Geostrophic Turbulence
Lessons learned from ocean observations

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Results from different PhD works:
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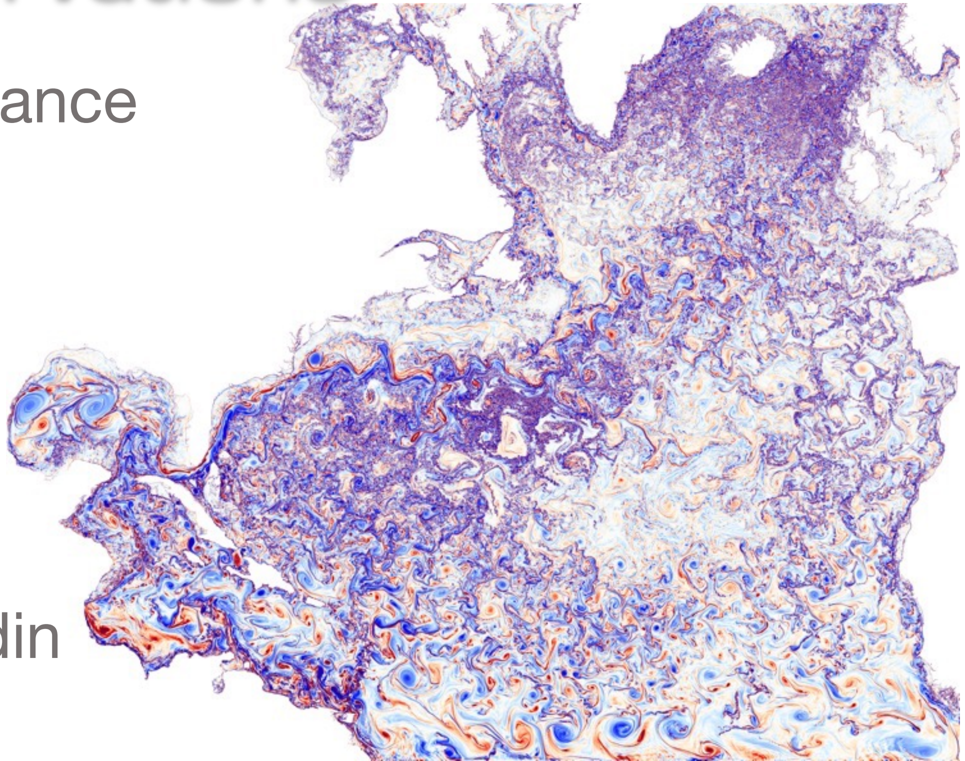
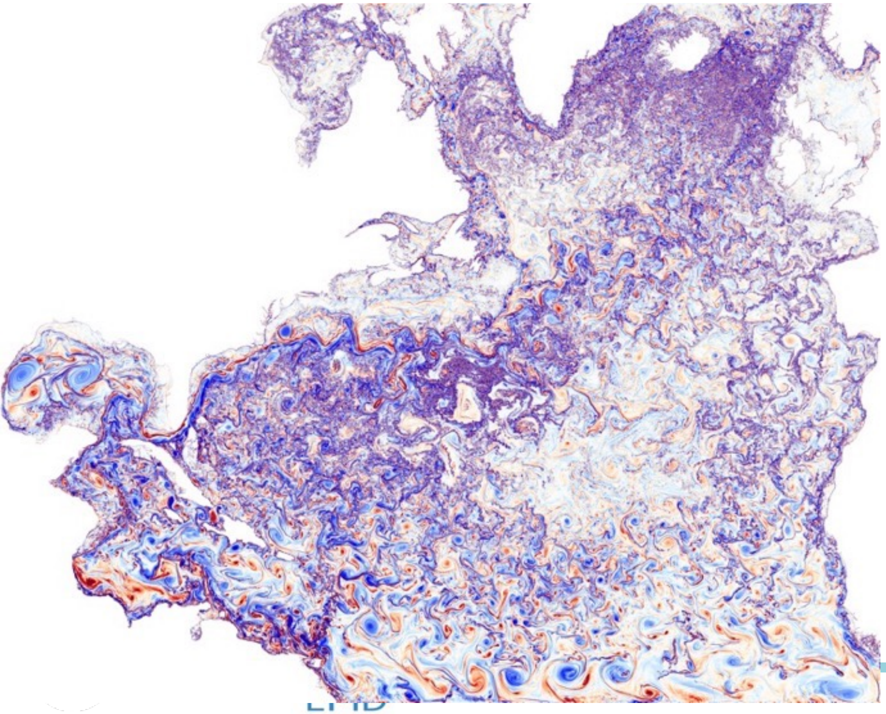
S. Coadou-Chavendon, G. Manta, Y. Chen

& from collaborations with:
B. Blanke, X. Carton, J. Karstensen, G. Reverdin



MOTIVATION

- **State of knowledge:** Observations and modelling still **raise more questions than answers** about the nature, phenomenology, and impacts of ocean small-scale dynamics (incl. geostrophic turbulence).
- **In situ limits:** Classical in situ **observations are sparse**, low-resolution, and snapshot-like (campaigns over weeks).
- **Satellite limits:** Satellite observations are **largely surface-restricted**.
- **Model limits:** Models remain constrained by **resolution, parameterizations, boundary interactions, forcing**, and **uncontrolled numerics** (e.g., numerical diffusivity, effective resolution), with **limited validation against real baroclinicity and dynamics**.

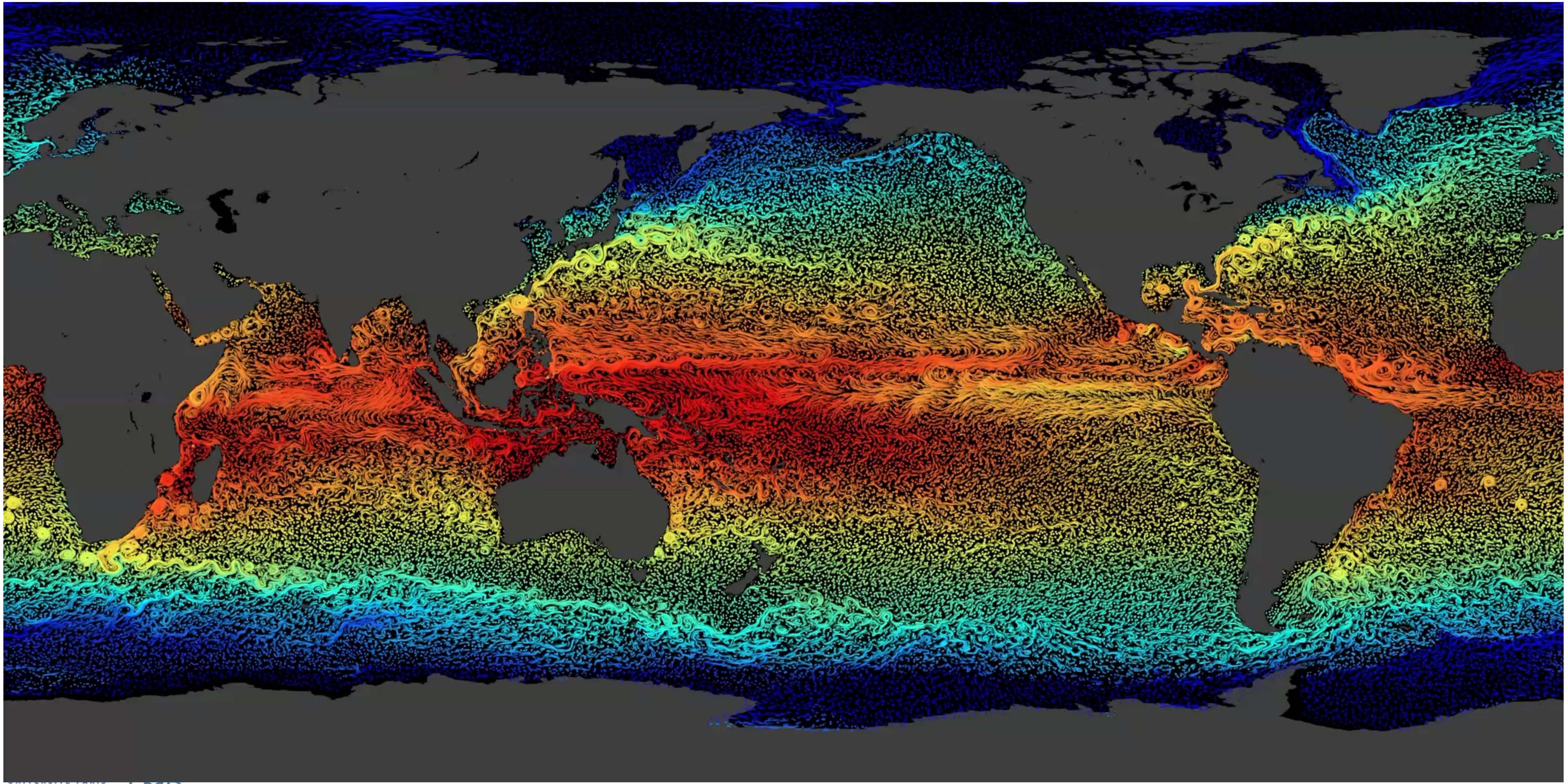


PLAN

Ocean Mesoscale Eddies: Structure and Evolution from Satellite and In Situ Observations

- How many eddies are there? Global and regional estimates
- Surface vs. subsurface signatures: what do we observe?
- Geostrophy, cyclostrophy… and beyond: what dynamics govern eddies?
- Are eddies truly coherent structures? What does "coherent eddy" actually mean?
- Open questions on eddy dissipation and lifespan

Ocean small-scale dynamics: ECCO Ocean State Estimate
(i.e. an ocean model assimilating satellite and in-situ observations)



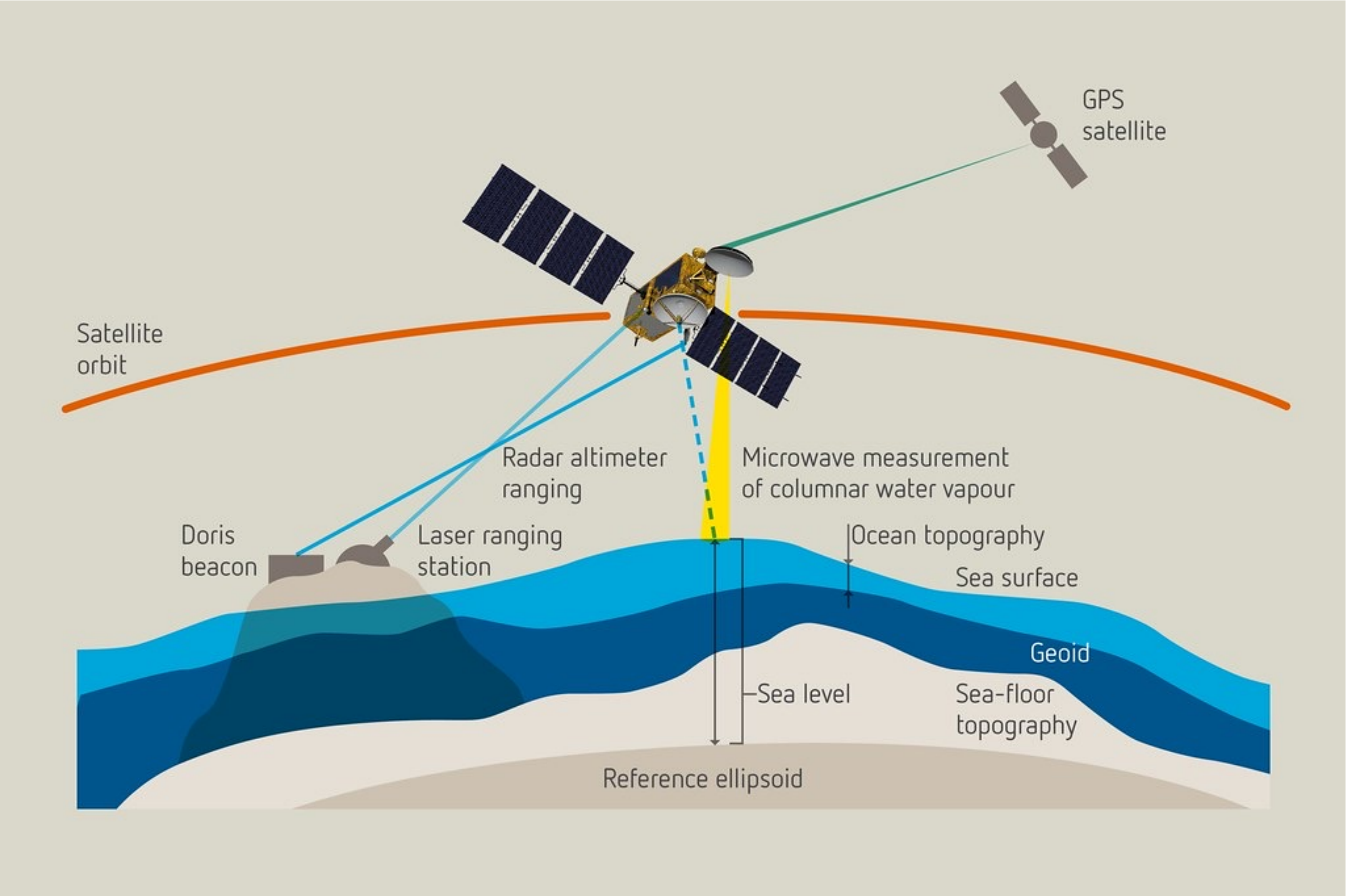
Satellite Radar Altimetry: What It Measures and How It Works

What Satellite Altimeters Measure

Satellite altimeters measure the height of the sea surface relative to the satellite, enabling estimates of:

Sea Surface Height (SSH)

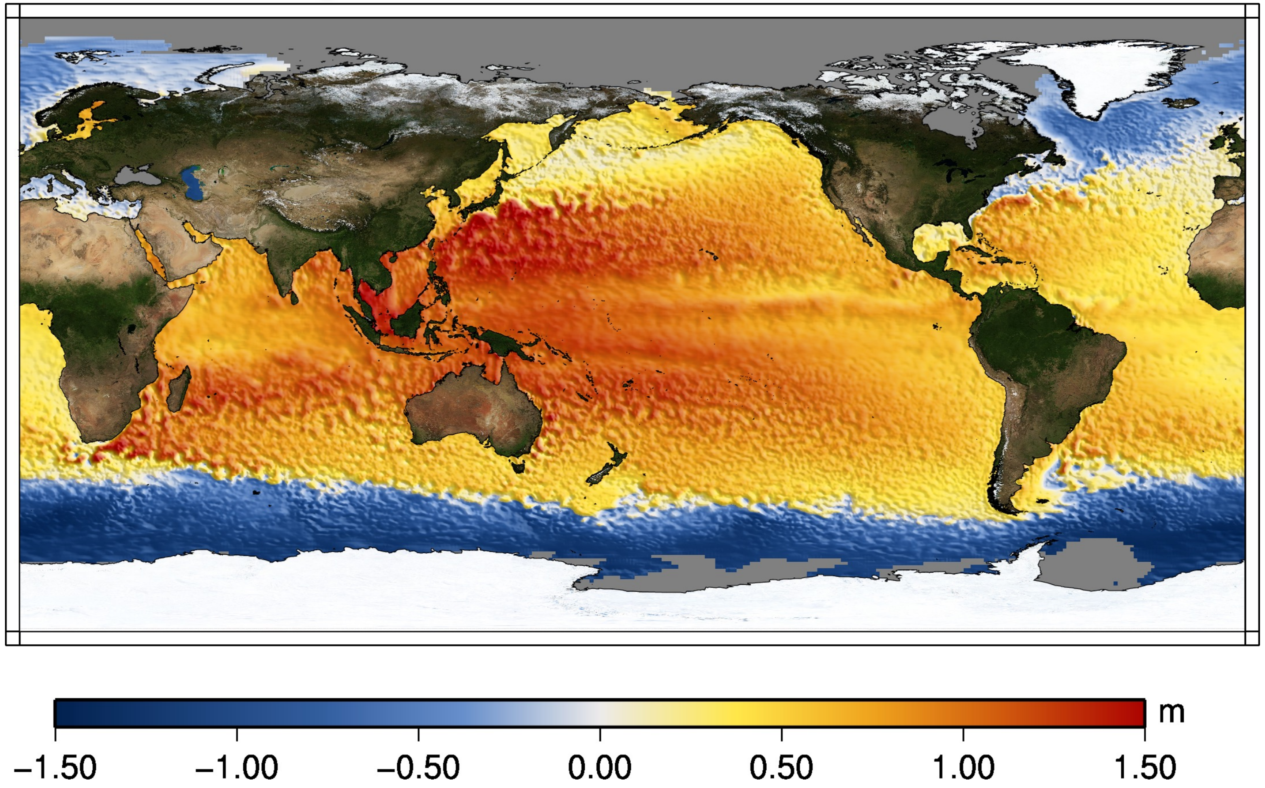
- The primary measurement: distance between the satellite and the sea surface.
- From SSH, we can derive:
  - ➢ Absolute dynamic topography (sea surface height relative to the geoid)
  - ➢ Ocean currents (via geostrophic balance)
  - ➢ Mesoscale eddies, fronts, and large-scale gyres



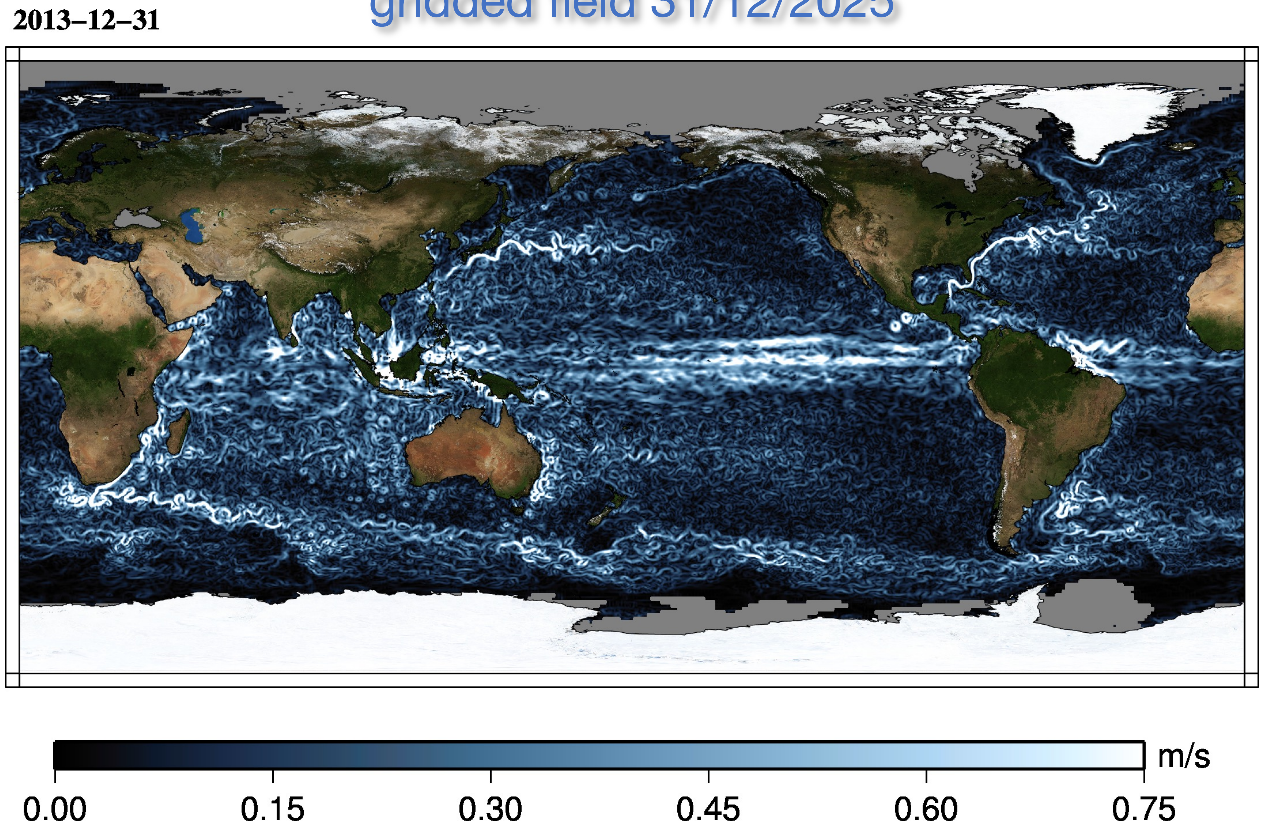
This diagram shows how the Jason satellite series measure ocean surface height.
Copyright 2015 EUMETSAT

