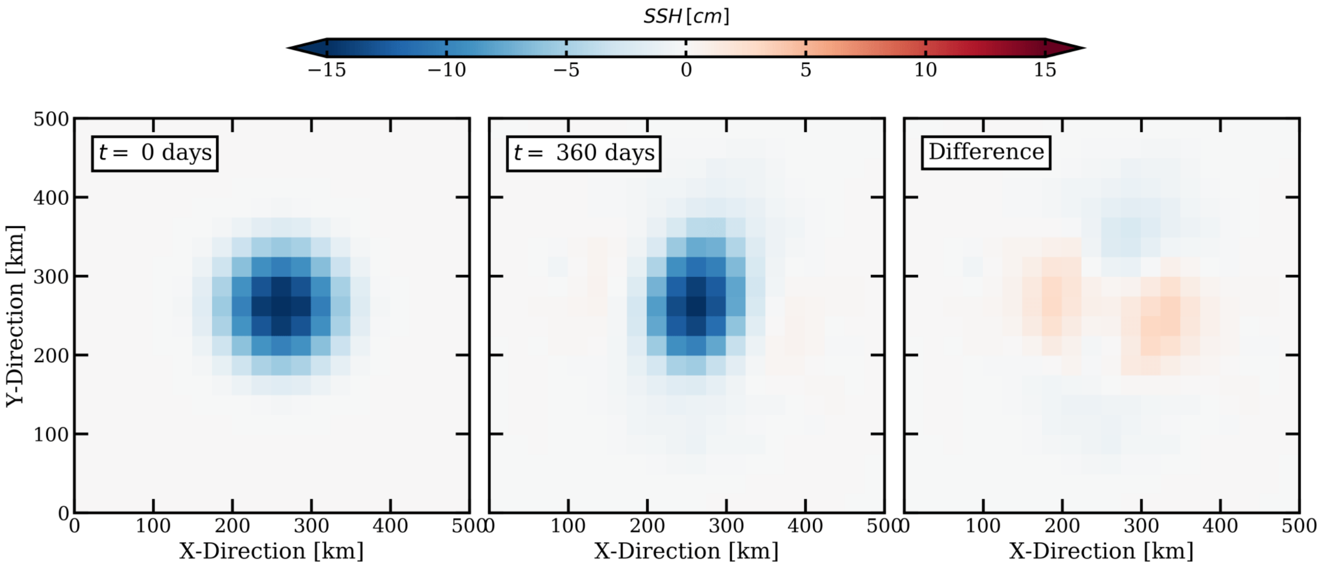


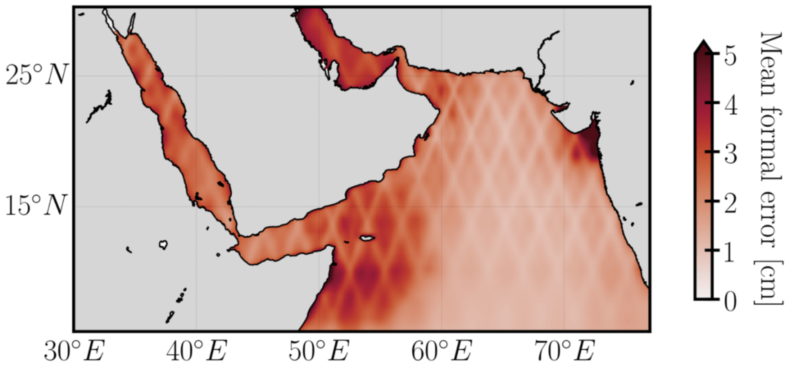
SSH signature of the eddy at the beginning and at the end of the simulation



Surface relative vorticity at t=360 days



SSH signature of the eddy at the beginning and at the end of the simulation

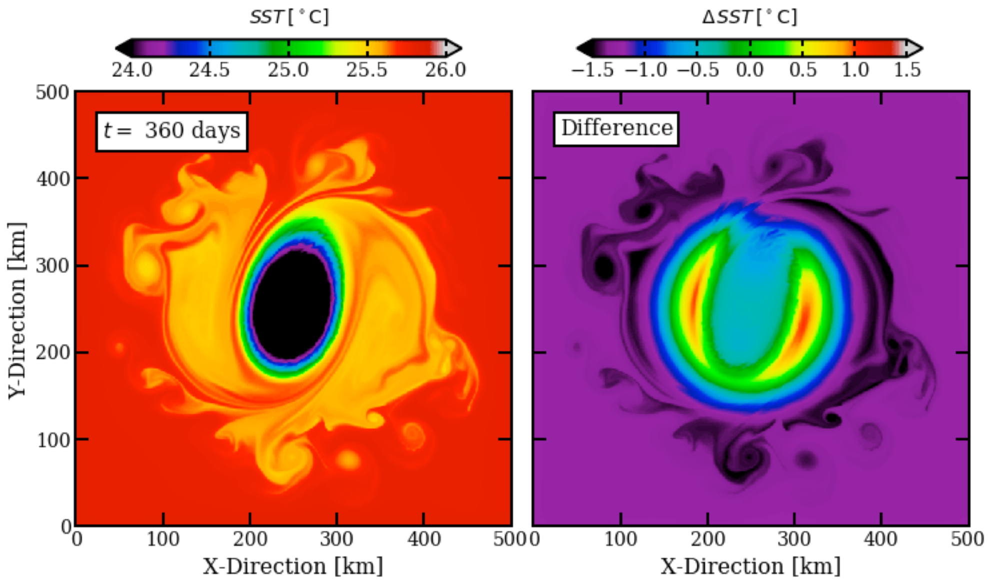


Formal mapping error[1] of the altimetric product used to construct the composite cyclone