Ocean small-scale dynamics: Satellite Altimetry observations

Ocean Absolute Dynamic Topography gridded field 31/12/2025

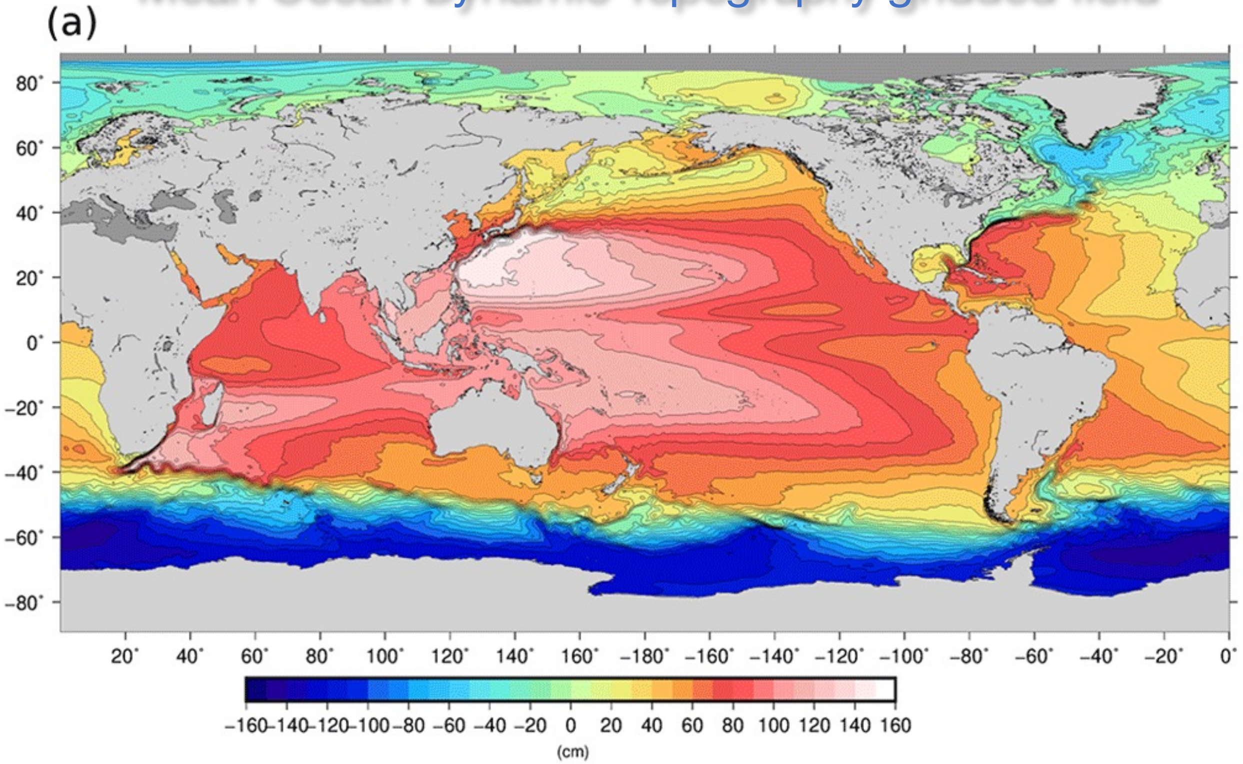


Derived Surface Geostrophic Velocity gridded field 31/12/2025

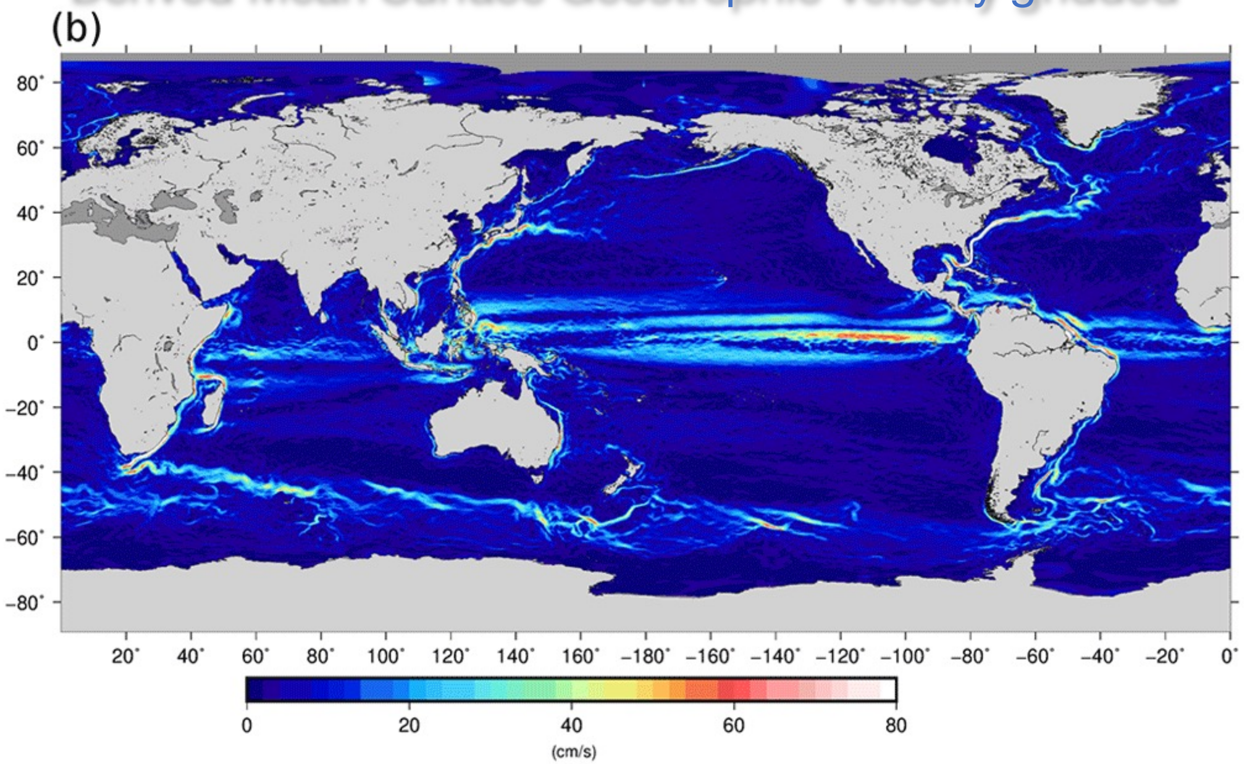


Ocean small-scale dynamics: Mean Dynamic Topography

Mean Ocean Dynamic Topography gridded field



Derived Mean Surface Geostrophic Velocity gridded



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What Dynamic Topography really is?

Dynamic topography (or **dynamic sea surface height**) is the part of the sea surface height that is caused by ocean dynamics—that is, by variations in density and pressure within the ocean, and by currents.

Formally:
Dynamic Topography = Sea Surface Height–Geoid Height

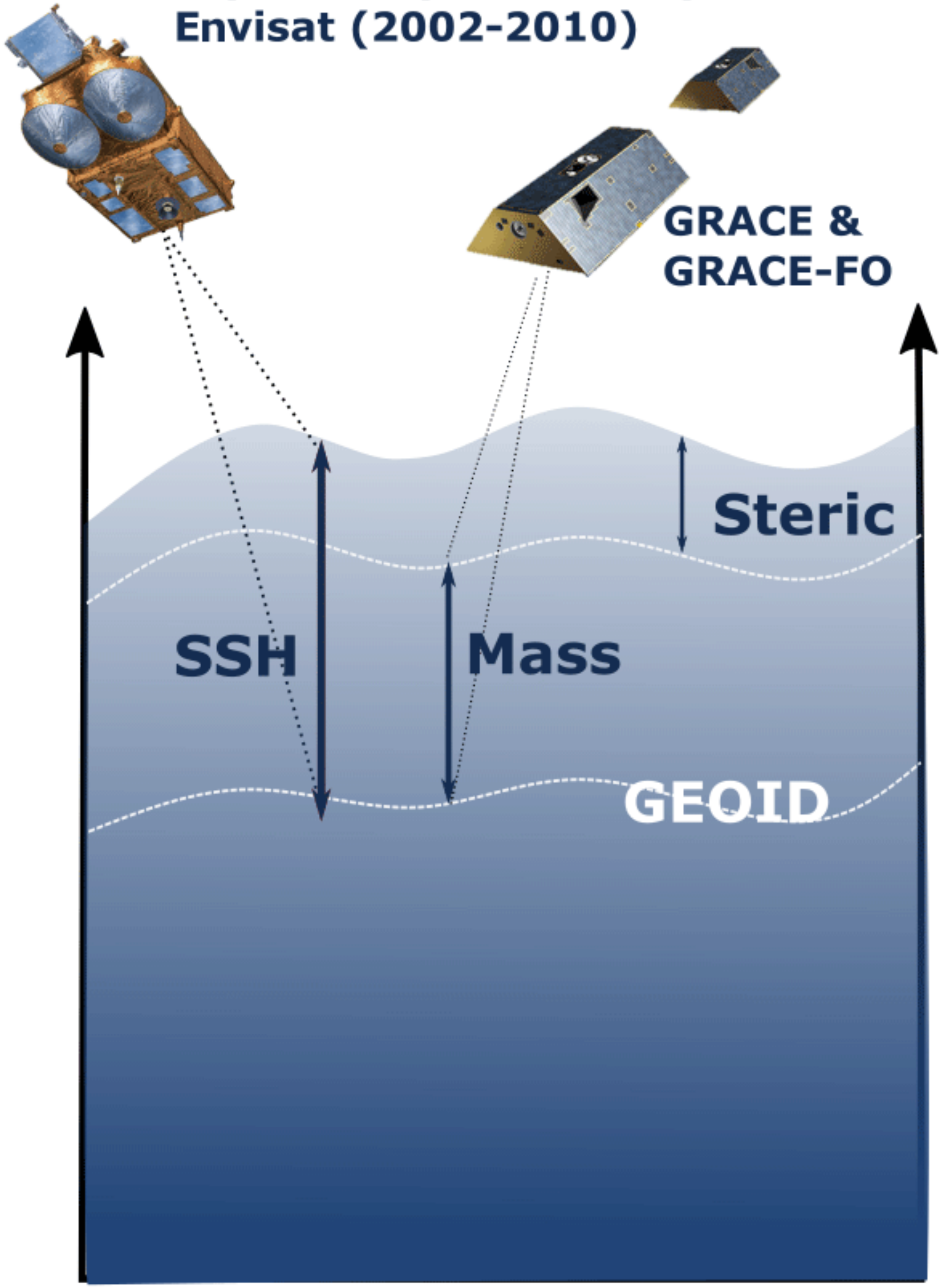
The geoid is the surface the ocean would have if it were at rest, without currents, only shaped by gravity.

Thus:

➡️ **Dynamic topography** = **how much the real sea surface deviates from the "resting" ocean.**

➡️ These deviations are signatures of **horizontal pressure gradients, density structure, and geostrophic currents**.

Steric height (or steric sea level) is the **portion of sea level change** caused **by variations in temperature and salinity** of the ocean, rather than by added water mass (like from melting glaciers).



Dynamic Topography ≈ Steric Height

The term **"steric"** comes from the Greek word "stereos," meaning **solid** or **volume**.

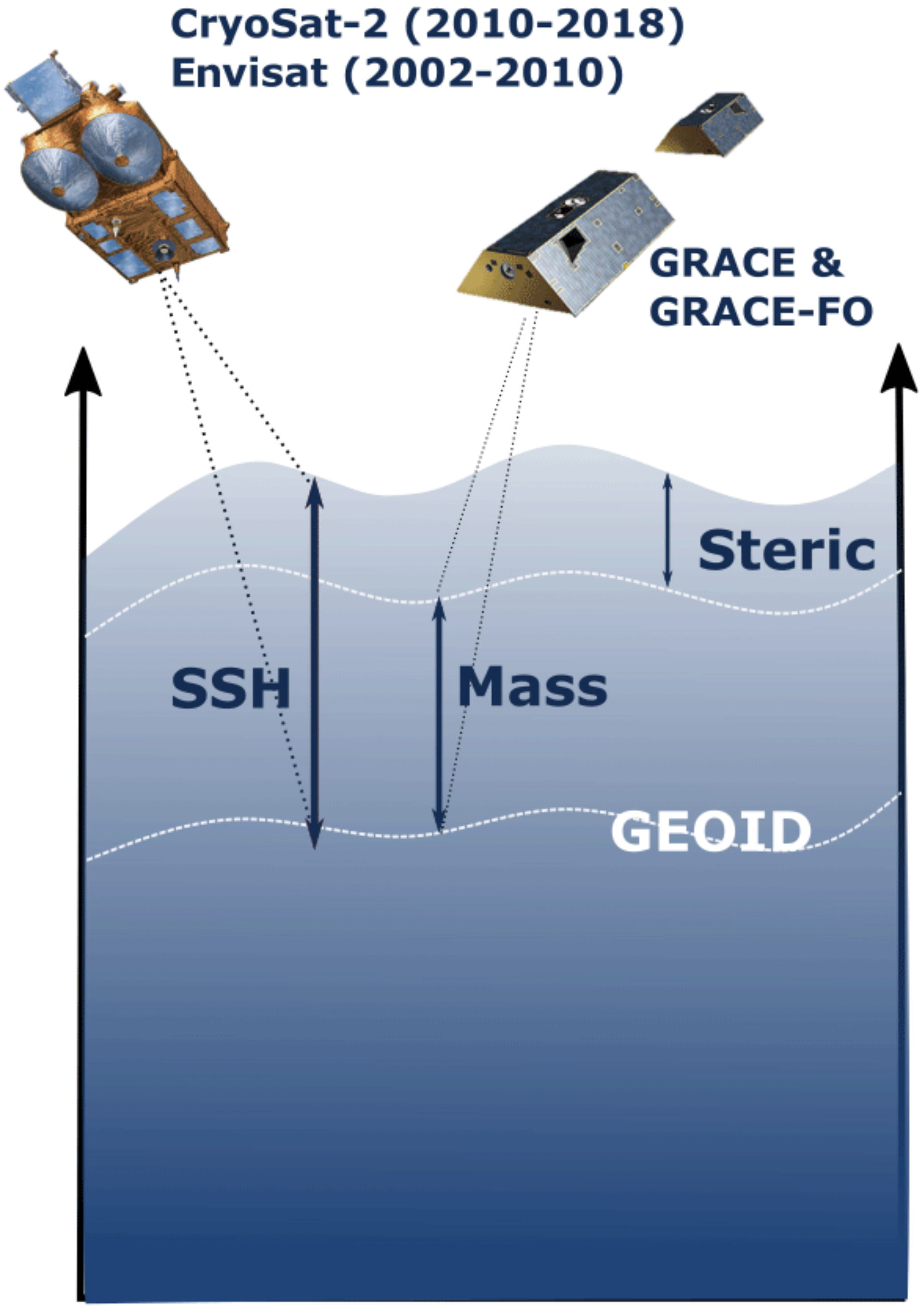
The **density of seawater** is affected by:

- 🌡️ **Temperature**: Warm water is less dense and expands.
- 🧂 **Salinity**: Saltier water is denser and contracts.

When ocean water becomes **warmer** or **less salty**, it expands, leading to **increased steric height**. Conversely, cooling or increased salinity reduces steric height.

$$\eta_s = \int_{-H}^{0} \left(\frac{\rho_0 - \rho(z)}{\rho_0} \right) dz$$

- η_s: Steric height
- $\rho(z)$: Density at depth z
- ρ_0: Reference density



Dynamic Topography ≈ Steric Height

CONCEPT	DESCRIPTION	ROLE
Steric Height	Sea level change due to temperature and salinity variations (i.e., water density changes)	Affects ocean volume, part of dynamic height
Dynamic Height	Vertical integration of specific volume anomaly (inverse of density) from reference pressure	Proxy for horizontal pressure gradients
Dynamic Topography	Ocean surface height relative to geoid, includes steric height + mass changes	**Represents the sea surface slope driving geostrophic currents**
Geostrophic Velocity	Current speed/direction resulting from balance between pressure gradient force and Coriolis force	**Derived from spatial gradients of dynamic height/topography**
Stream Function	**Scalar function whose gradients give velocity components (for incompressible 2D flow)**	**In oceanography, dynamic height acts as this in geostrophic balance**

Dynamic height, Satellite Altimetry observations, Stream function and Geostrophic velocity

Dynamic Height:

$$D(p) = \int_{p_0}^{p} \delta(p')\, dp'$$

- $\delta(p)$: specific volume anomaly (function of temperature & salinity)
- p_0: reference pressure
- $D(p)$: dynamic height at pressure level p

Dynamic height includes steric effects since it comes from T/S-dependent density.

Geostrophic Velocity from Dynamic Height

In the **geostrophic approximation**, we relate horizontal pressure gradients to currents:

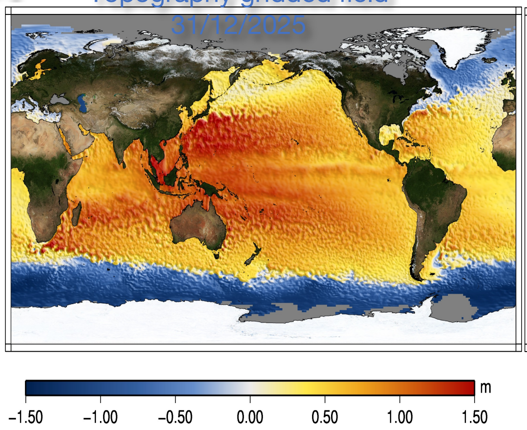
$$u_g = -\frac{g}{f}\frac{\partial D}{\partial y}, \quad v_g = \frac{g}{f}\frac{\partial D}{\partial x}$$

- u_g, v_g: zonal and meridional geostrophic velocity components
- g: gravity
- f: Coriolis parameter
- $\frac{\partial D}{\partial x/y}$: slope of dynamic height

Dynamic height acts like a stream function for geostrophic currents!

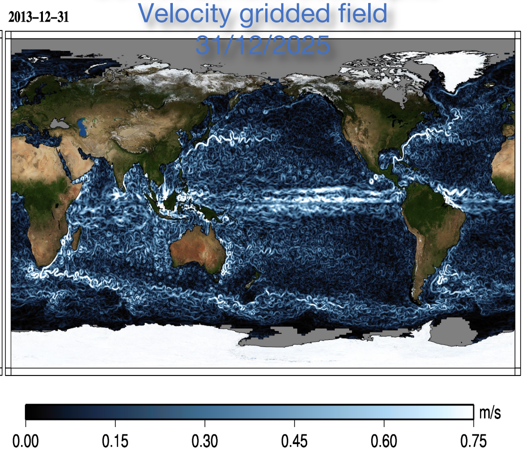
Ocean Absolute Dynamic Topography gridded field

31/12/2025



Derived Surface Geostrophic Velocity gridded field

31/12/2025



Dynamic Topography and Absolute Surface Currents

The **absolute dynamic topography (ADT)** provided by altimetry is:

$$\mathrm{ADT} = \mathrm{SSH}_{\mathrm{measured}} - \mathrm{Geoid}$$

- Similar to dynamic height but referenced to the **actual sea surface**, including both steric and mass-driven height changes.
- Velocities: $$u = -\frac{g}{f}\frac{\partial(\mathrm{ADT})}{\partial y}, \quad v = \frac{g}{f}\frac{\partial(\mathrm{ADT})}{\partial x}$$

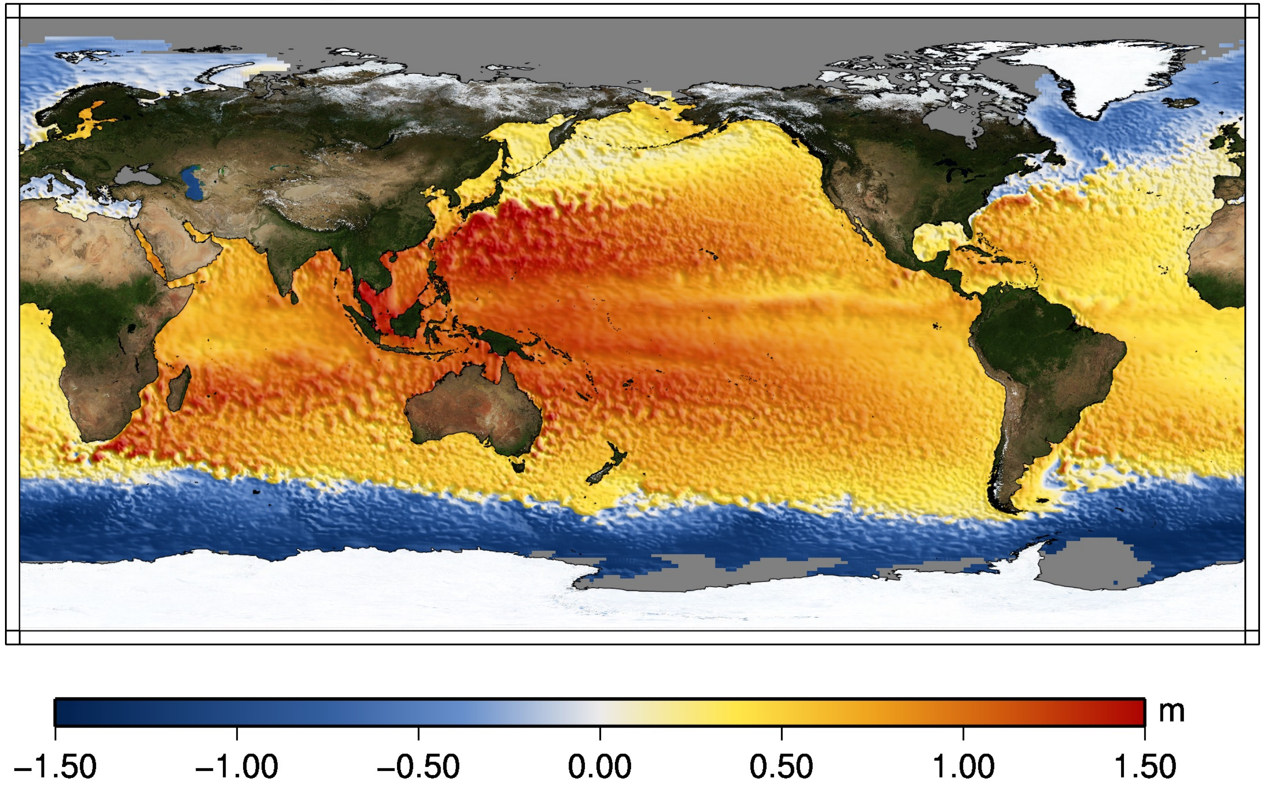
Surface currents are largely **geostrophic** outside of equatorial zones.