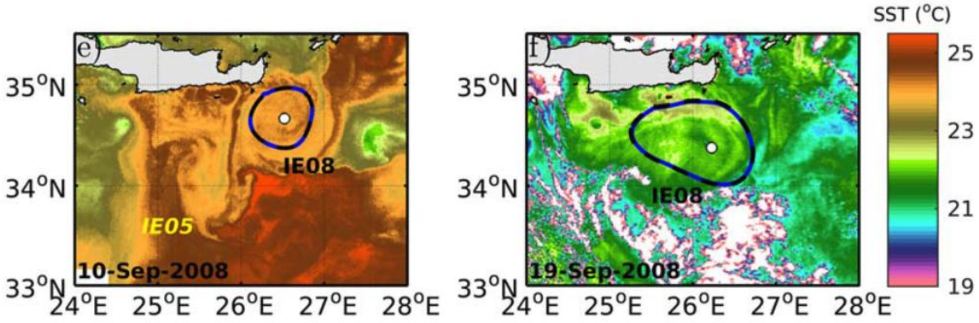
The destabilization (at meso and submesoscale) of the eddy cannot be seen in the SSH field

→ *To study the destabilization of eddies using data, needs to use other datasets (SST[2,3], chlorophyll-A[4,5]…)*

[1]*Le Traon et al. 1998,* [2]*Assassi et al. 2016,* [3]*Ioannou et al. 2017,* [4]*Lévy et al. 2018,* [5]*Ciani et al. 2021*



SST signature of the eddy at the end of the simulation

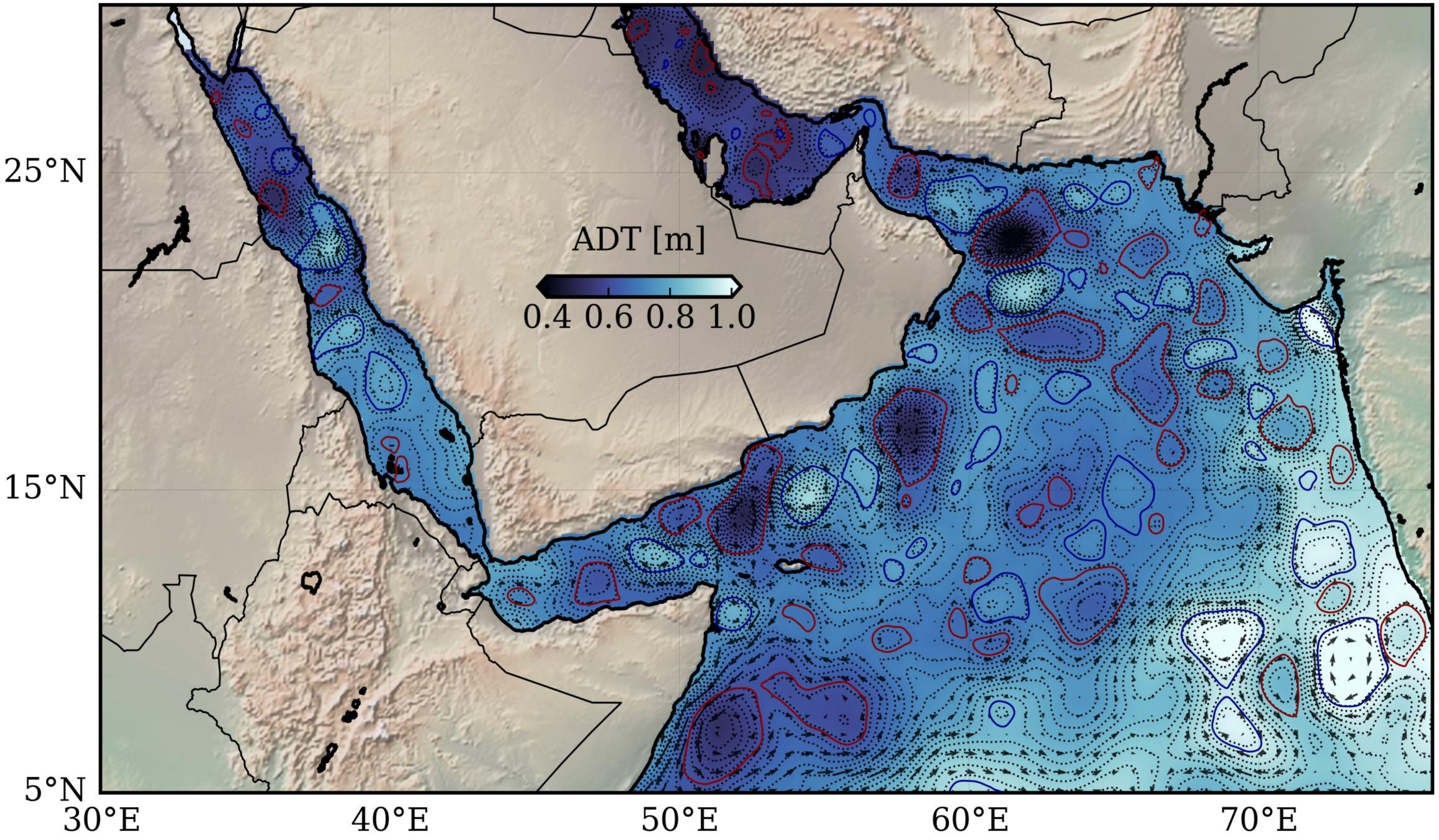


Ierapetra Eddy Sea SST signature from satellite data[1]