Hence, **dynamic height or topography gradients** directly provide information on surface dynamics for:

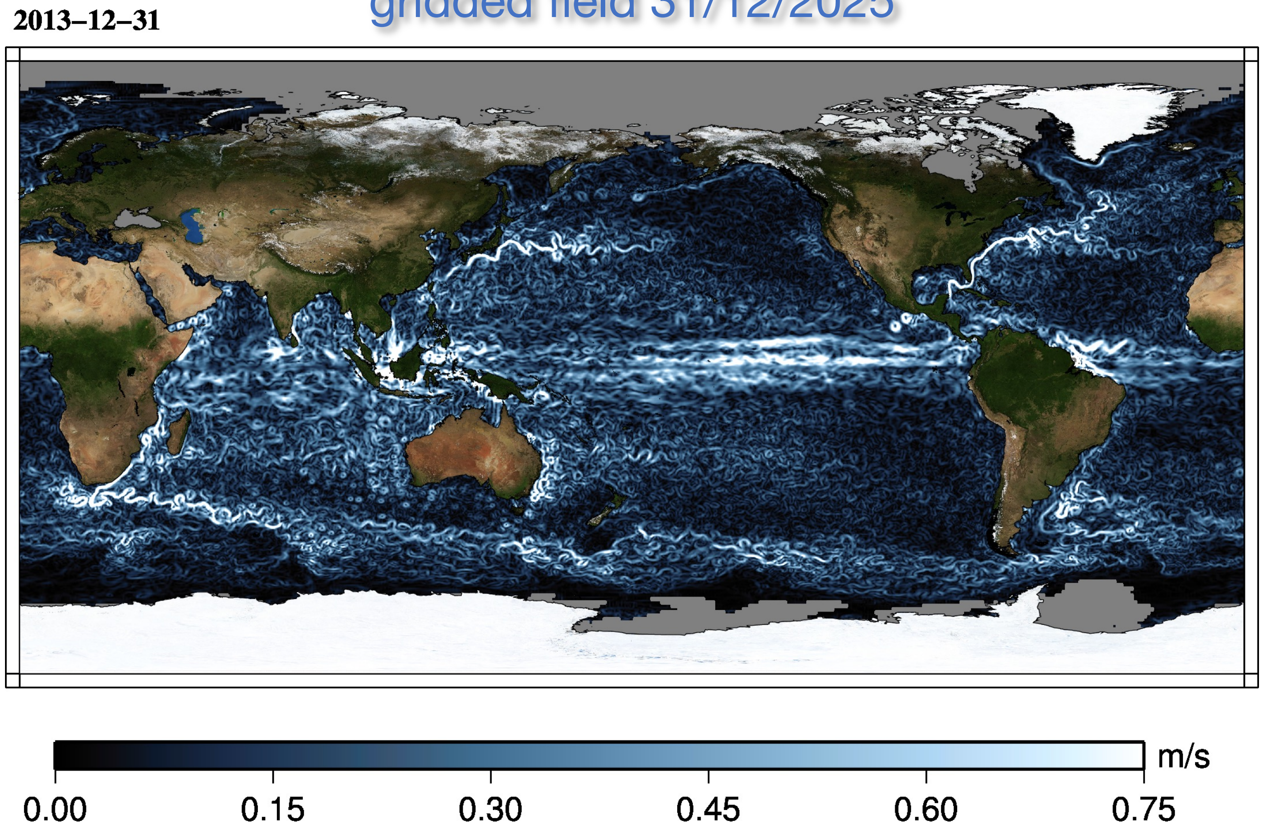
The **Gulf Stream,** the **Kuroshio,** the **Antarctic Circumpolar Current**

Dynamic height, Satellite Altimetry observations, Stream function and Geostrophic velocity

Ocean **Absolute Dynamic Topography** gridded field 31/12/2025



Derived Surface Geostrophic Velocity gridded field 31/12/2025



Ocean small-scale dynamics: ECCO Ocean State Estimate
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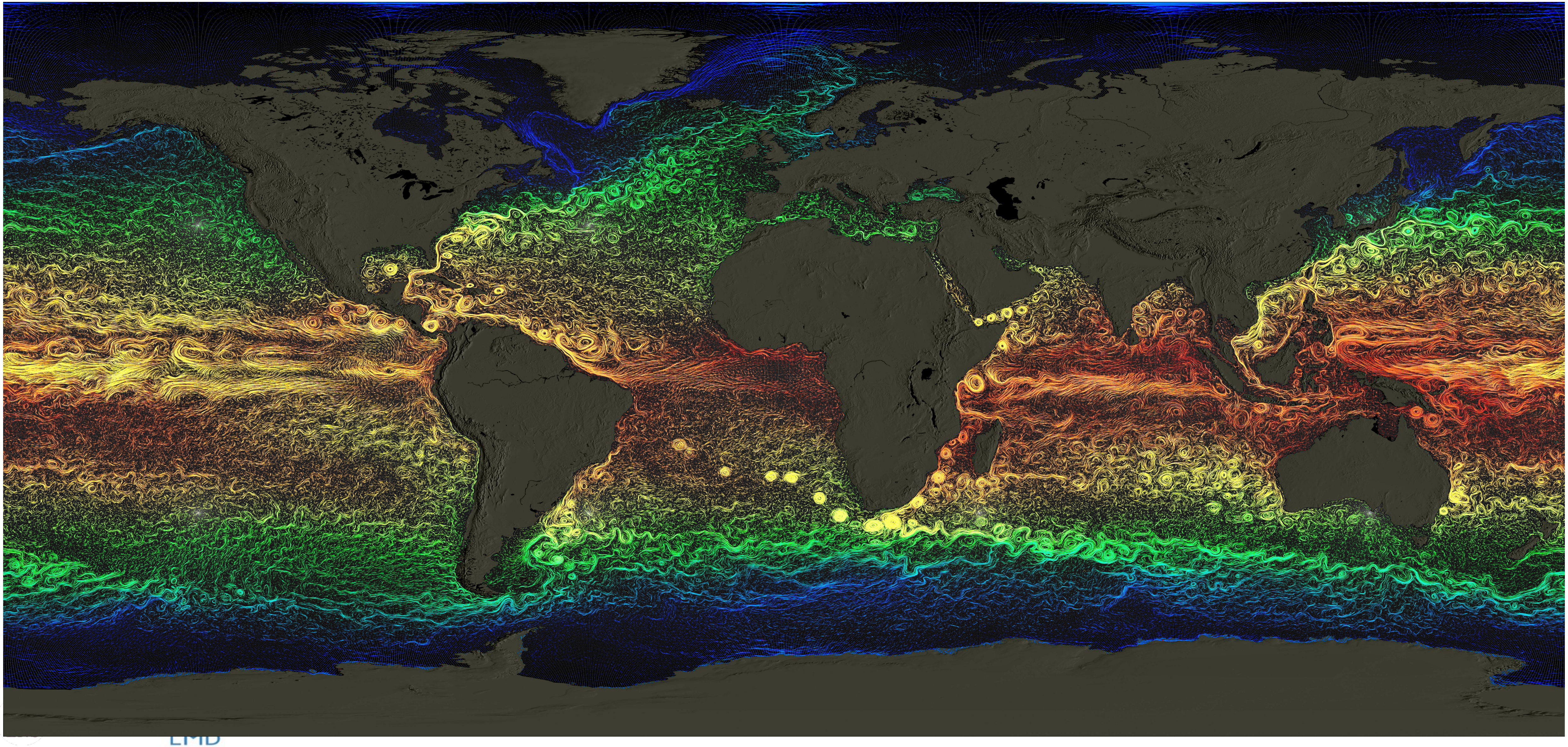
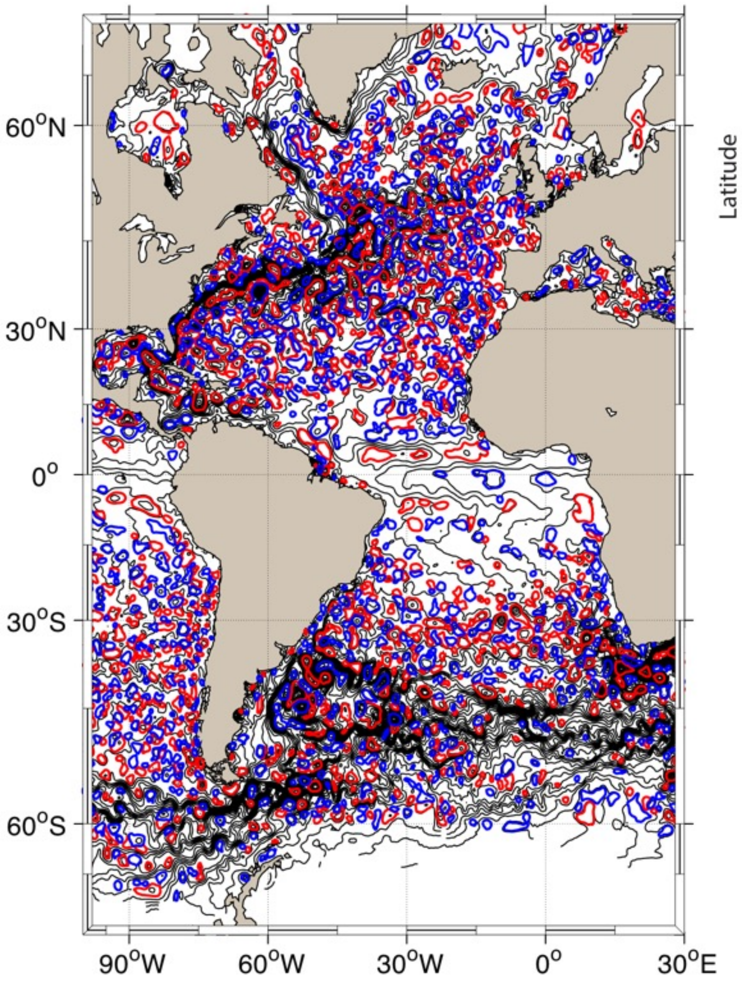
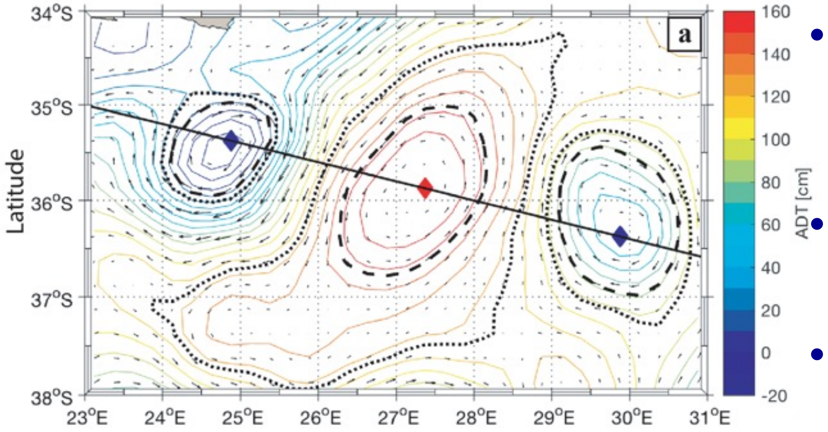
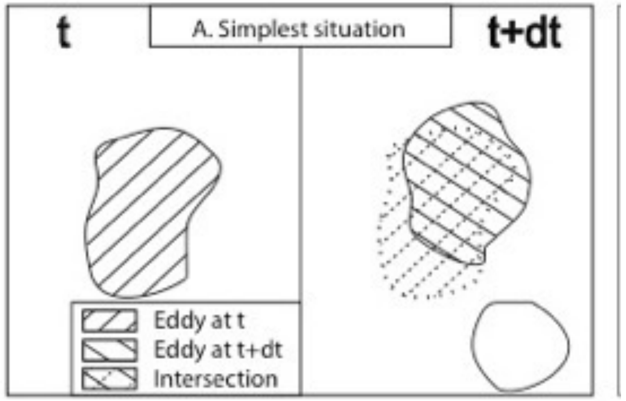


Identifying Ocean Mesoscale eddies from Satellite Altimetry Automatic Detection Algorythms: **The TOEddies Atlas**







- Applied on Absolute Dynamic Height (**ADT**) field which is the **Surface Geostrophic Stream Function**
- Based on defining the farthest **closed contour around an extreme**
- Defined by **two contours**: the outermost and the azimuthal maximum velocity

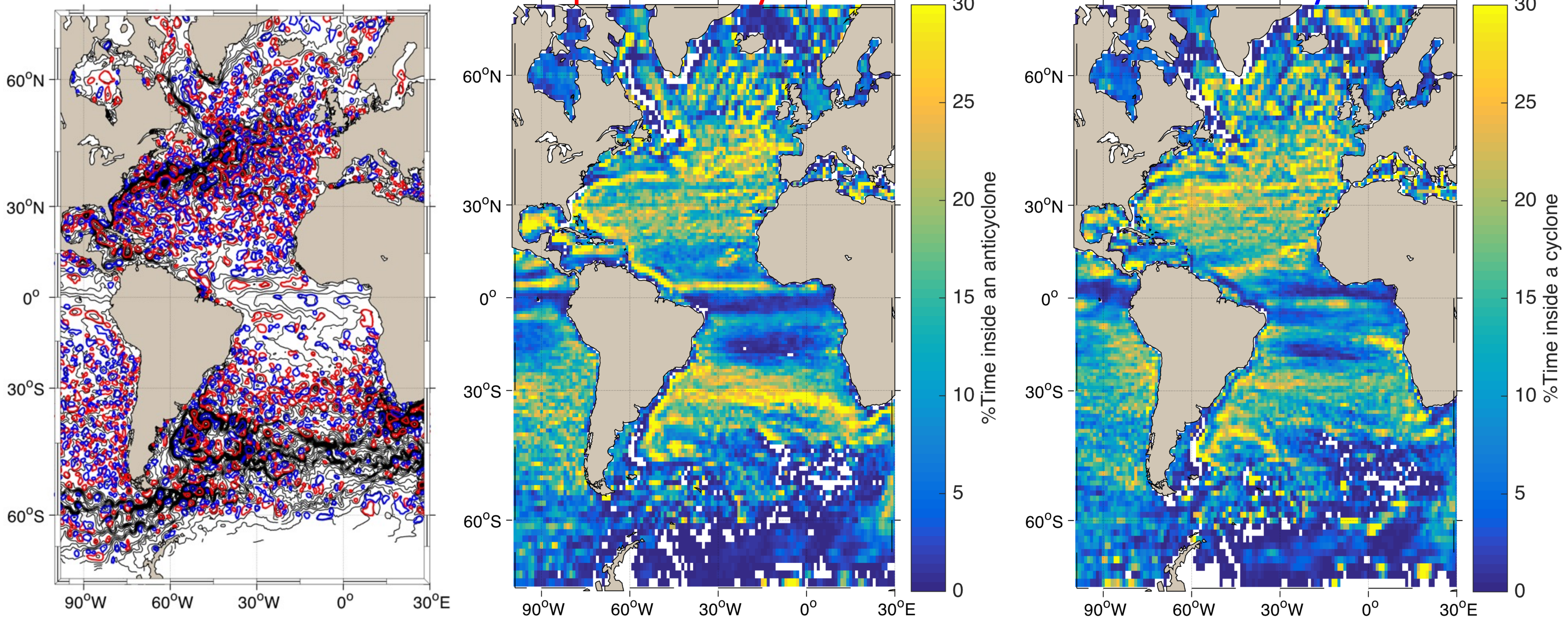
- One eddy is tracked in time with a condition that areas of one eddy at two subsequent (daily) time steps need to superimpose at 50%
- It needs also to be "detectable" in ADT field during at least 5 days

TOEddies, Laxenaire et al., 2018: 2019; 2020

Identifying Ocean Mesoscale eddies from Satellite Altimetry Automatic Detection Algorythms: **The TOEddies Atlas**

1°x 1° % Time of presence Anticyclones

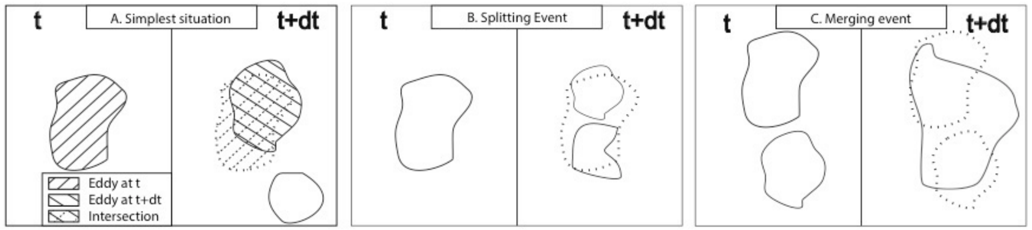
1°x 1° % Time of Presence Cyclones



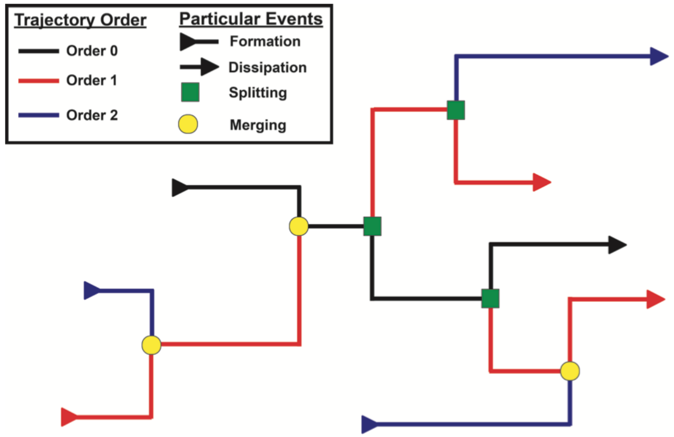
TOEddies, Laxenaire et al., 2018: 2019; 2020

Agulhas Rings: An Eddy NETWORK/LIFE-TREE

Tracking eddies including eddy merging and splitting

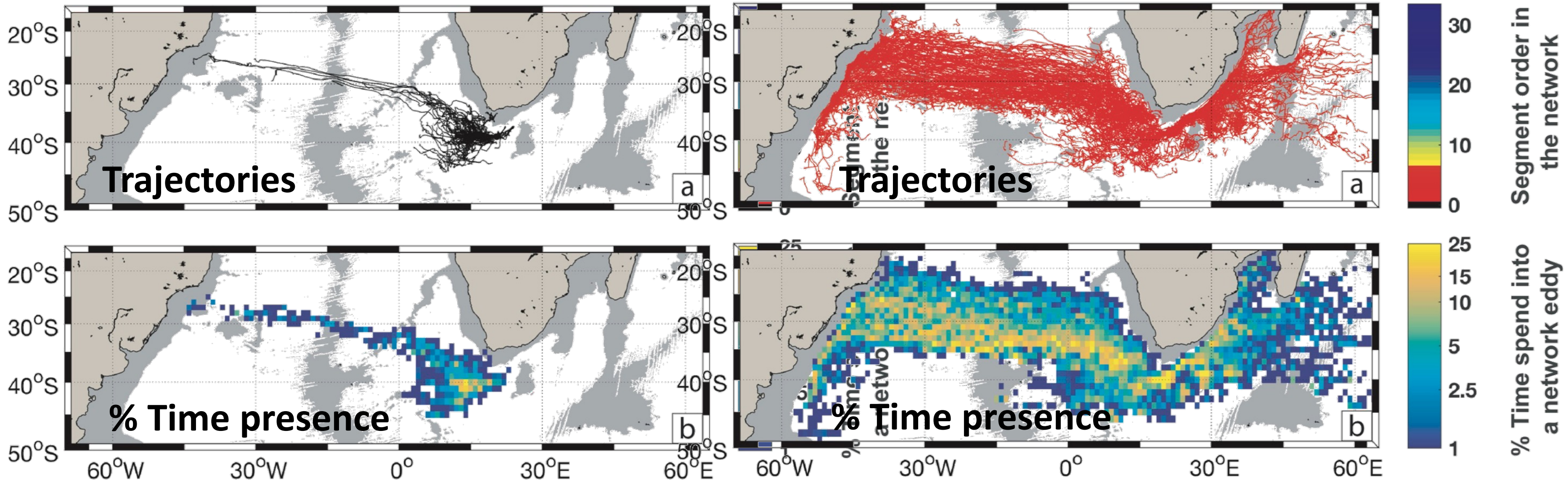


Similar to Qiu-Yang Li et al. 2016

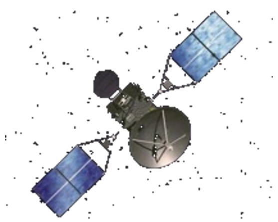


Eddies & Trajectories: A **eddy network/life-tree** as eddies are very dynamical, they merge and split

Agulhas Rings 0 Order Trajectories | **Agulhas Rings 1-6 Order Trajectories**



TOEddies, Laxenaire et al., 2018:



The TOEddies Global Ocean Atlas

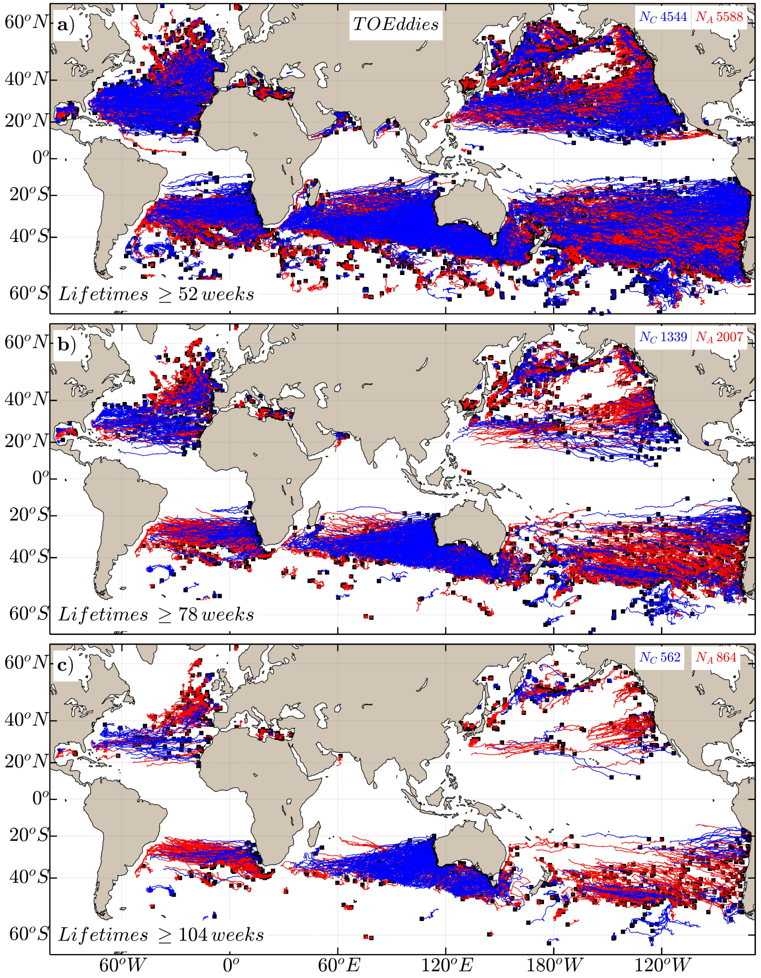
Eddies Atlas & Argo profiles colocalisation

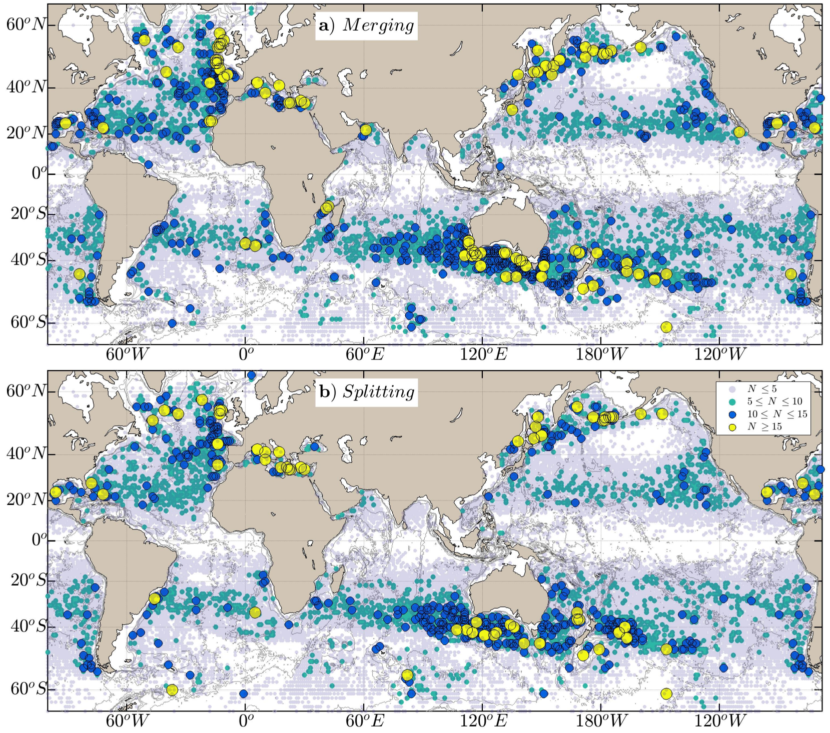
Preprint Article Version 1 Preserved in Portico This version is not peer-reviewed

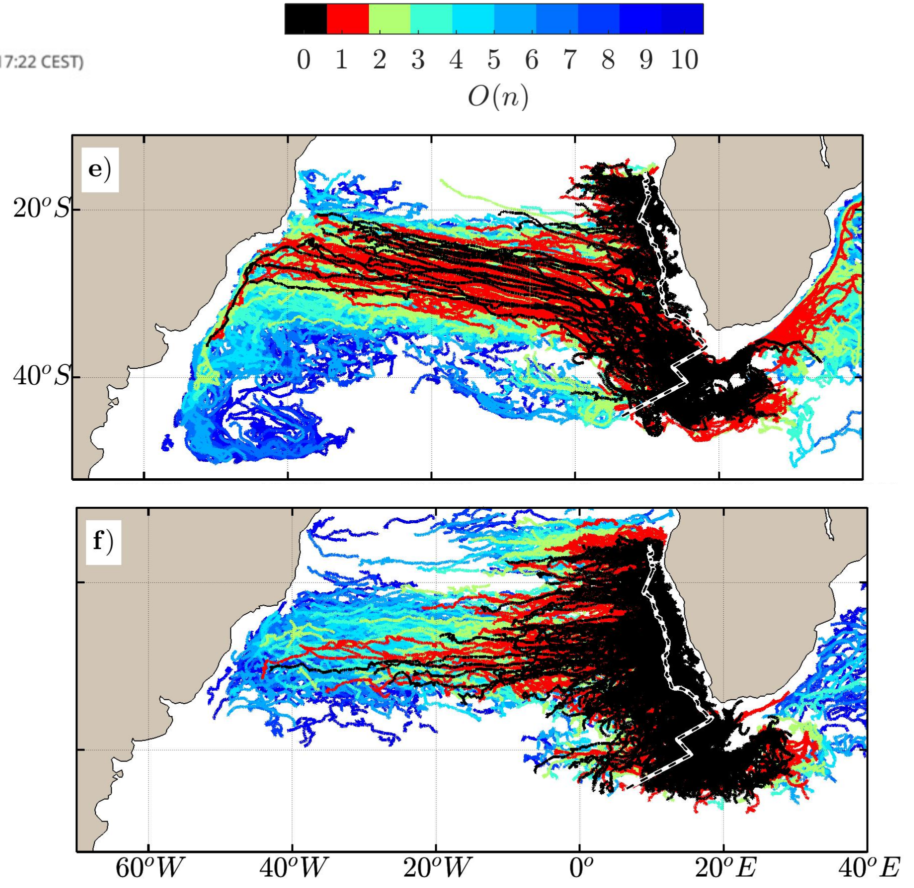
Global Assessment of Mesoscale Eddies with TOEddies; Comparison between Multi-Datasets and Colocation with In-Situ Measurements

Artemis Ioannou *, Lionel Guez, Remi Laxenaire, Sabrina Speich

Version 1 : Received: 8 October 2024 / Approved: 9 October 2024 / Online: 9 October 2024 (07:17:22 CEST)







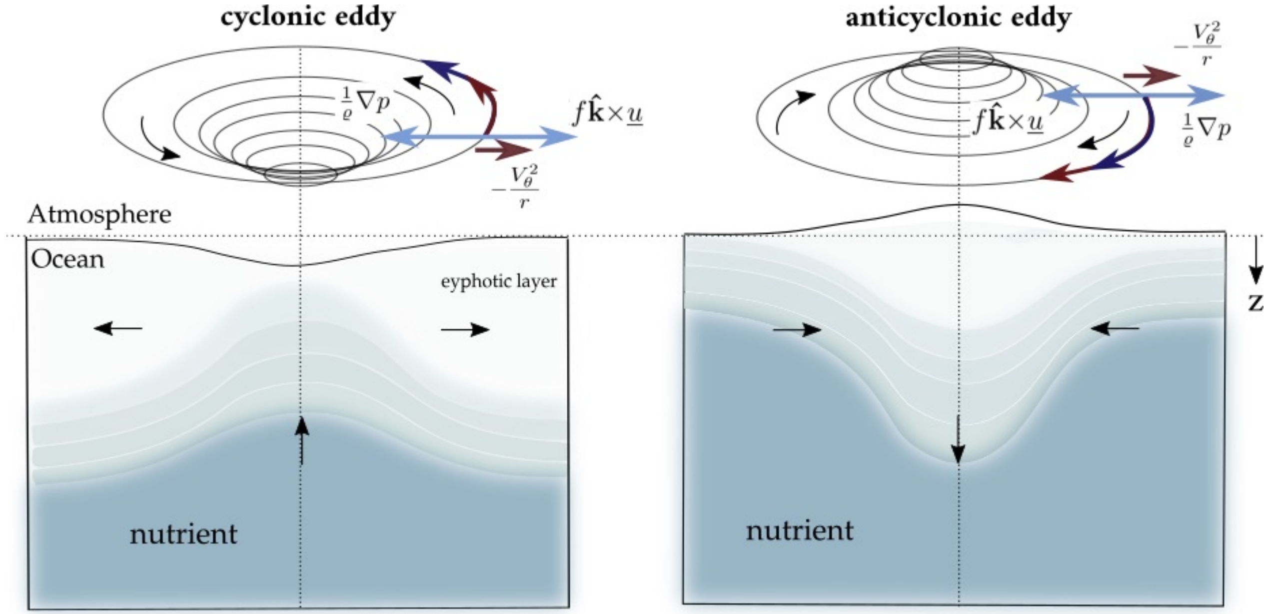
Ioannou et al., 2024 ESSD

Ocean Mesoscale Eddies:
What we have understood so far **from Satellite Altimetry**

- **Upper-ocean dynamics** is **highly turbulent**, with pervasive **mesoscale jets and eddies**.
- **Mesoscale eddies** are **nearly ubiquitous** (weaker occurrence near the equator).
- **Eddies** **frequently split and merge**.
- An eddy **does not follow a single trajectory**; tracking requires a **network/lineage approach** (parent–child links).
- Eddies have **long lifespans** — from **months to years**.

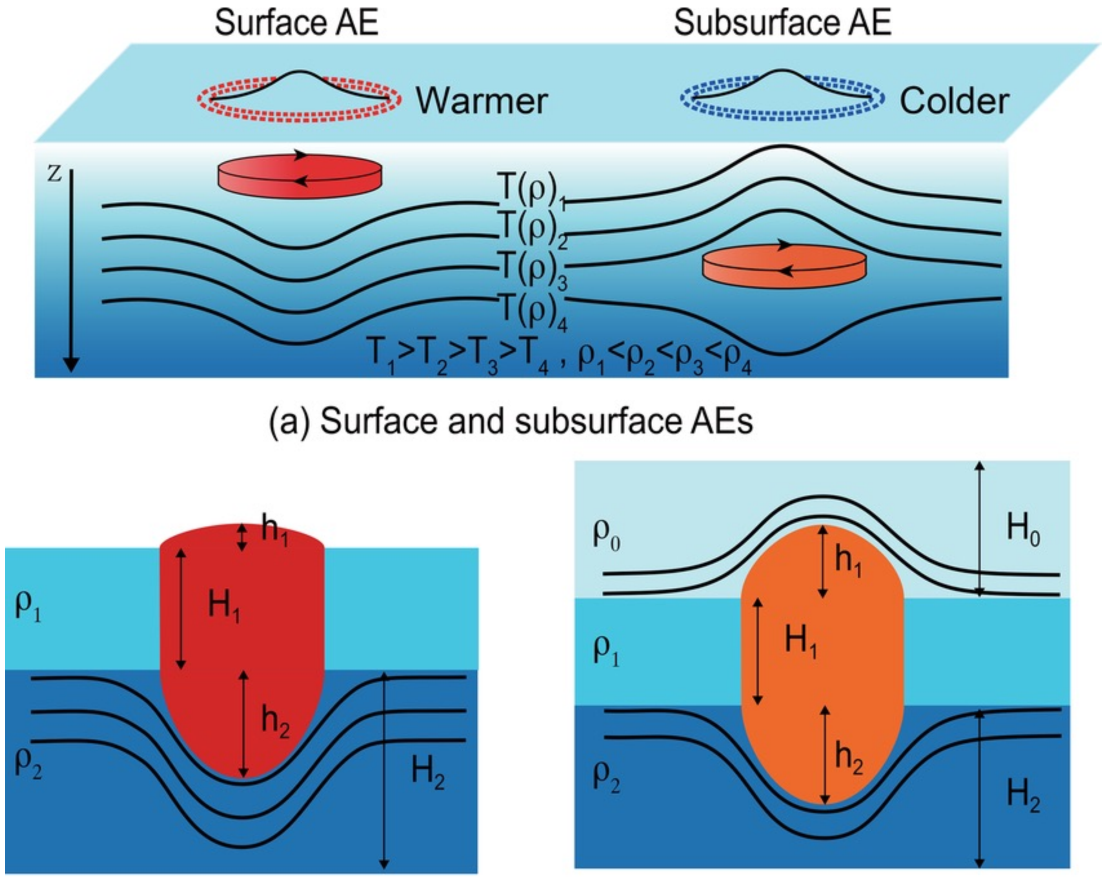
Physical properties we know about Mesoscale Eddies

Surface height and vertical structure
of **cyclonic** and anticyclonic eddies



Moschos, 2023

Surface and subsurface anticyclonic eddies

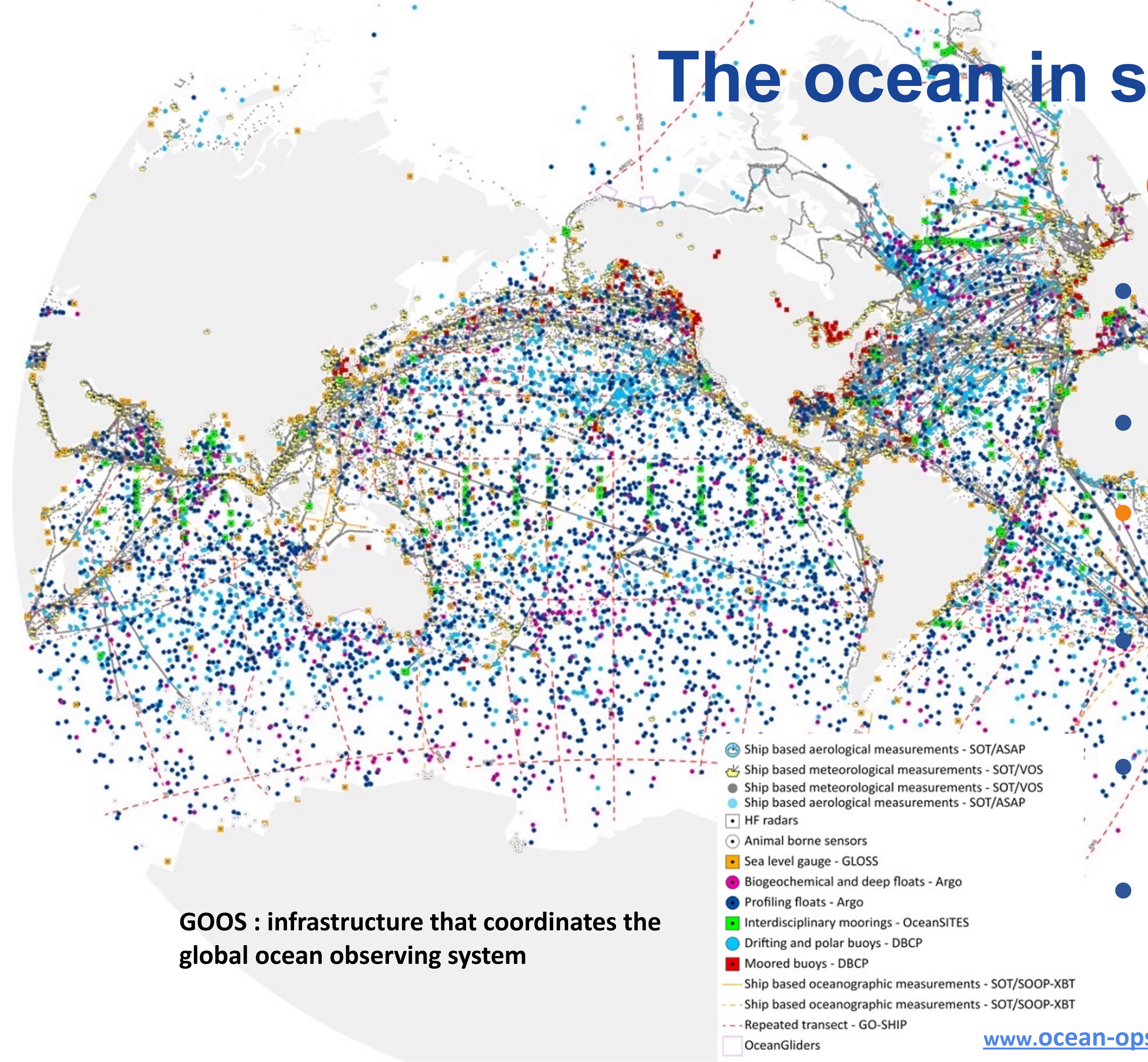


Wang et al., 2019

(b) Two-layer eddy models

The ocean in situ observing system

GOOS & the Ocean in GCOS



GOOS : infrastructure that coordinates the global ocean observing system

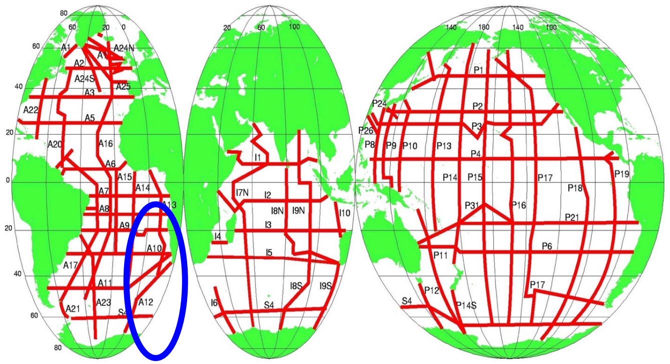
- **A true global collaboration: 84 countries, 8,900+ observing platforms, 13 global networks (+ 3 emergings)**
- Ocean and marine meteorological Essential Ocean/Climate Variables
- **>120,000 observations delivered per day to operational services** across climate, weather and hazard warnings and ocean health
- **Today it covers only 65%** of the needed observations in physics, much less in chemistry & biology
- **The whole system is extremely fragile** funded through research project and programs. It is not sustained and rest on individual scientists
- Mandate from UNFCCC

www.ocean-ops.org/reportcard2023

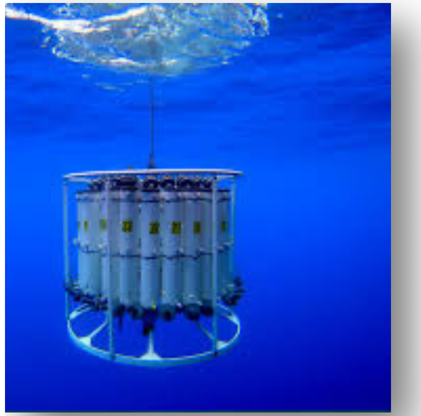
Measuring the Ocean Subsurface: In Situ Observations

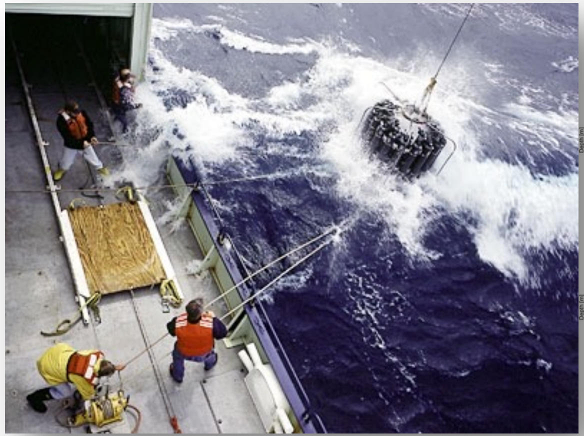
The World Ocean Circulation Experiment
WOCE “during” the field phase (1990–1998)

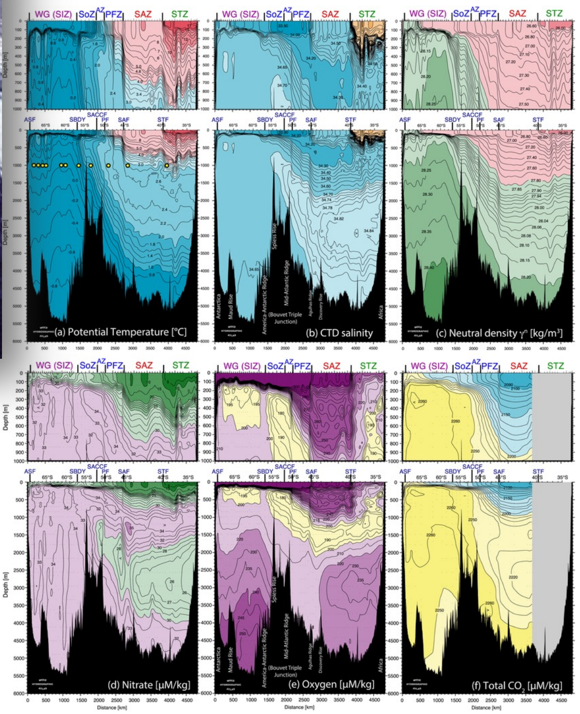
- Nearly **30 countries** contributed ships, instruments, satellites.
- Major goals:
  - Develop and test **ocean models** for climate prediction.
  - Quantify **large-scale heat and freshwater fluxes**, water-mass formation and ventilation, and variability on months–decades.
- Observing system elements:
  - **Global hydrographic & tracer programme** (~30 000 high-quality CTD/tracer stations on trans-oceanic sections).
  - Moored arrays, drifters, XBTs, **satellite altimetry** (TOPEX/Poseidon, ERS-1/2) integrated into design.



WOCE Hydrographic Programme One-Time Survey
(Penny Holliday, WOCE IPO)





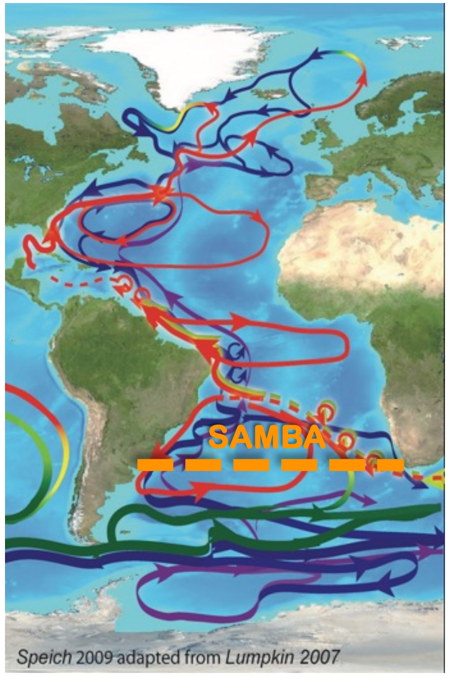


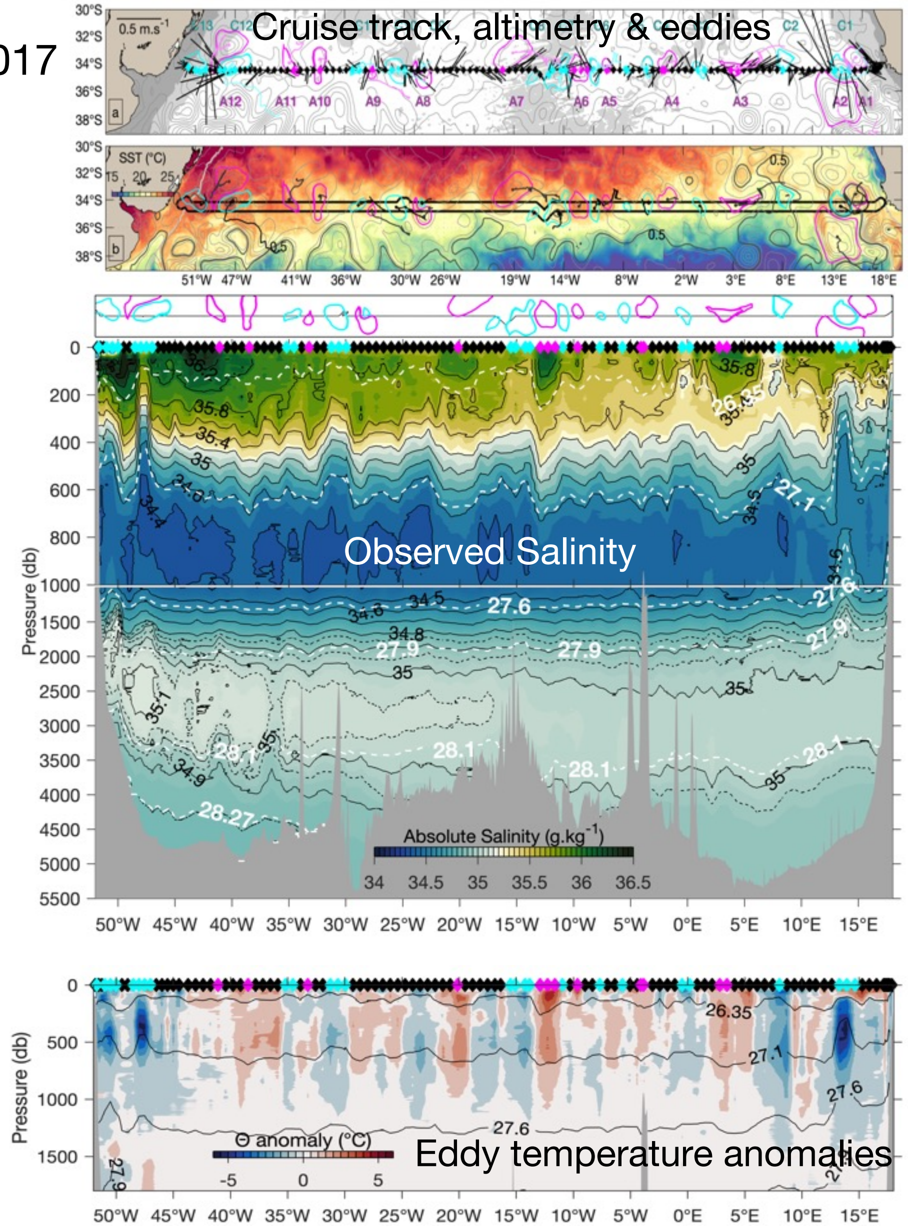
Today (WOCE legacy): The GO-SHIP program

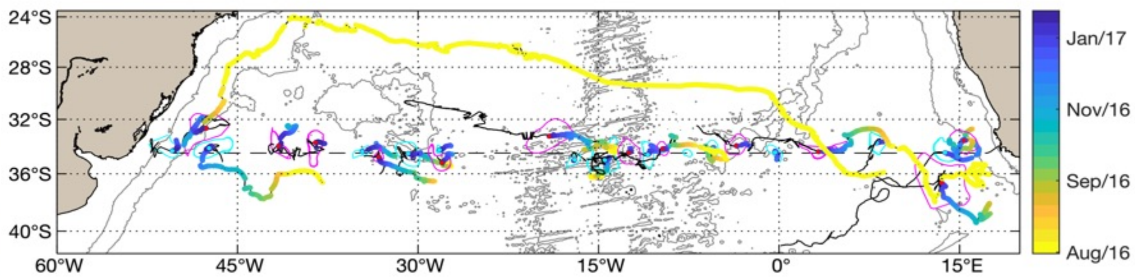
Repeat hydrography: decadal repeats of many WOCE lines, extending the time series for heat and carbon uptake.