The destabilization (at meso and submesoscale) of the eddy can be seen in the SST field

→ *This might allow to assess the realism of this idealized setup, and determine the most instable modes of "real-life" oceanic eddies*

[1]*Ioannou et al. 2017*



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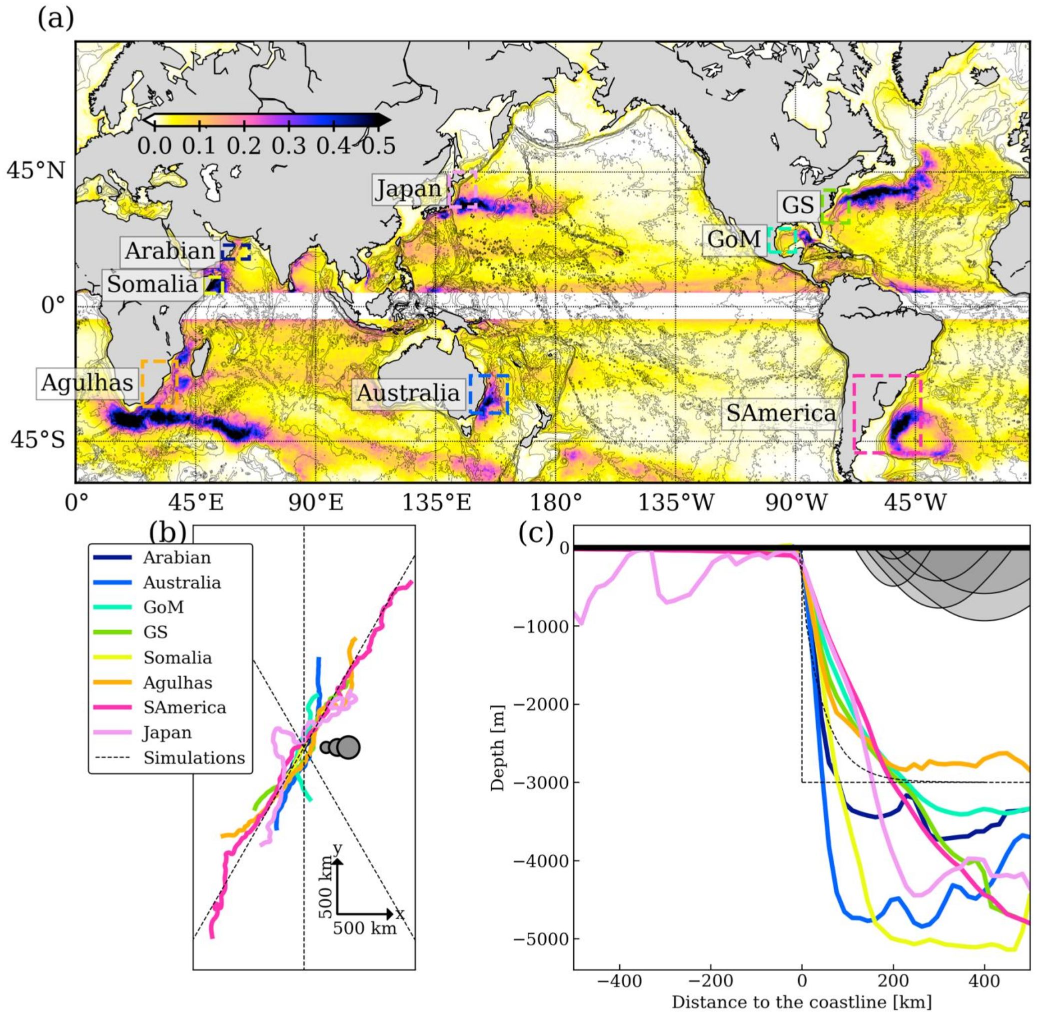
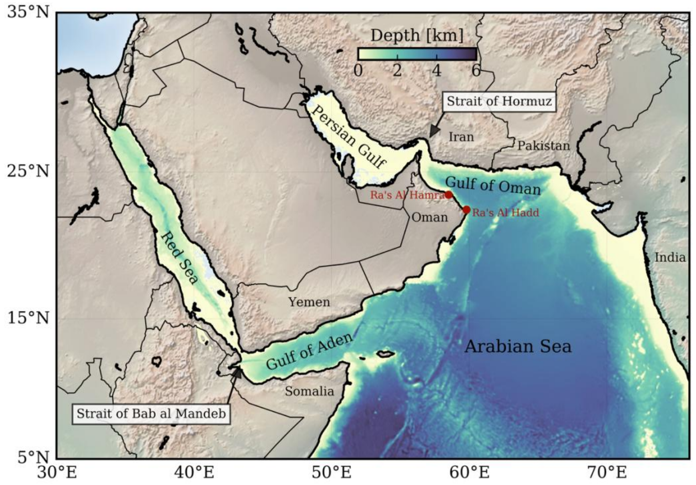


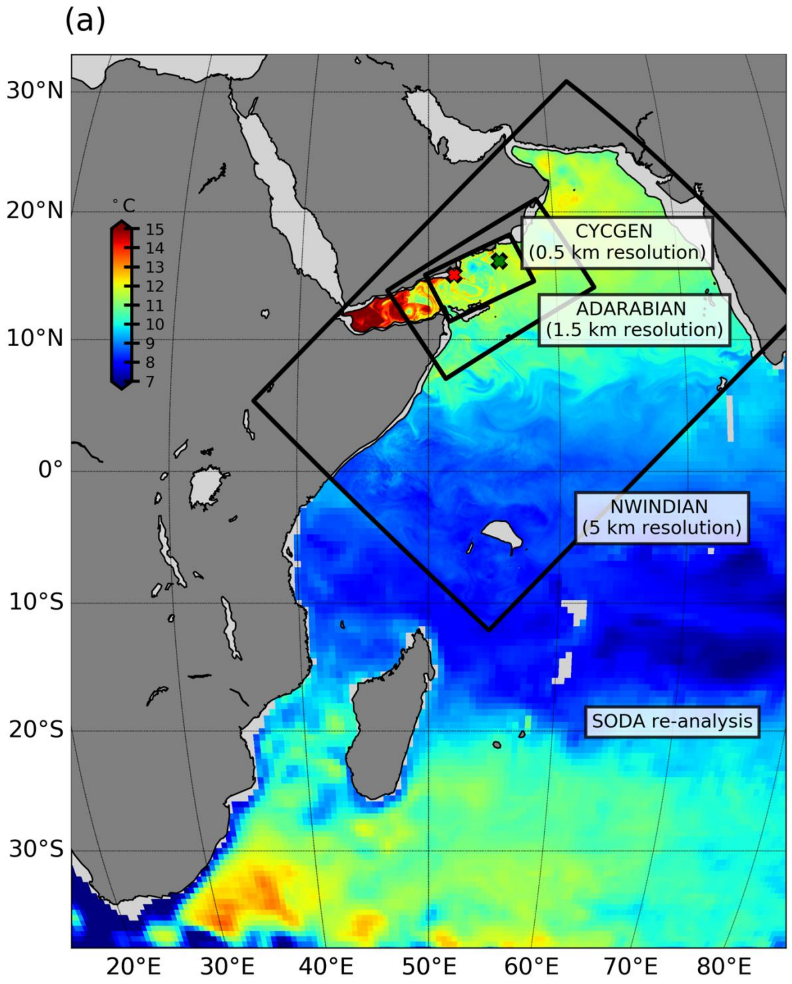
Principal western boundary systems and associated topography



Bathymetry of the Arabian Sea

Presence of shelfs and topographic anomalies near western boundaries leading to a possible modification of the vortex-wall interaction

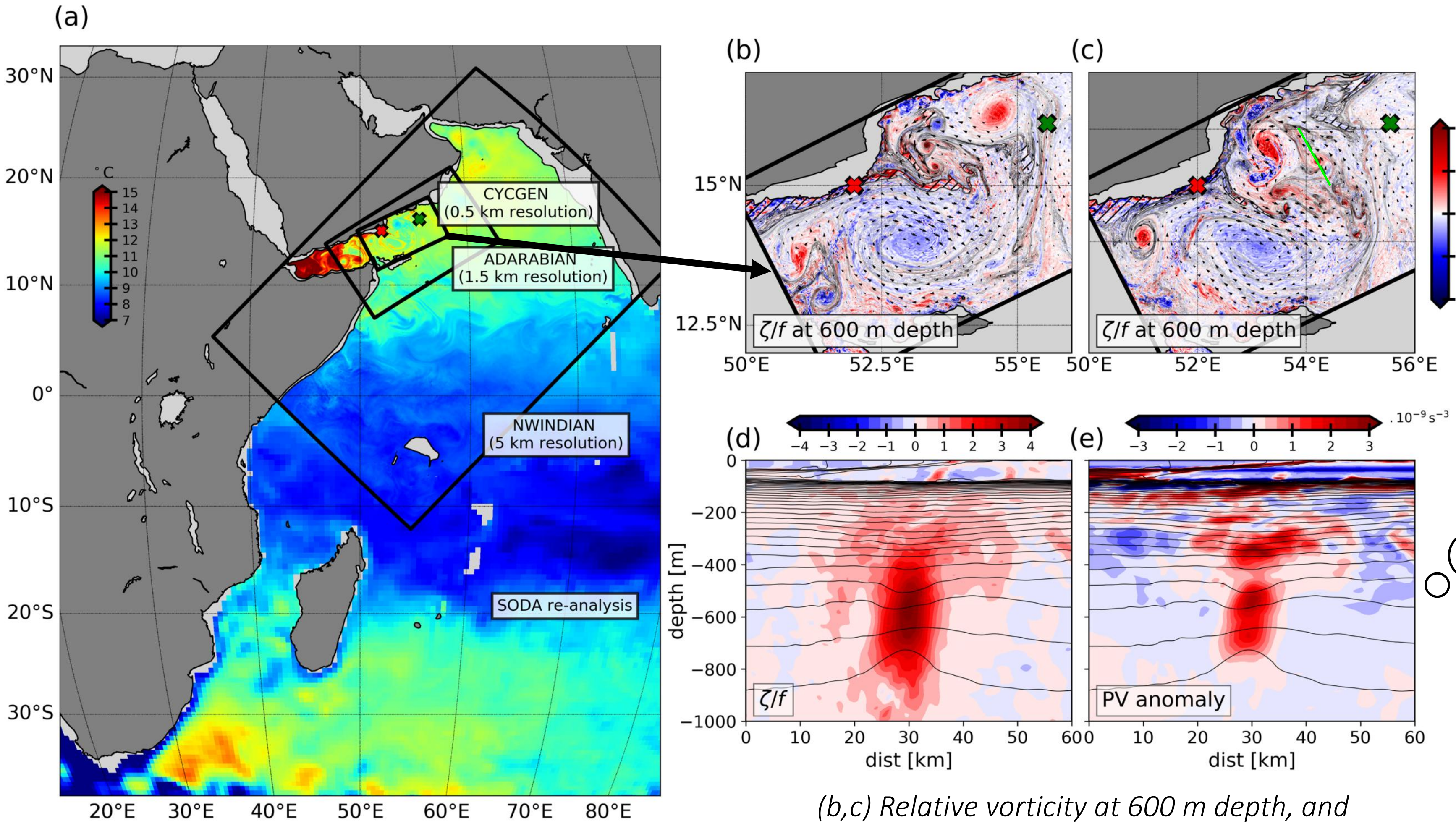
→ Need to consider the generation of topographic Rossby waves and lee eddies near western boundaries