Improving large-scale GO-SHIP transport estimates

SAMBA Line, Jan-Feb 2017







Observed eddies tracked in time by altimetry (TOEddies) – Lagrangian eddy transport estimate

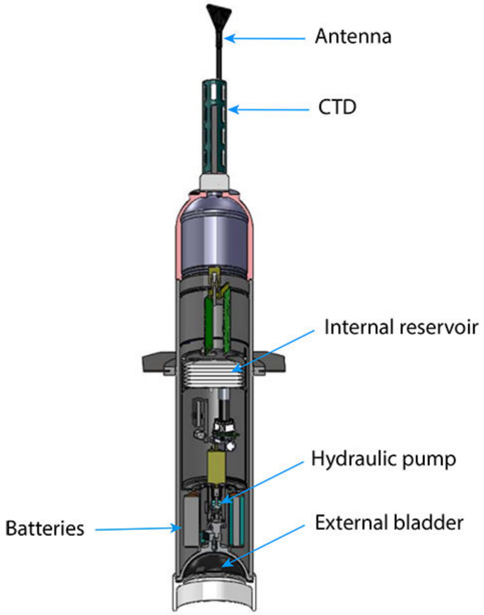
- Mesoscale eddies impact transport of properties
- Access to Eulerian and Lagrangian transport estimates associated to eddies

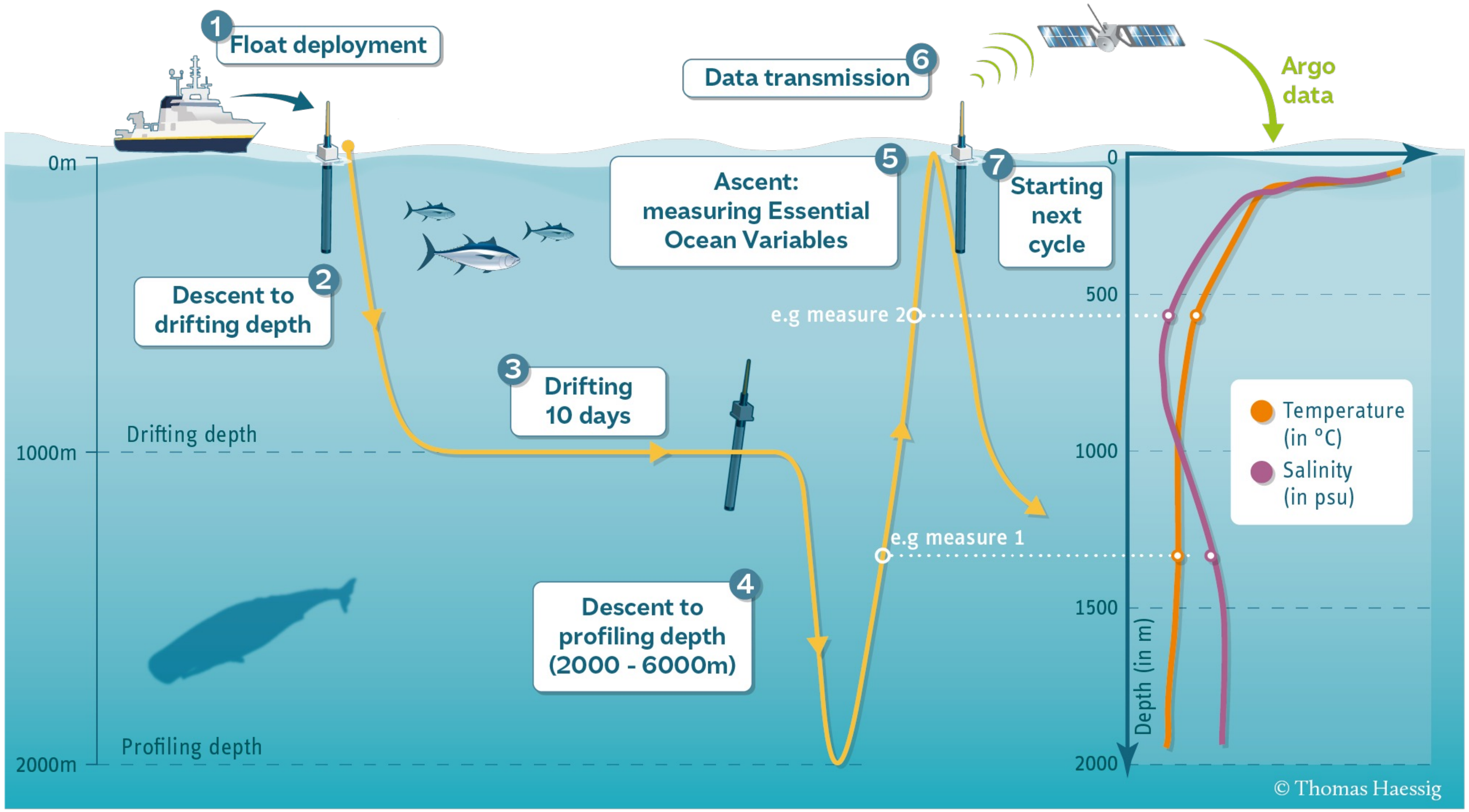
Manta et al., 2021

nics

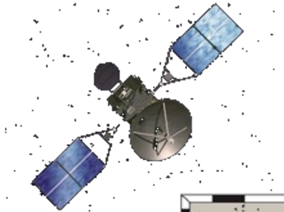
Measuring the Ocean Subsurface: In Situ Observations

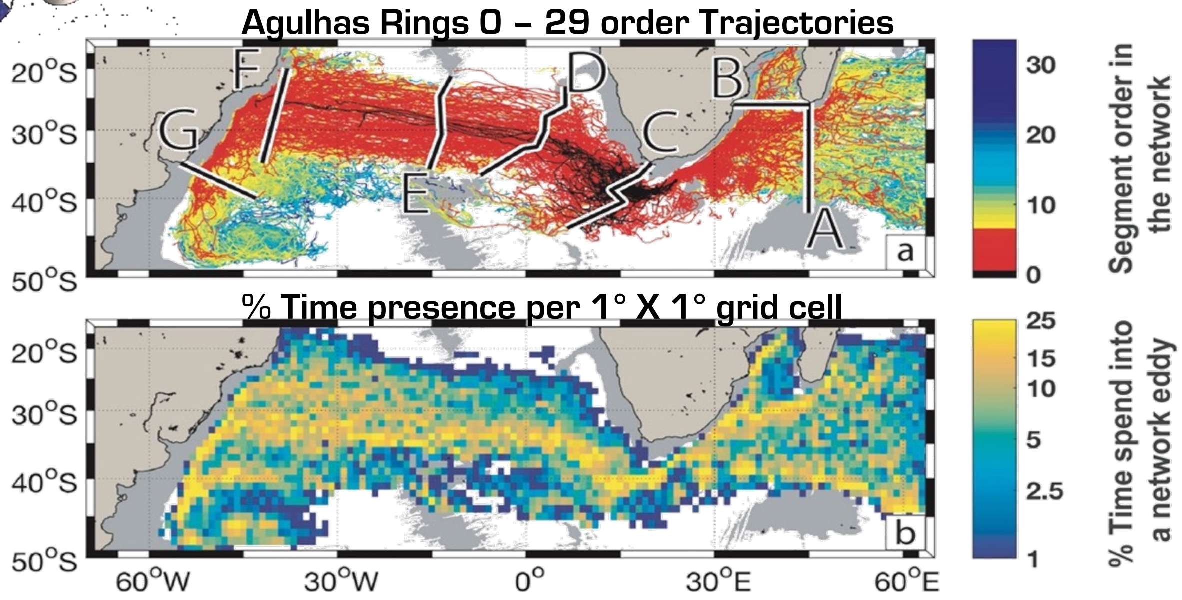
The Argo Profiling Floats: Since 2000 (2005 for a global coverage)

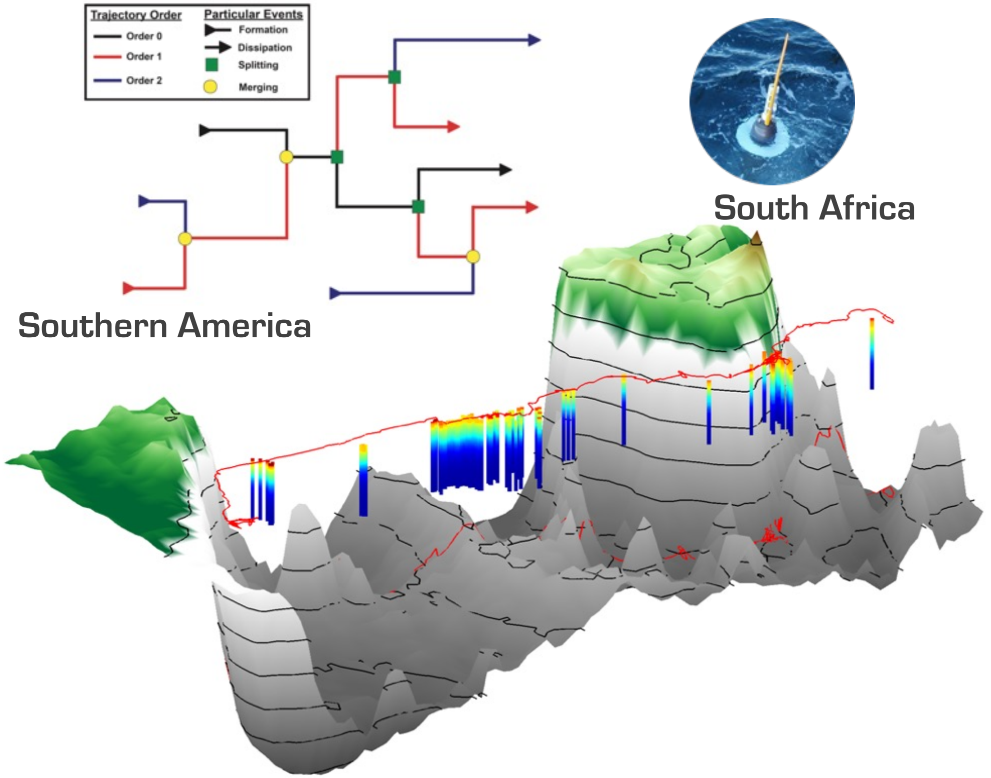


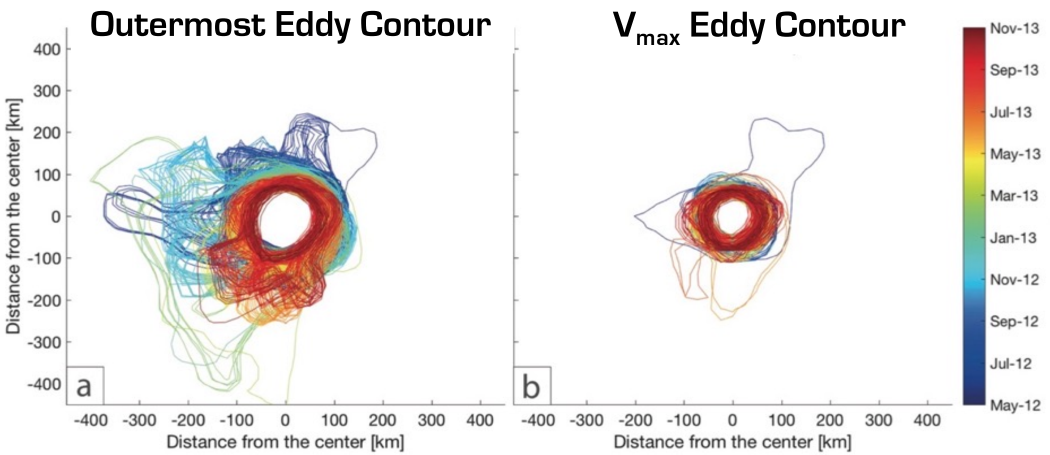


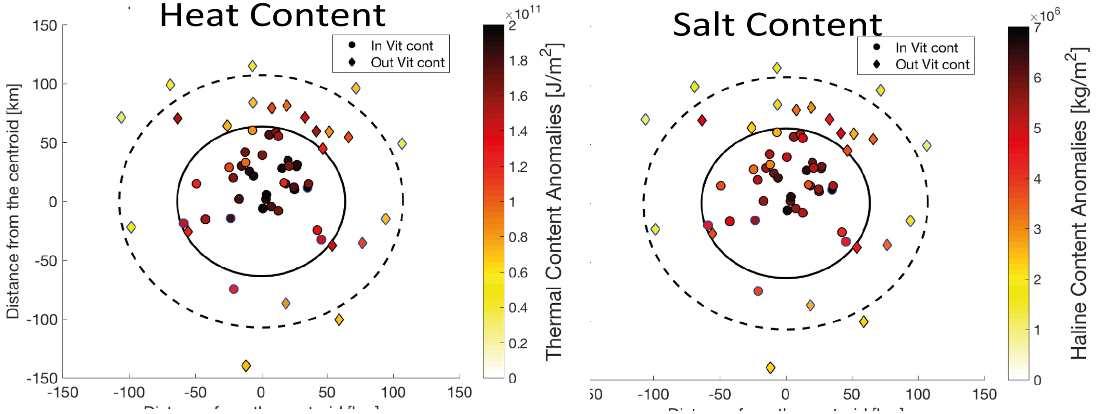
Agulhas Rings





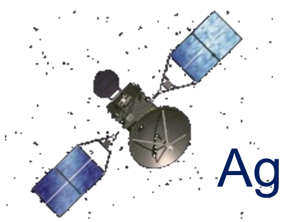






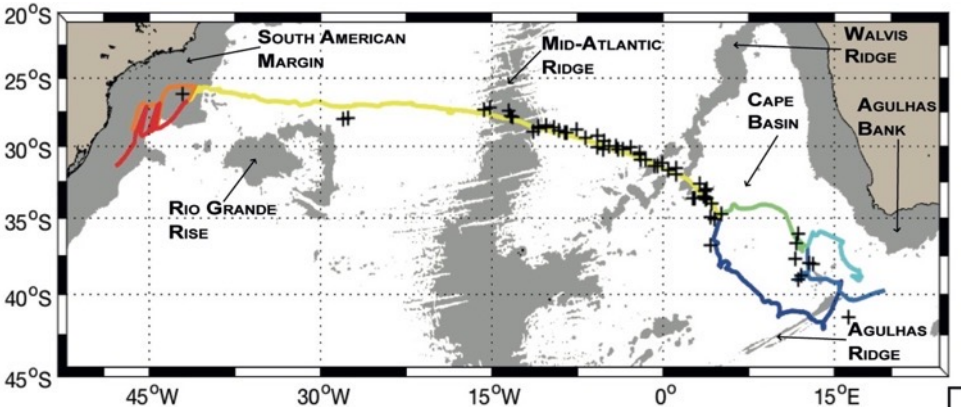
TOEddies provide a co-location of eddies (core) and Argo profiles

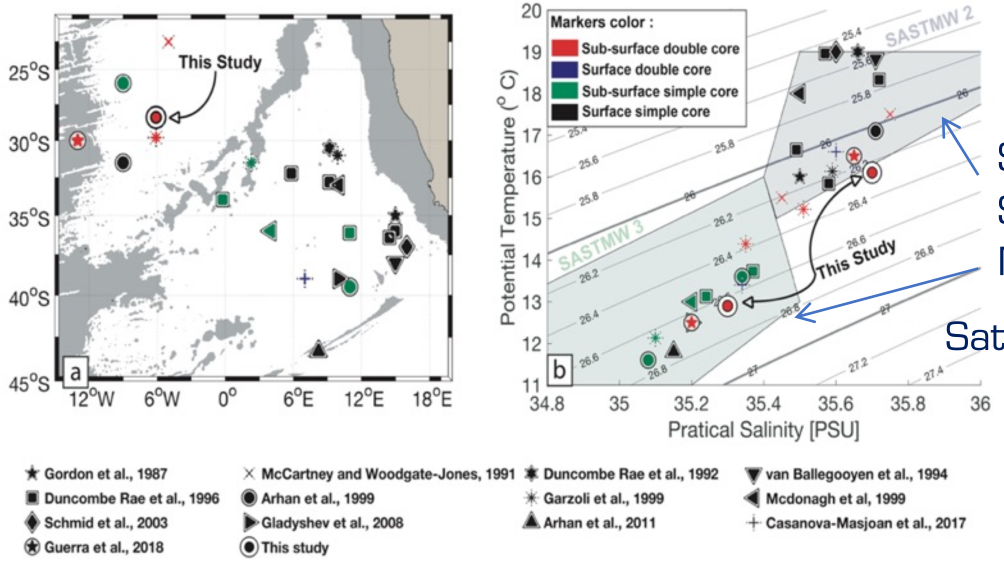
Laxenaire et al., 2018; 2019; 2020



Reconstructing 3D eddy structure using Argo profiles

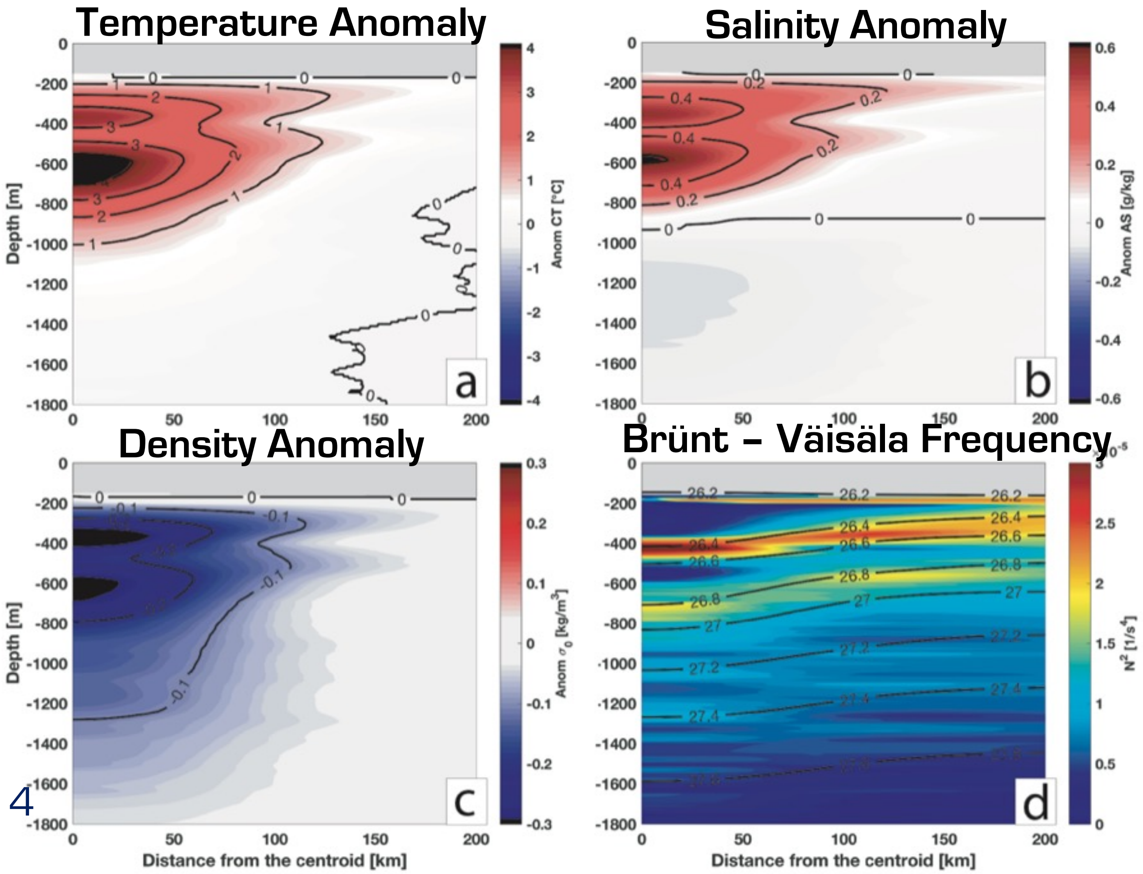
Agulhas Rings heat and salt anomaly concentrated at the subsurface in cores of Mode Waters