Setup of a realistic simulation designed to study the interaction between vortices and the coast of Yemen

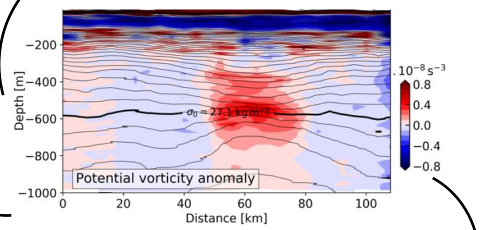
Presence of other vortices, bottom friction, and boundary layer near western boundaries

→ *Study the vortex-wall interaction in realistic simulations*

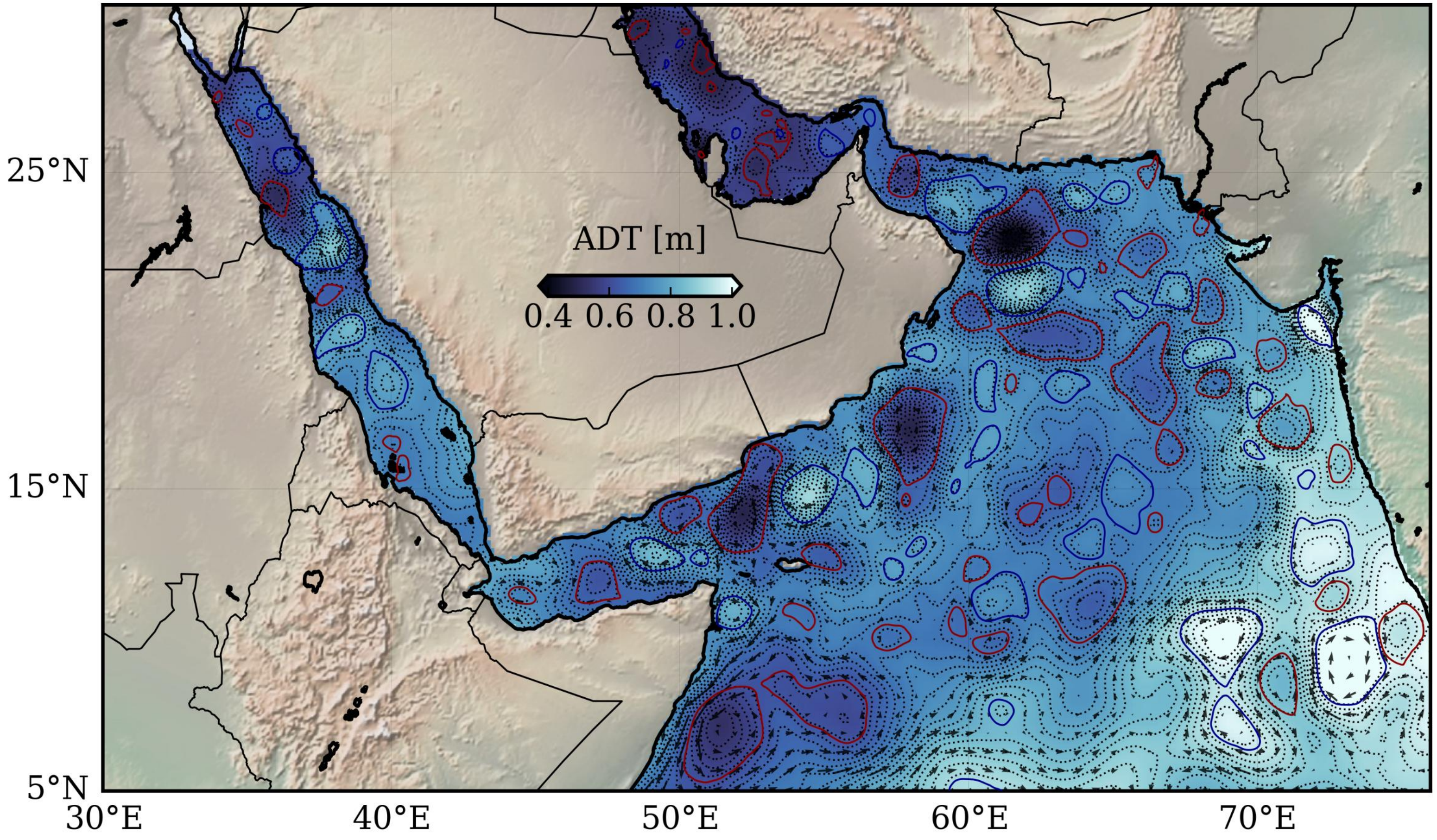


Setup of a realistic simulation designed to study the interaction between vortices and the Somalian coast

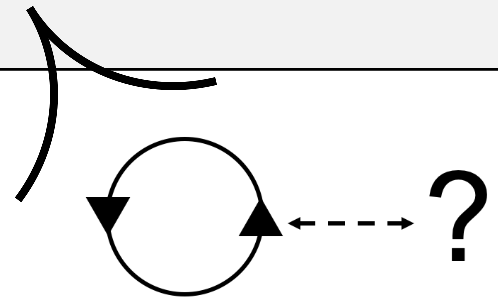
(b,c) Relative vorticity at 600 m depth, and (d,e) vertical section of relative vorticity and PV along the green line shown in (c).



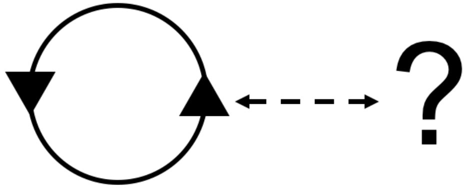
The cyclonic SCV observed during PHYSINDIEN 2019



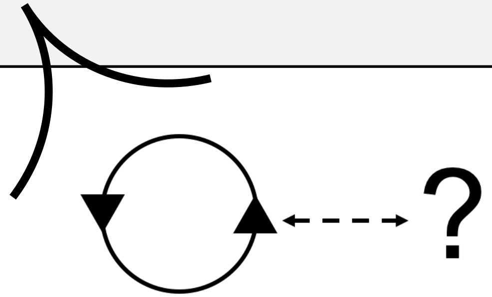
Altimetry on 18 February 2015; contours of cyclonic (red) and anticyclonic (blue) eddies detected from altimetry with a dedicated algorithm

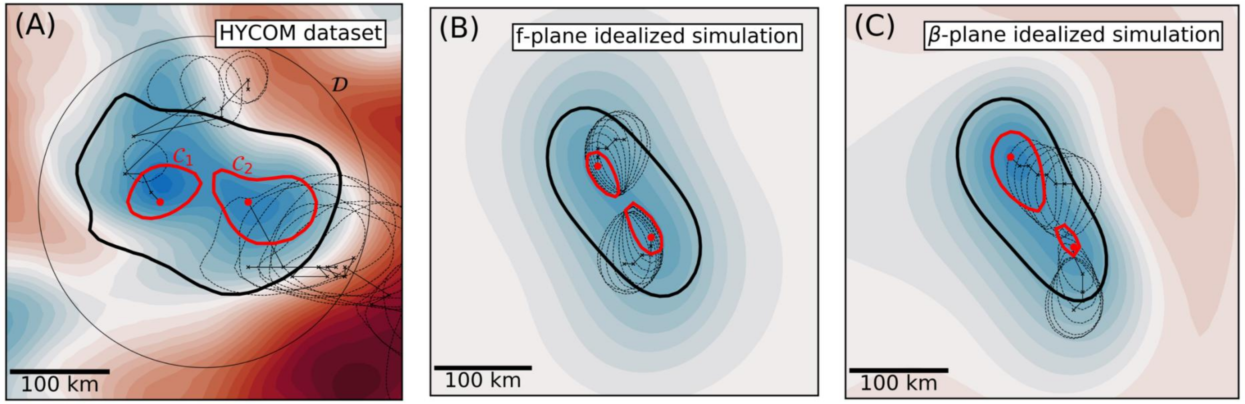


4- What are the characteristics of the interaction between vortices and other dynamical structures ?[1,2,3]

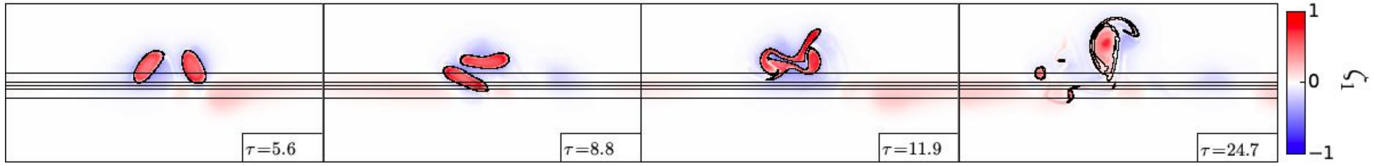


[1]*de Marez et al. 2017,* [2]*de Marez et al. 2020d,* [3]*de Marez & Carton 2021b*