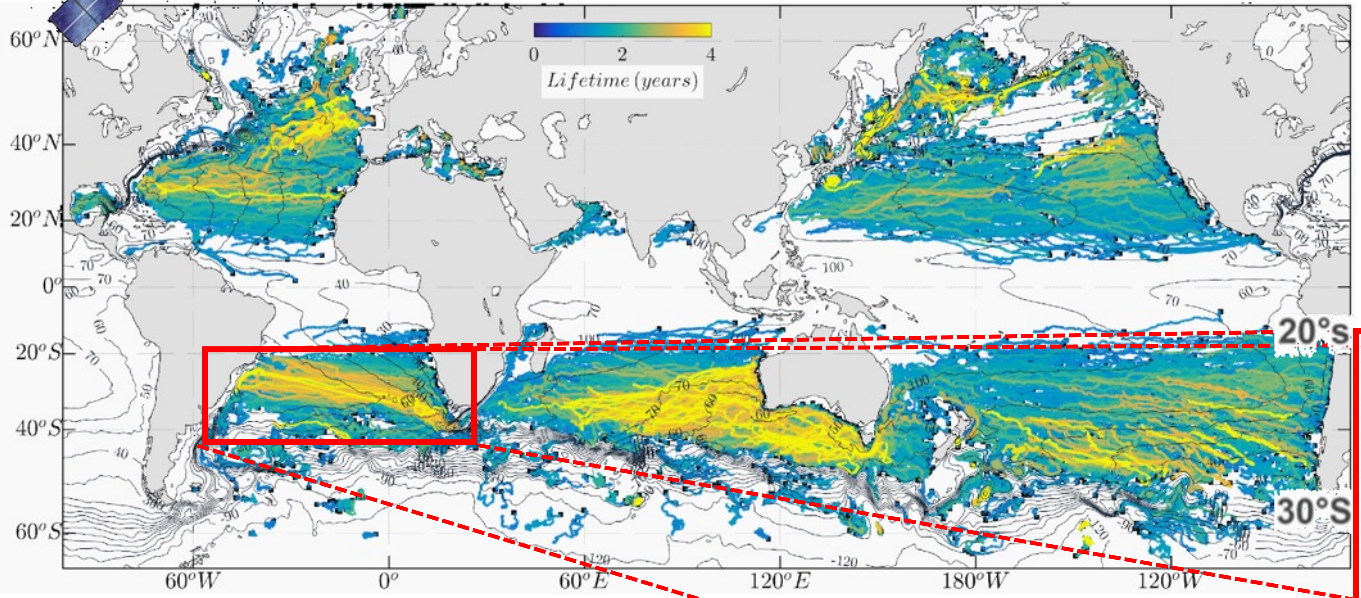
South Atlantic Subtropical Mode Waters

Sato & Polito 2014



Laxenaire et al., 2019

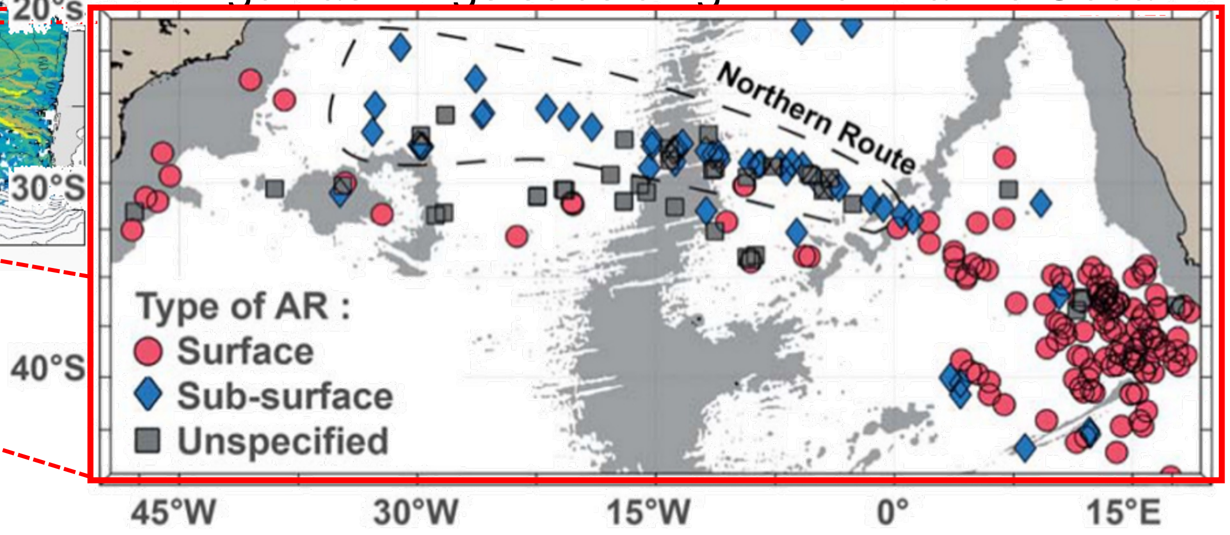
Agulhas Rings rapid subsidence in the ocean interior



Laxenaire et al., 2020
Ioannou et al., 2022; 2024

TOEddies colocalized with Argo profiles

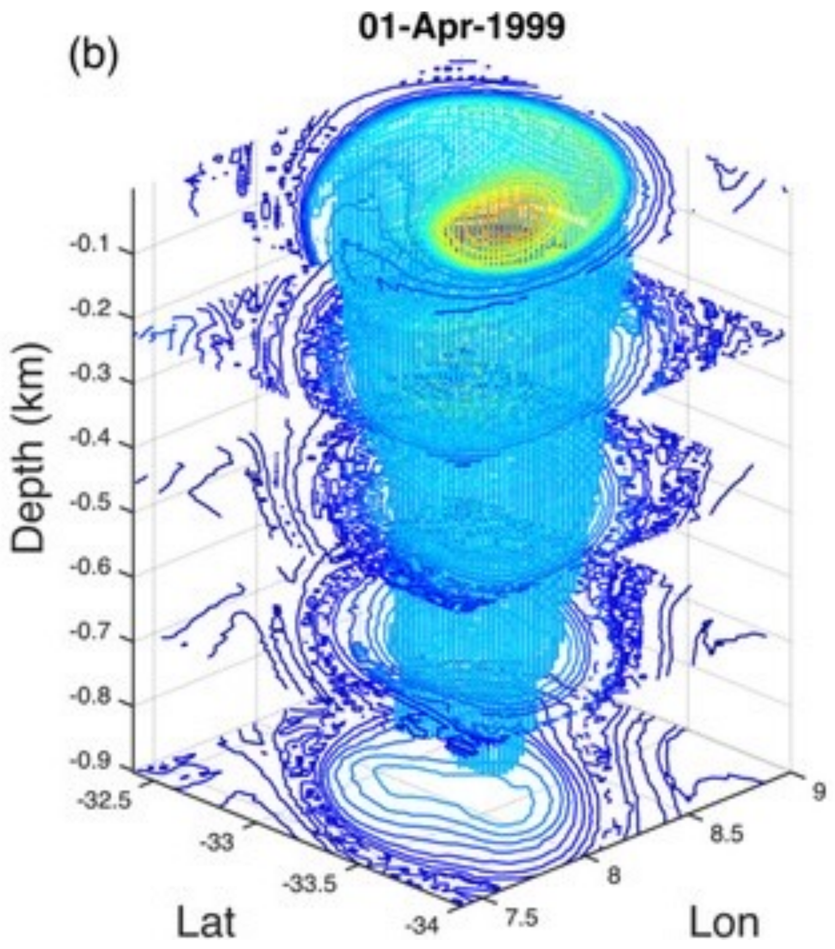
Agulhas Rings subsiding in the Atlantic Ocean



- **Agulhas Rings subside in the ocean interior** in the Cape Basin (Southern and central Agulhas Rings routes) or just before (southern routes) because they are denser than the environnant waters due to the strong cooling before and within the Cape Basin. This is why their upper ocean imprints (SST, SSS, SSH, gesotrophic velocities) disappear or decrease rapidly

Ocean Mesoscale Eddies:
What we have understood so far from
Satellite Altimetry + Argo float profiles and sparse ship hydrography

- **Anticyclonic eddies can move in the ocean for months to years, conserving water mass properties.**
- **Mesoscale eddies** observed/detected from satellite altimetry can be **surface and subsurface intensified**.
- **Eddies can subduct/subside along their trajectories.**
- **Subtropical anticyclonic eddies** can **precondition Mode Water formation** and can contain important volume of these waters in the ocean interior (i.e., they ventilate the ocean thermocline)
- **Eddy (multiple) merging** can result in **different vertical cores of water masses**.



Ocean Mesoscale Eddies:
They can live for years, conserving thermohaline properties ...
Are ocean mesoscale eddies COHERENT? What is Coherence, by the way ?

Common Definitions of the Word "Coherence"

- **16th century:** Harmonious, logically connected
- **19th century:** Mass or matter that adheres or clings firmly to a whole, united by a force of cohesion (*Oxford Dictionary*)

Hussain et al. (1983, 1986)

- First physical and phenomenological definition:
- **A coherent structure is a mass of inviscid turbulent fluid exhibiting a large-scale vorticity component that instantaneously dominates the three-dimensional vorticity of the turbulence**.
- Statistical tools to separate coherent parts from incoherent parts
  - **POD:** Proper Orthogonal Decomposition

BUT complex mathematical definitions and tools

- For some, *coherent* = large-scale structures with their own spatial extent
- "Coherent" is what we observe
- Even Hussain wrote: "*In principle, it is preferable to leave concepts such as coherent structures implicit.*"

1980s: Application to Oceanic Eddies

- *McWilliams* (1984, 1986), Numerical simulations, Geostrophic Turbulence
- **Large eddies characterized by:**
  - Their spatial domain where a coherent vortex maintains its influence and structure
  - A dominant vorticity component
  - Inviscid fluid ⇒ Coherent in Hussain's sense
  - Eddies « persist » and are characterized by their ability to resist straining deformations from neighboring structures and to maintain their identity over time, often growing through mergers with weaker vortices

BUT, for McWilliams, *"coherent"* simply means **"long-lived"**

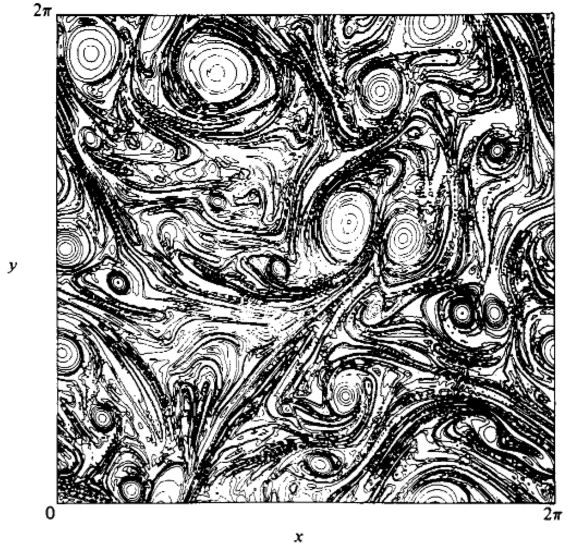


FIGURE 9. $\text{Log}_{10}|\zeta|$ at $t = 16.5$ with contours every 0.25 between −0.5 and 1.5.

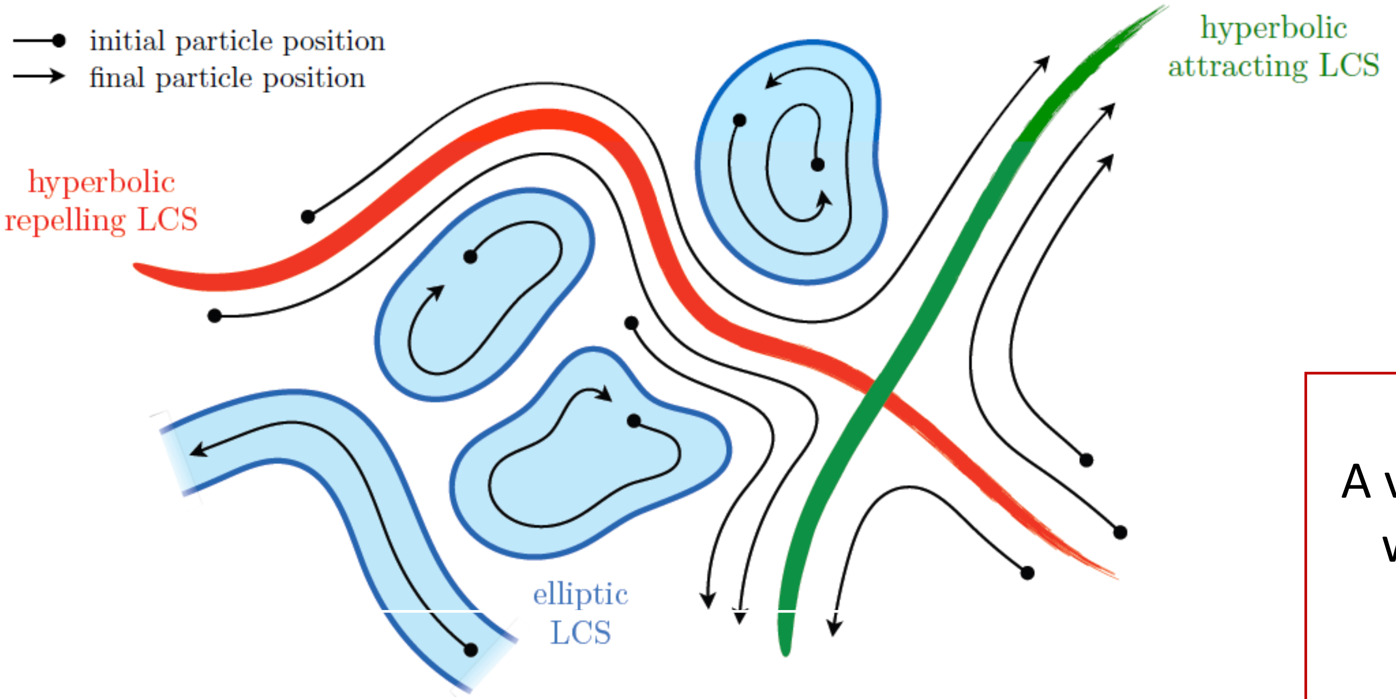
Kinematic Coherence (KC):
Rotational flow sufficiently persistent and created by turbulence (J. McWilliams, 1991.
It is an **Eulerian criteria**

Ocean Mesoscale Eddies: Are they coherent structures?

Mixing and the Lagrangian Theory

Starting from the 2000s, **Idea: understand fluid-particle trajectories to quantify mixing**

- ➢ Development of a **Lagrangian framework**
- ➢ **Closed trajectories** (rather than streamlines) to detect a vortex



Adapted from *Mowlavi et al. (2021)*

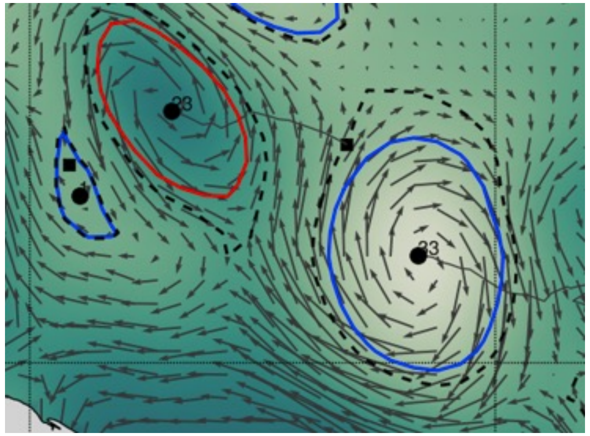
- Eddies can be considered as elliptical **Lagrangian Coherent Structures** (LCSs, closed trajectories)

Material coherence (MC):
A vortex is coherent as long as it has not lost the water it trapped at the time of its formation.
(Béron-Vera, 2013; Haller, 2016)
Lagrangian criteria

Ocean Mesoscale Eddies: Are they coherent structures?

Kinematic Coherence (KC)

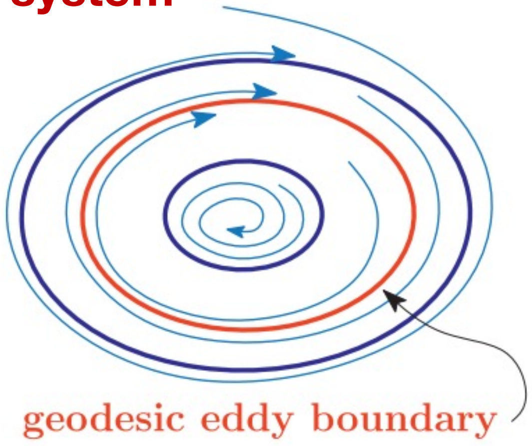
- Temporal **persistence** of the flow
- **Eulerian criteria for detecting boundaries**
  - Okubo-Weiss, SSH (TOEddies), V_{max}
- **Closed streamlines**
- **Core** = **Open system**
- It works on snapshots



Contours fermés d'Absolute Dynamic Topography (ADT) (TOEddies, Laxenaire et al. 2018)

Material Coherence

- **"Trapped" water**
- **Lagrangian criteria for detecting boundaries**
  - LCSs, LAVD, geodesic, etc.
- **Closed trajectories**
- **Core = a closed system**

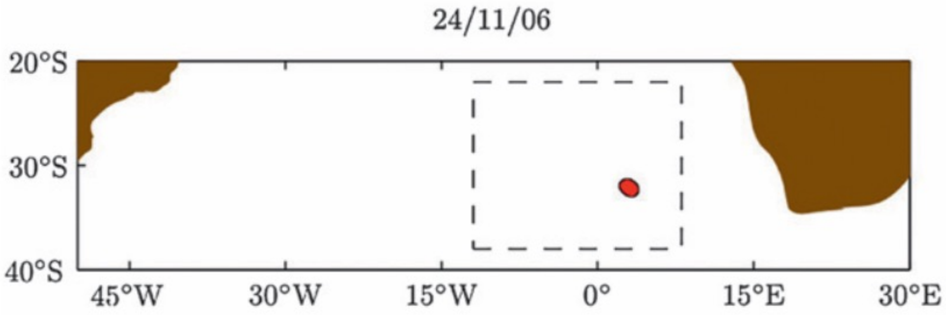


Beron-Vera et al. 2013

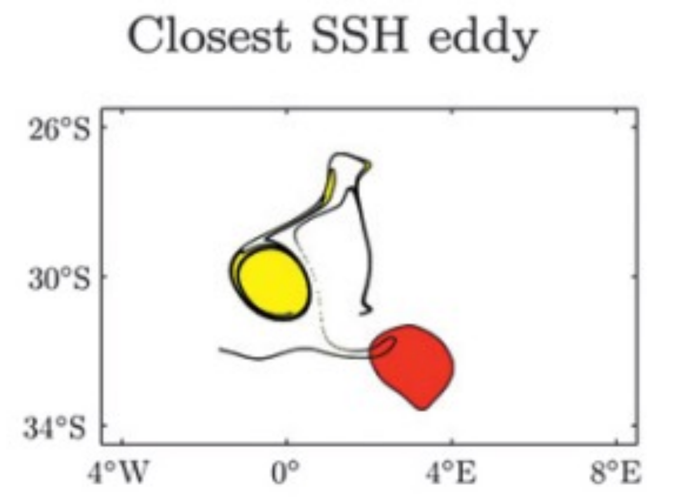
Ocean Mesoscale Eddies: Are they coherent structures?

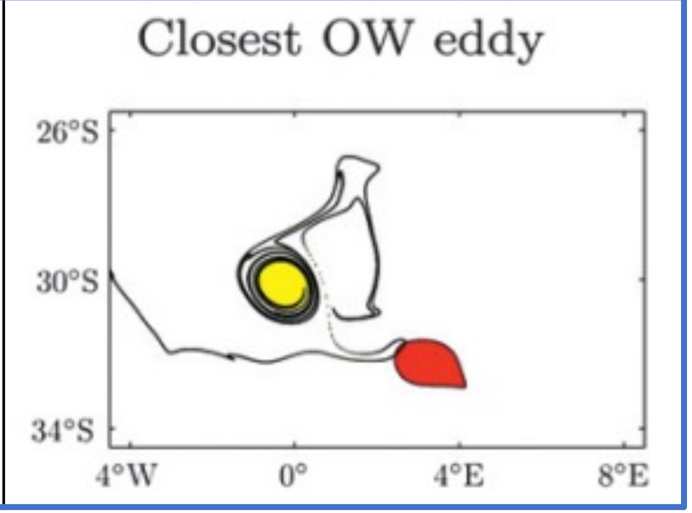
Comparaison between Kinematic and Material Coherence

- Béron-Vera et al. 2013
  - Sea Level Anomaly (SLA) at 1/4° from Le Traon et al. 1998
  - Geostrophic velocity from SLA

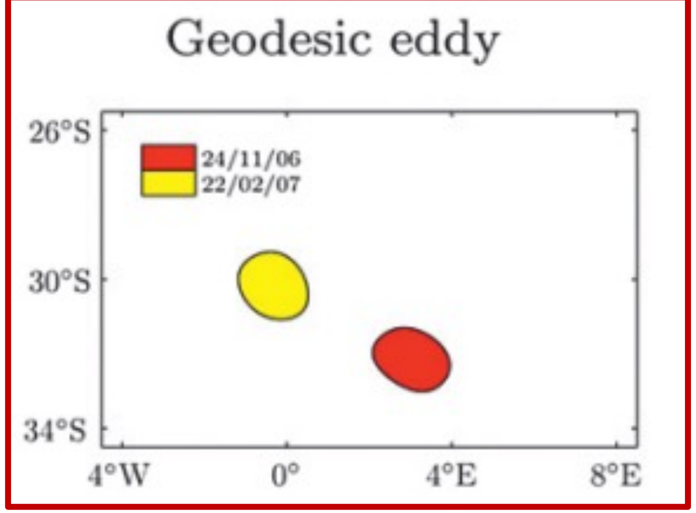


Eulerian Criteria	
Outermost closed SLA contour	**Rotation dominates over deformation**



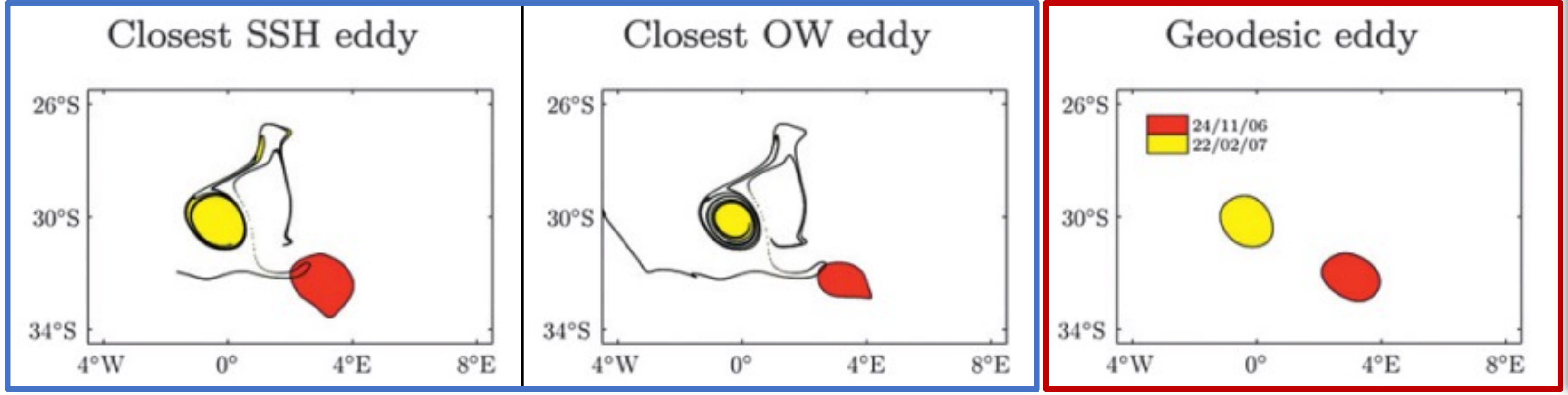


Lagrangian Criteria
The outermost closed trajectory that is closest to being geodesic

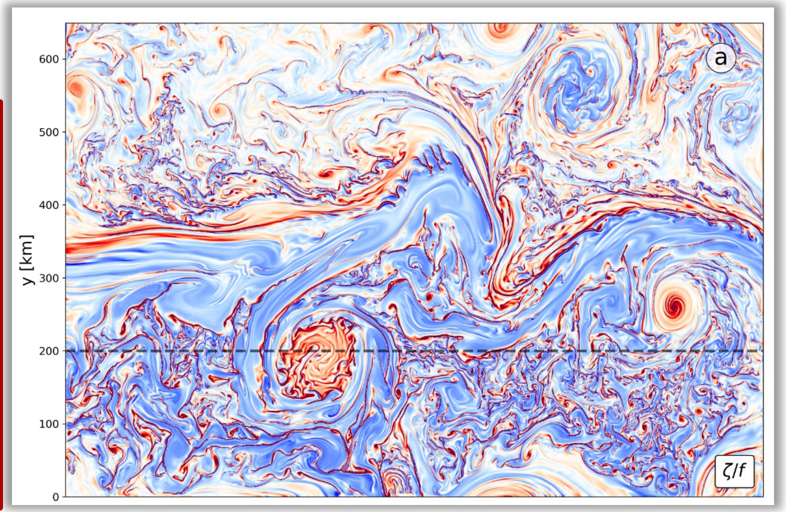


Comparaison between Kinematic and Material Coherence

Eulerian Criteria	Lagrangian Criteria



Béron-Vera et al., 2013



Gula et al. 2021

Remarks and Issues:

- Lagrangian approach is better for transport
- Boundaries do not coincide
- Works well on smoothed 2D surface fields
- What about the 3D aspect?
- Material coherence can only be tested through temporal tracking… not validated by *static diagnostics/snapshots of velocity*

Challenges / Key Issues:

- Impact of eddies on tracer transport
- No consensus on this transport
- Uncertainty regarding the influence of eddies on ocean circulation
- Raises fundamental questions about mixing dynamics

Ocean Mesoscale Eddies: Are they coherent structures?