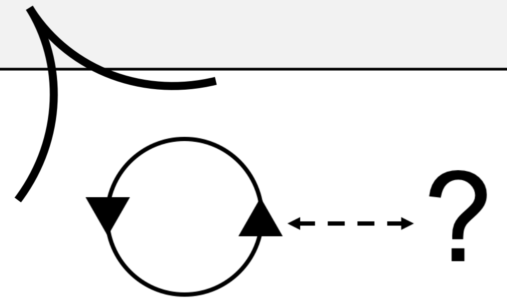
Example of a detected merging event involving two cyclones (a), and idealized simulations on the f-plane (b) and the β-plane (c)

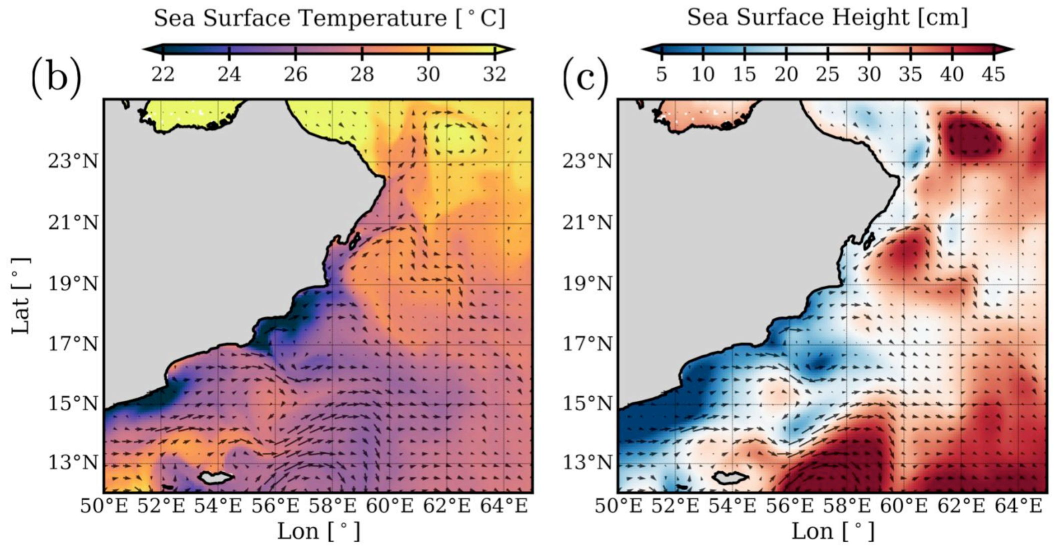


Example of an idealized simulation of cyclones merging in the presence of a continental shelf

The interaction between vortices leads to the generation of different regimes depending on the vortex characteristics and their environment

→ Study of vortex merger in the Arabian Sea and the global ocean context using altimetric data and idealized simulations

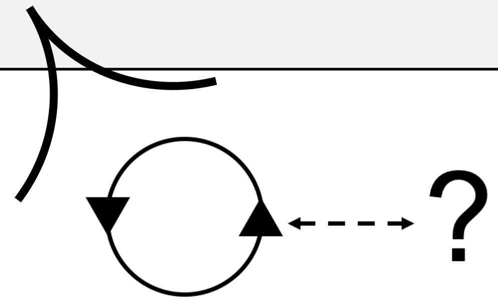


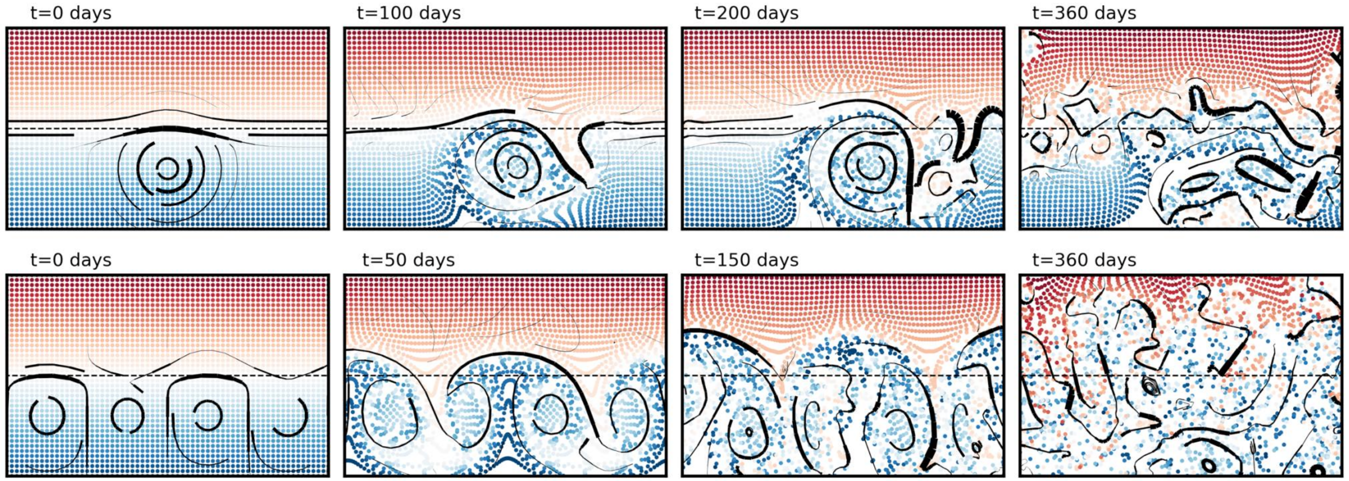


Interaction between the Omani upwelling and the mesoscale eddy field as observed by satellite on 05/08/2020, SST (left), SSH (right)

In the Arabian Sea, the mesoscale eddy field interacts with the Omani upwelling as vortices are pushed towards the coast

→ *Study of the upwelling-vortex interaction in idealized simulations, and its impact on cross-shore particle exchange*

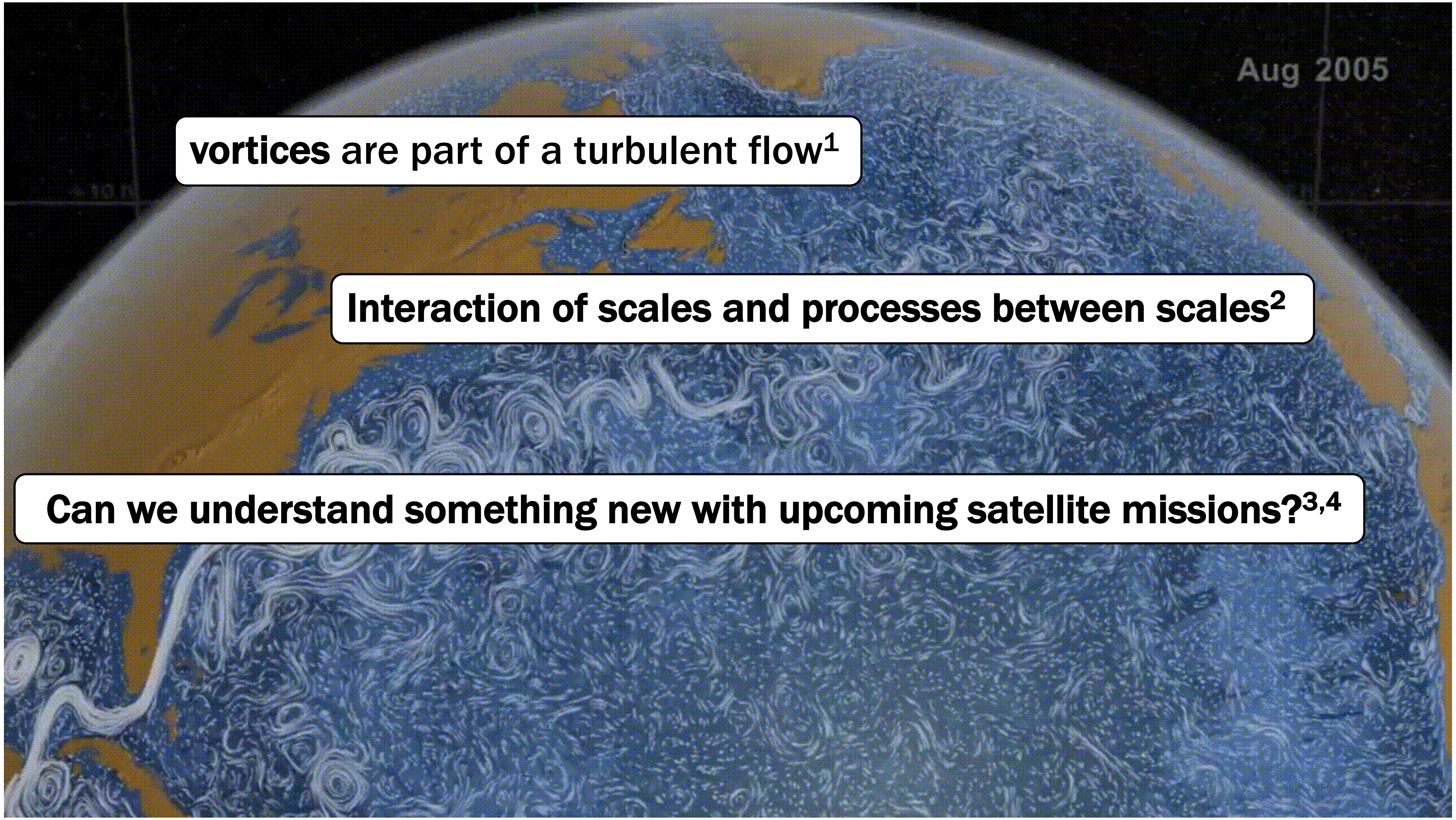




Example of simulation outputs of upwelling-vortex interactions in single (top) or multiple (bottom) eddy cases

In the Arabian Sea, the mesoscale eddy field interacts with the Omani upwelling as vortices are pushed towards the coast

→ *Study of the upwelling-vortex interaction in idealized simulations, and its impact on cross-shore particle exchange*



Surface currents in a high resolution simulation of the Earth's oceans (svs.gsfc.nasa.gov)

[1]McWilliams 1984, [2]Danilov 2000, [3]Fu & Ferrari 2008, [4]Callies 2019a

Thanks for listening