- How can we **define the 3D boundary of mesoscale eddies**?
- Is it possible to find an **alternative definition of coherence** to reconcile material coherence (MC) and kinematic coherence (KC), and make it testable with in situ data?

How?

Use **in situ observations** and **numerical simulations** to analyze the 3D structure of mesoscale eddies.

Theory very often tested on idealized cases

What we need to determine in practice:

1. **Eddy boundaries**
2. **Eddy core**

If an eddy is *materially coherent* *(Béron-Vera & Haller Lagrangian definition)*

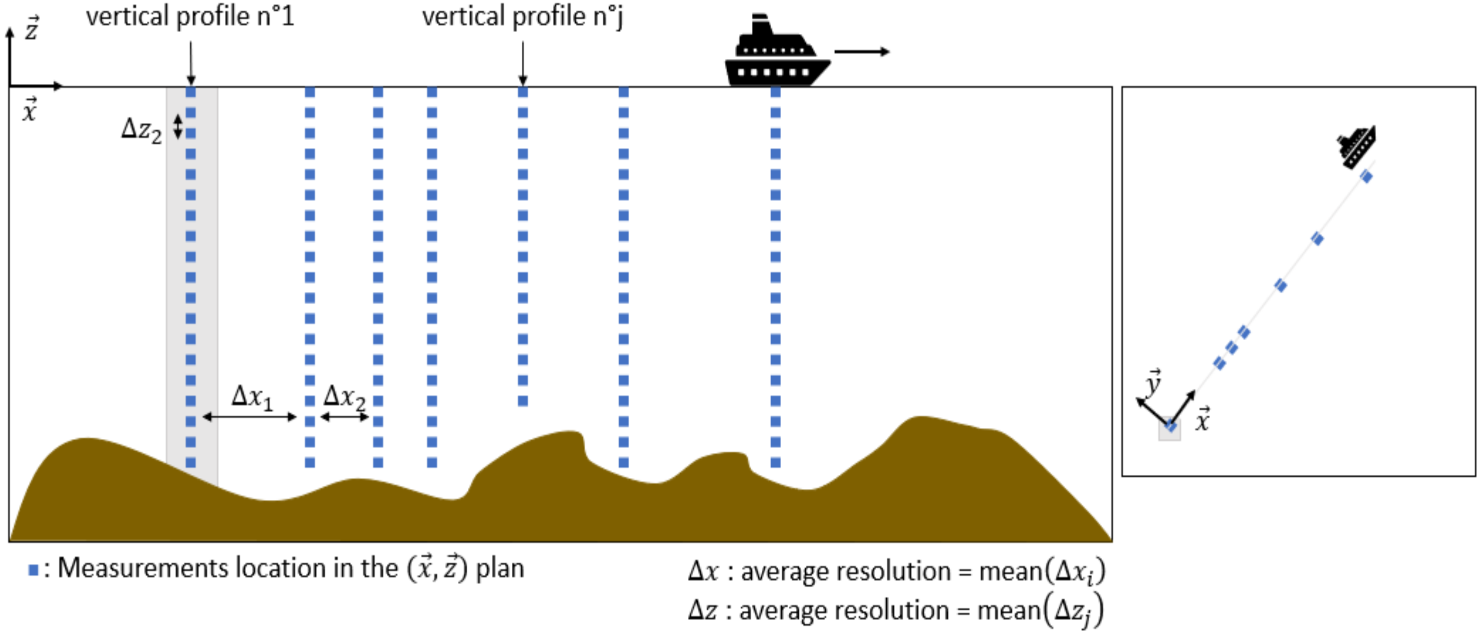
- **Its core is conserved over time** **(**McWilliams, *"coherent"* simply means **"long-lived")**
- **Core water properties remain nearly unchanged**

Key question

- **What physical processes maintain this long-term coherence?**

About the resolution of ocean observations

- **Hydrographic Data (T, S, P) Resolution**:
  - Horiz. : ~1 – 40 km
  - Vert. : ~1 m
- **Velocity Data (ADCPs) Resolution:**
  - Horiz. : ~0,3 km
  - Vert. : ~8 – 32 m
- **Common Grid:**
  - Horiz. : 1 km
  - Vert. : 1 m

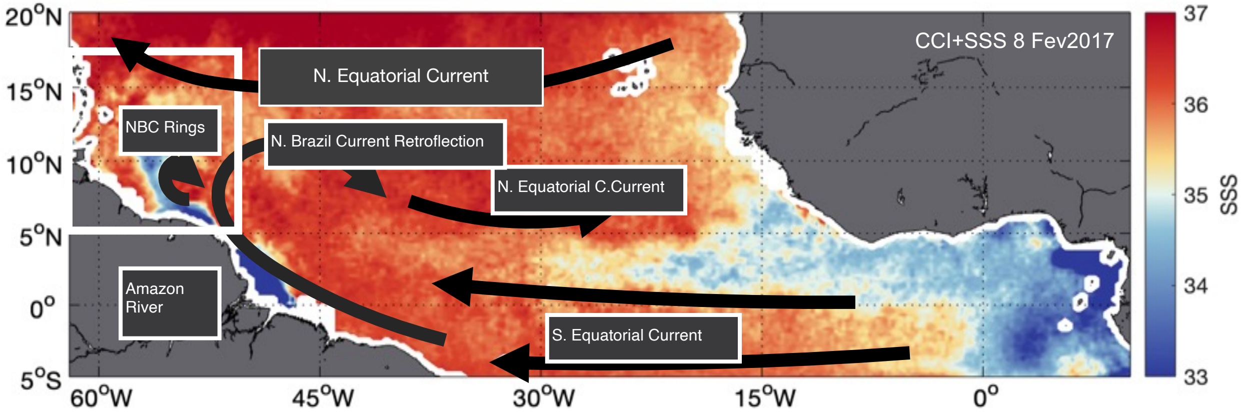


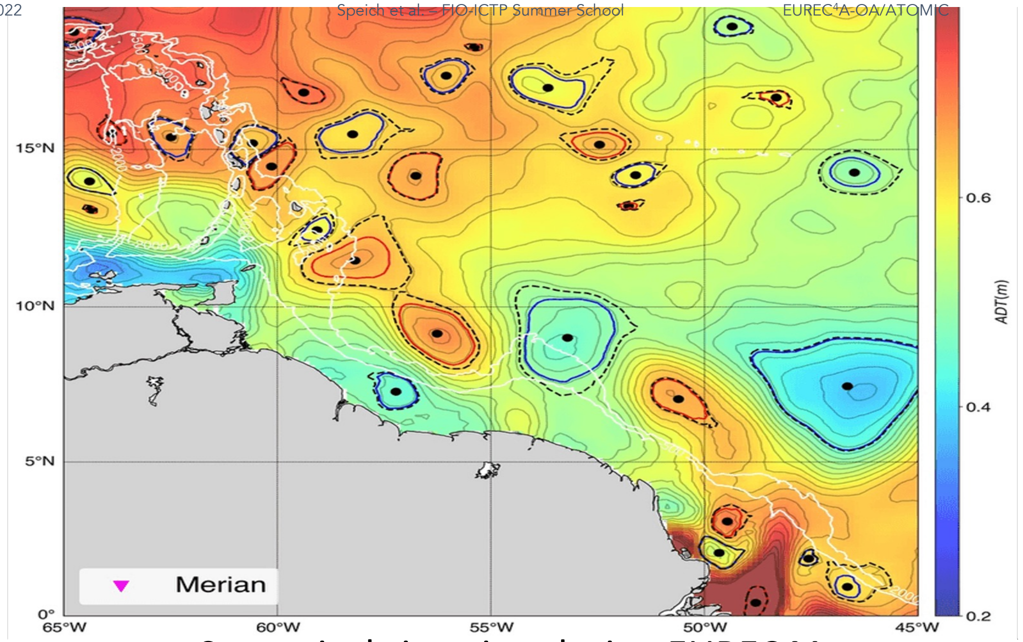
- **Study limitations:**
  - Resolution
    - ➢ Gradients
  - Ship transects far from the eddy center
  - Sampling when the eddy is moving

EUREC^{4}A-OA Field experiment strategy

Speich et al., JPI Ocean & Climate 2019

- Use of satellite observations (SMOS, SMAP, ADT, CLS SST, CLS Chl-a) and different observing devices to determine the daily observing strategy
- Use of the tool Tracking Ocean Eddies (TOEddies) in Near Real Time (NRT)
- Use of various measurement devices

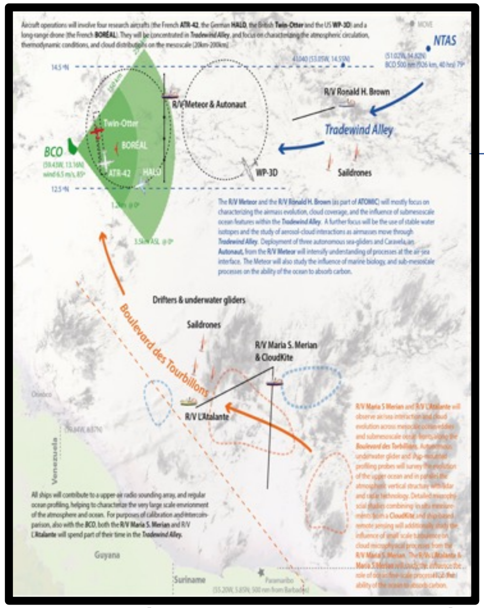




Synoptical situation during EUREC4A

Outcome of the experiment: A dataset of very high-resolution co-localized OA vertical profiles

EUREC^{4}A-OA/ATOMIC-OA: The field experiment



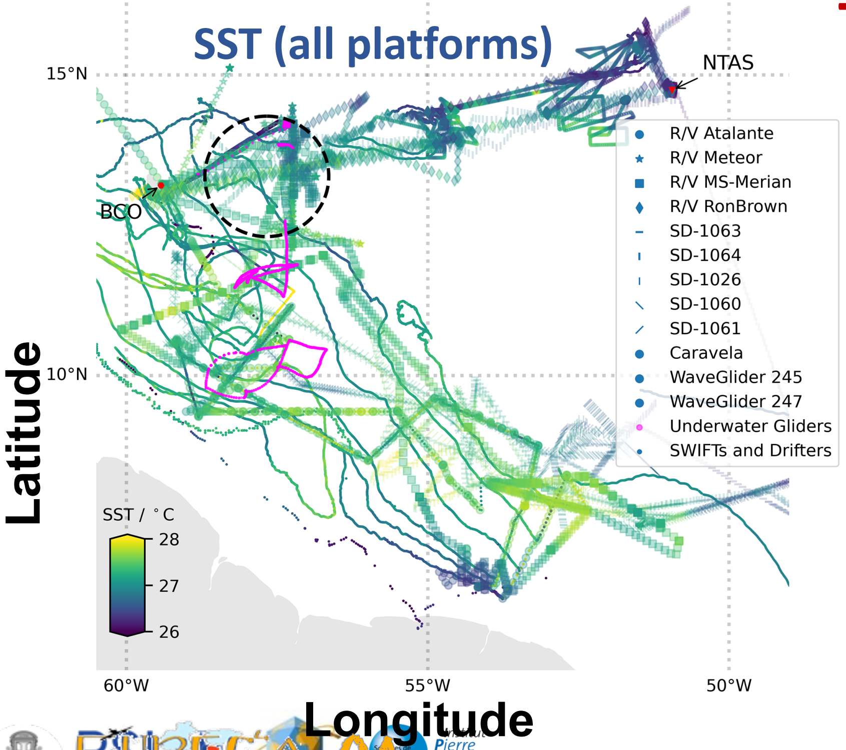
Jan-Feb 2020 Stevens et al., 2021

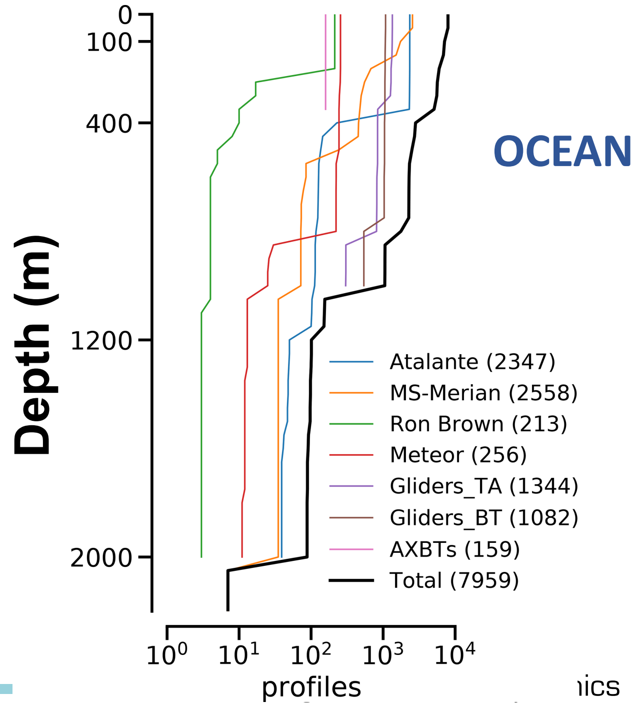
Ocean (& Atmosphere) sampling:

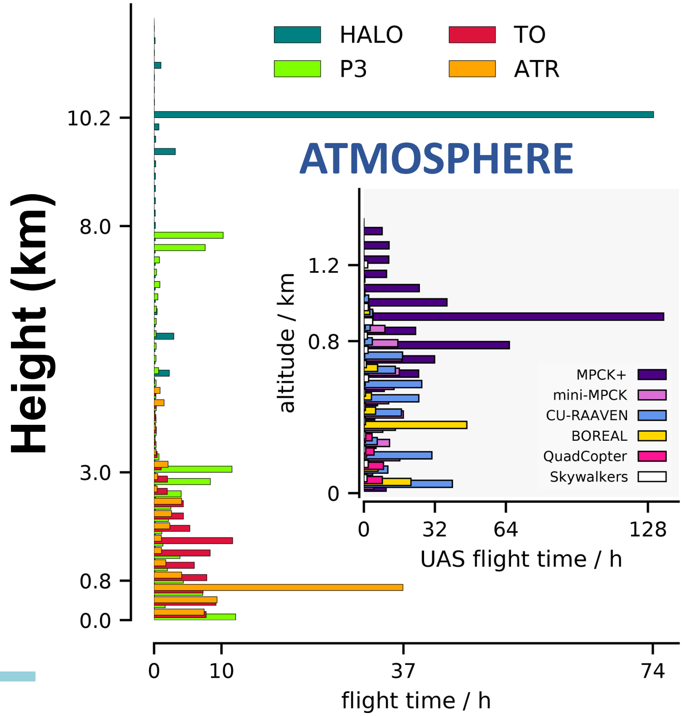
Ships: TSG, ADCPs, CTD, uCTD, MVP, VMP/MSS, CO2, water isotopes, areosols sampling, radiosondes, Atmospheric mast, lidars, radars, ….

Uncrewed platforms: drones, Saildrones, wavegliders, BGC Argo floats, drifters, ocean gliders

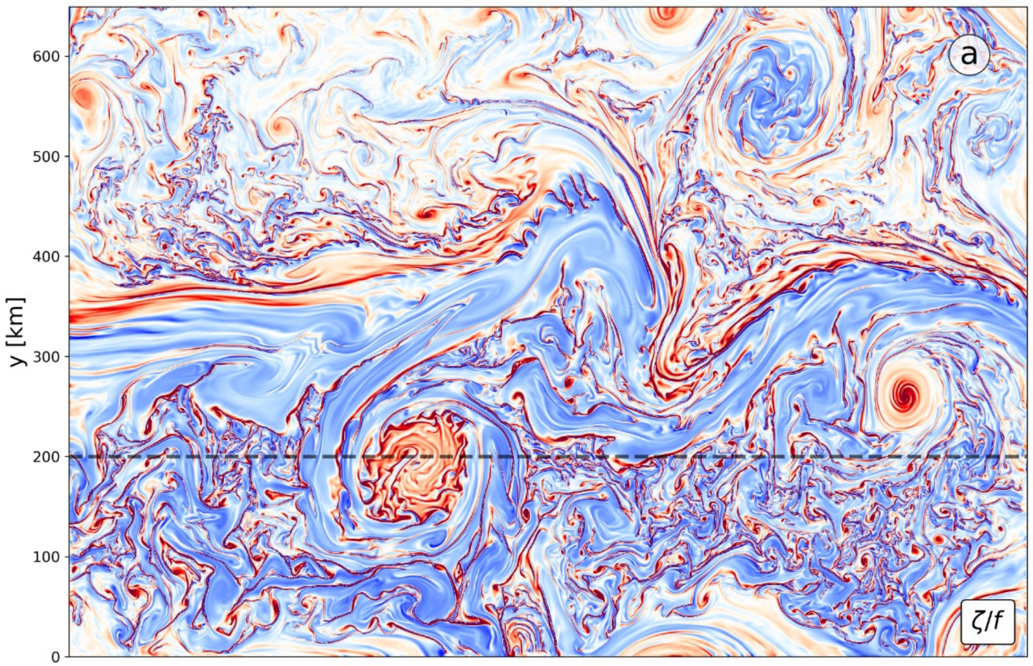
THE OBSERVATIONS WE COLLECTED



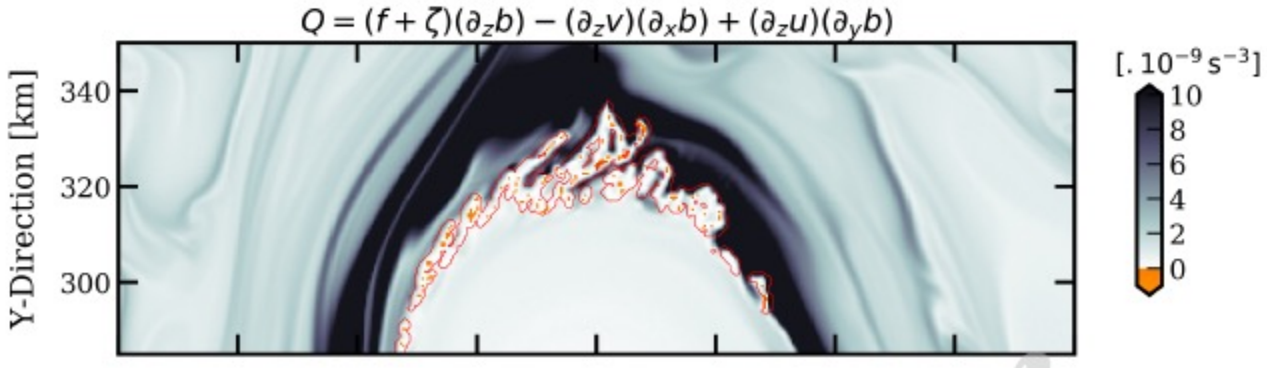




Eddy boundary: A region of loss of coherence



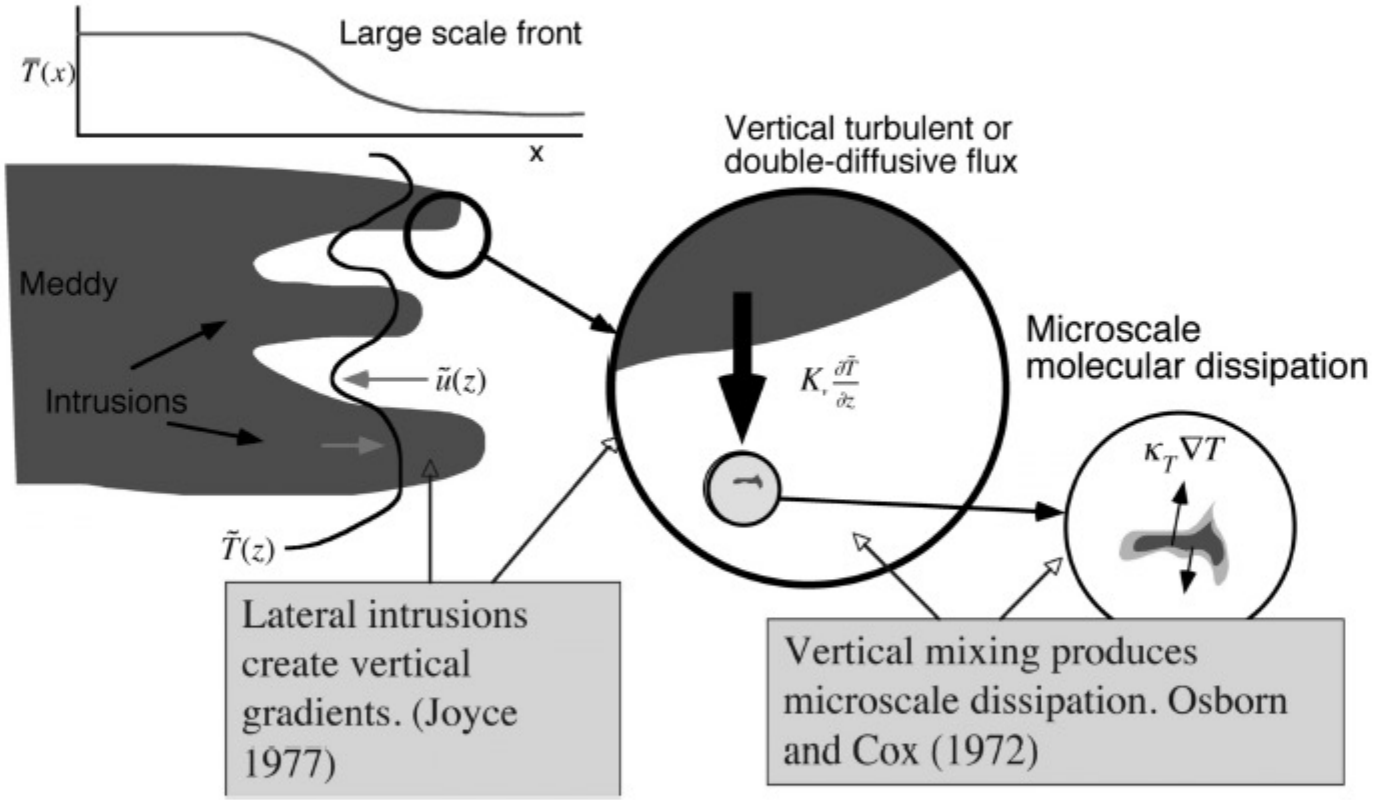
Gula et al. 2021
GIGATL 0,5 km, Gulf Stream



de Marez et al. 2020
CROCO, PE 0,5 km, CE isolé

Boundary :
- Loss of order
- Loss of a dominant vorticity component
  ⇒ **Loss of Kinematic Coherence**

Eddy boundary: A region of turbulence



Ruddick et al. (2010)

Boundary :

- Lateral intrusions
- **Fine-scale instabilities**
- The trapped water encounters the surrounding water

  ⇒ **A turbulent region**

Ocean Mesoscale Eddies: Defining their 3D structure

Step 1: Defining the Eddy Boundary

Approach based on the Ertel Potential Vorticity (EPV)

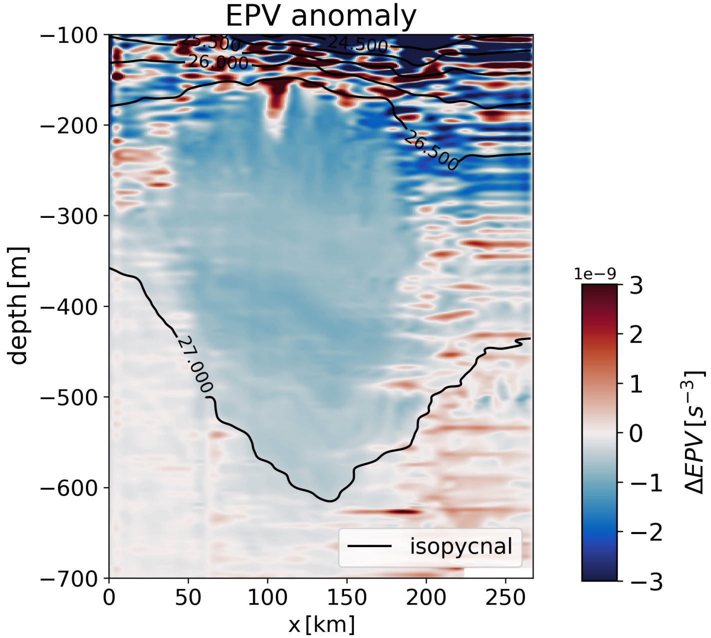
Ertel, H. (1942). Ein neuer hydrodynamischer Wirbelsatz. *Meteorologische Zeitschrift*, 59, 271–281.

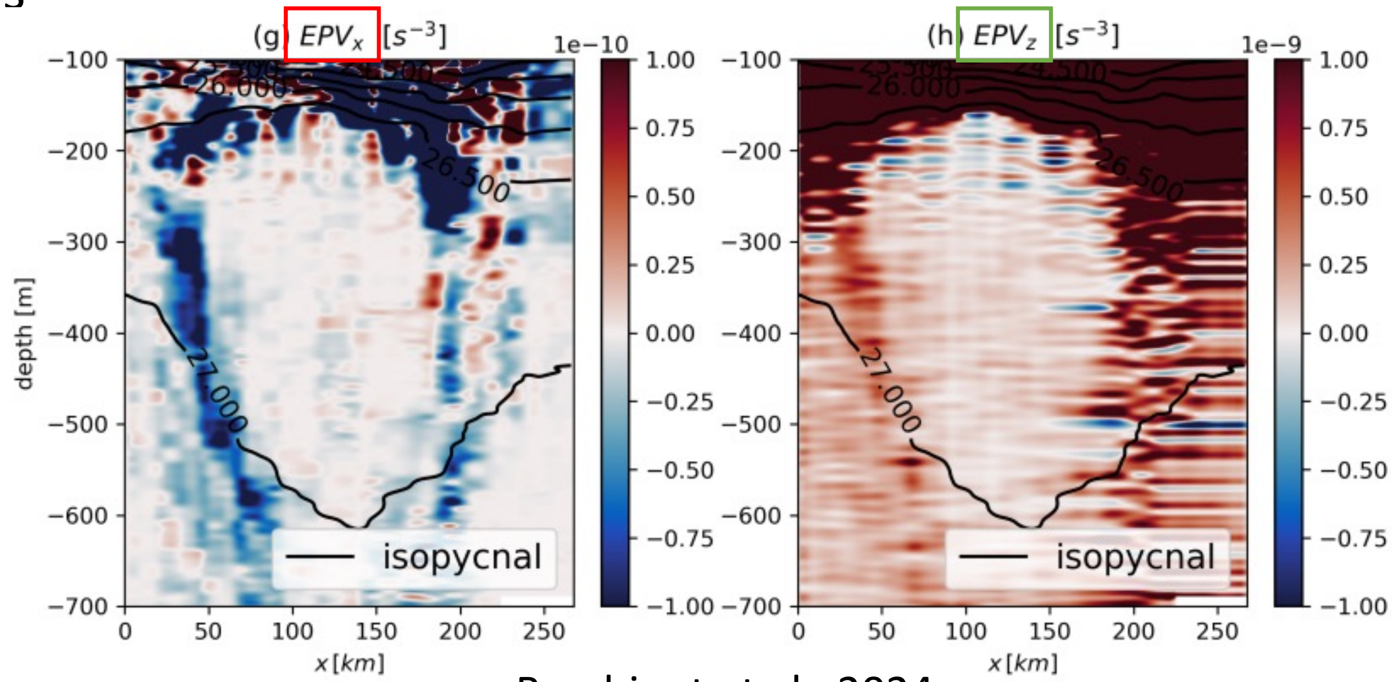
- Historically, an **eddy** is a **potential vorticity anomaly**
  - Ertel PV (Ertel, 1942) : $\mathrm{EPV} = \left(\vec{\zeta} + 2\overrightarrow{\Omega_T}\right) \cdot \vec{\nabla} b$
  - $\Delta\mathrm{EPV} = \mathrm{EPV_x} + \Delta\mathrm{EPV_z}(\sigma)$
  - Sign change at the boundary.
- **Approach:** Analysis of the different terms

2D Vertical Sections:

$$\mathrm{EPV} = \mathrm{EPV_x} + \mathrm{EPV_z}$$

$$\mathrm{EPV} = -\frac{\partial b}{\partial r}\frac{\partial V_o}{\partial z} + (\zeta + f_0)\frac{\partial b}{\partial z}$$

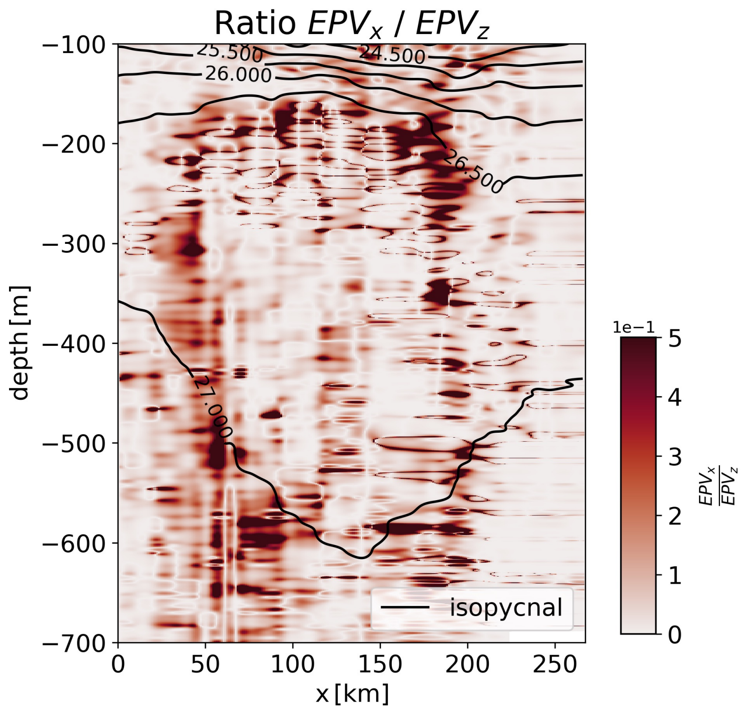


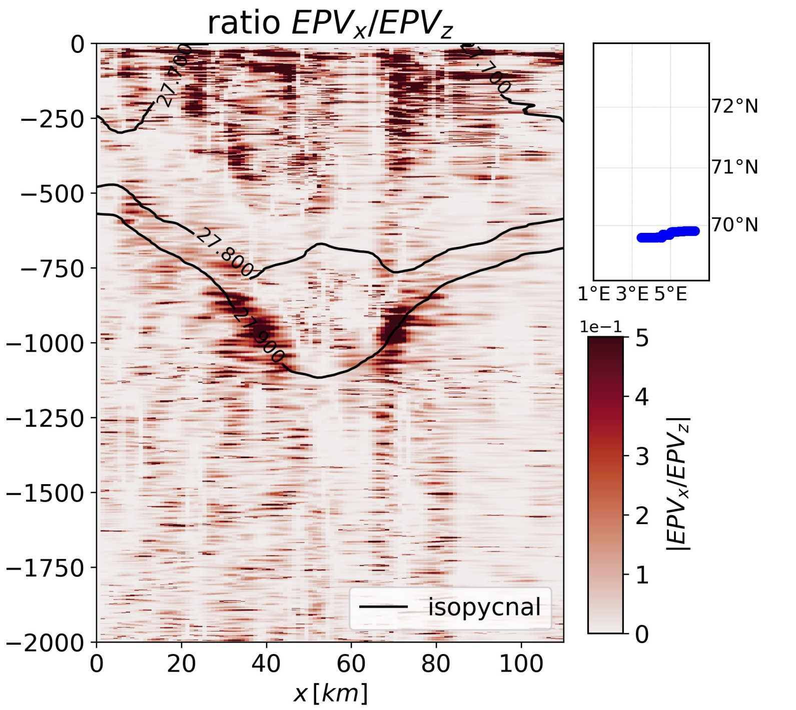


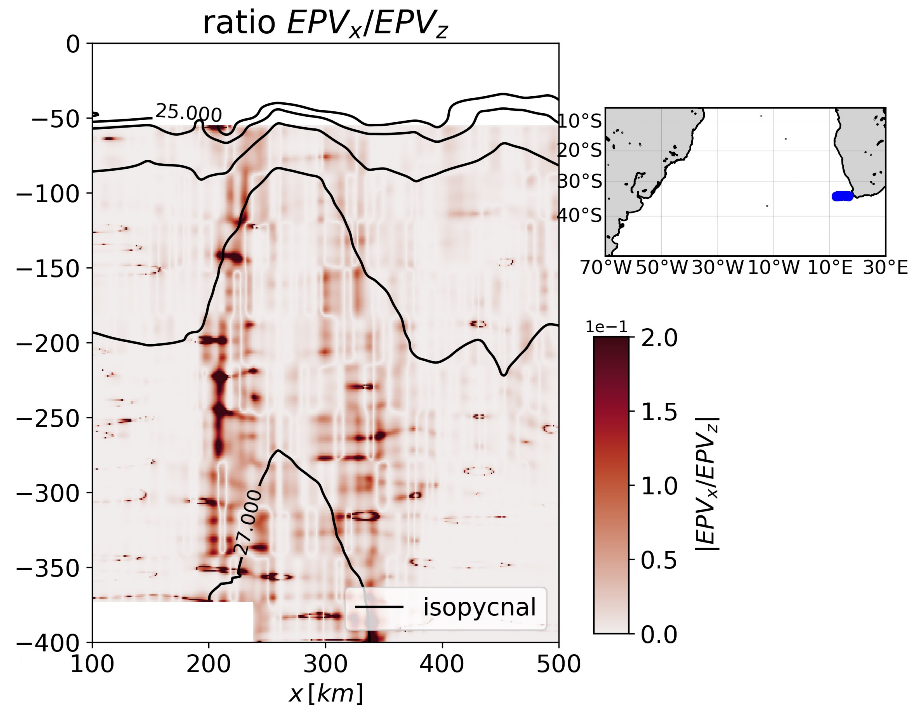
Barabinot et al., 2024

Step 1: Defining the Eddy Boundary
It constitues A Frontal Region

- Our criterion: $\alpha = \frac{|EPV_x|}{|EPV_z|} = \frac{\text{Baroclinicity}}{\text{vorticity+stratification+Coriolis}}$







From observations: $\alpha = \mathbf{O(Ro)}$

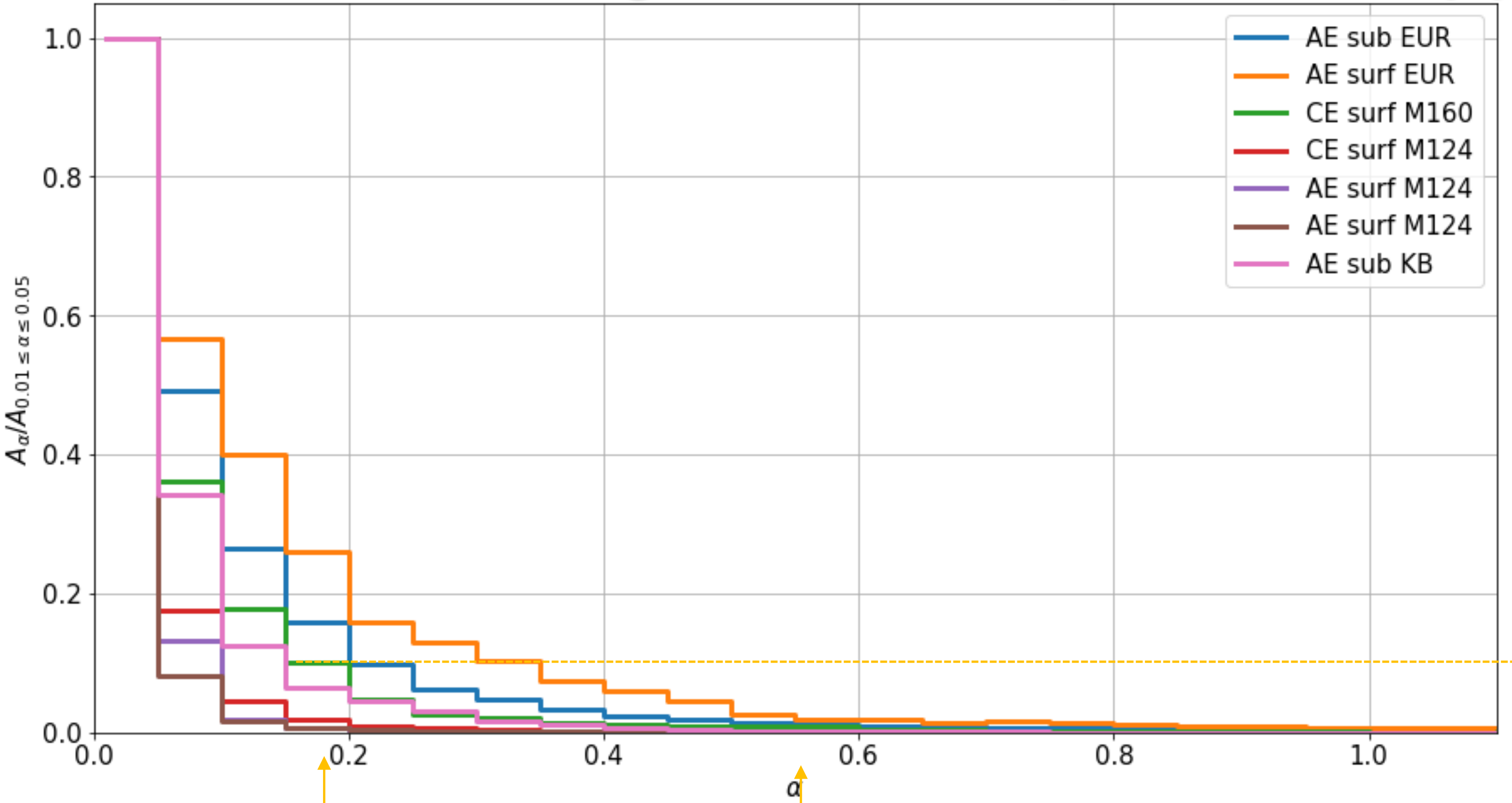
Vertical recirculation with **frontogenesis** and **symmetric instabilities**
(Hoskins & Bretherton, 1972)

Barabinot et al., 2024

Ocean Mesoscale Eddies: Defining their 3D structure

Step 1: Defining the Eddy Boundary

A Frontal Region defined by an Area = f(α), with α > 0.01



Sections verticales 2D :

$\mathrm{EPV} = \mathrm{EPV_x} + \mathrm{EPV_z}$

$\mathrm{EPV} = -\frac{\partial b}{\partial r}\frac{\partial V_o}{\partial z} + (\zeta + f_0)\frac{\partial b}{\partial z}$

Barabinot et al., 2024

$< 10\%$

$1\% < \mathrm{EPV_x} < 5\%\ \mathrm{EPV_z}$

$\mathrm{EPV_x} = 40\%\ \mathrm{EPV_z}$

$\mathrm{EPV_x} = \mathrm{EPV_z}$

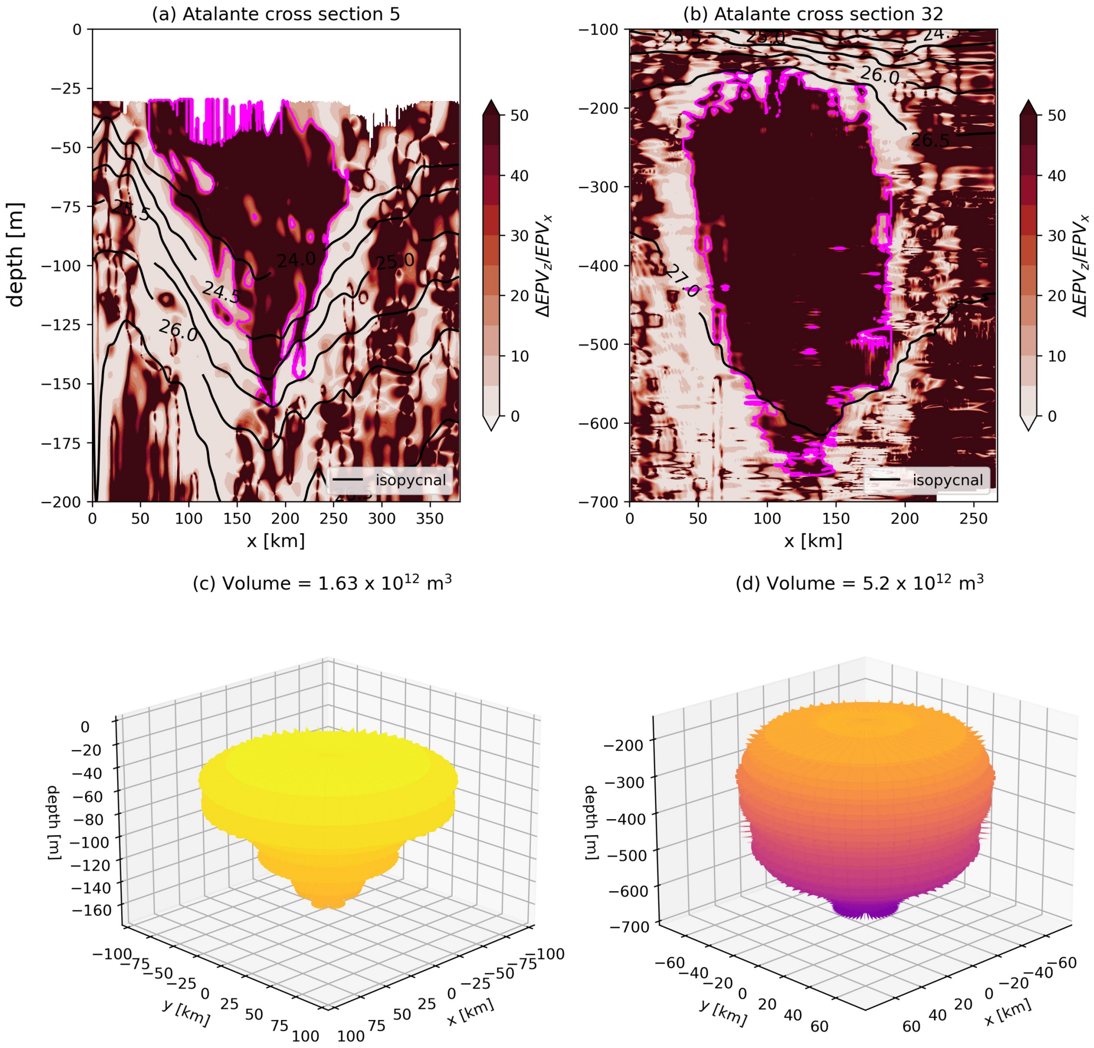
Step 2: Defining what exactly the Eddy Core is

- **Eddy Core** :
  - Region where the **baroclinic term** $\mathrm{EPV_x}$ is negligible compared with the anomaly of the vertical term $\mathrm{EPV_z}$

$$\left|\frac{\Delta \mathrm{EPV_z}}{\mathrm{EPV_x}}\right| > \beta$$

  - $\Delta \mathrm{EPV_z}(\sigma) = \mathrm{EPV_z}(\sigma) - \overline{\mathrm{EPV_z}}(\sigma)$
  - $\beta = 50$

- **The volume least prone to symmetric instabilities**



Barabinot et al., 2025a

Ocean Mesoscale Eddies: Are they coherent structures?

What we have determined so far : Ocean Observations & EPV equation

2D Vertical Sections:

$$\mathrm{EPV} = \mathrm{EPV_x} + \mathrm{EPV_z}$$

$$\mathrm{EPV} = -\frac{\partial b}{\partial r}\frac{\partial V_o}{\partial z} + (\zeta + f_0)\frac{\partial b}{\partial z}$$

Barabinot et al., 2024; 2025a

1. **Eddy boundaries** $\alpha = \frac{|\mathrm{EPV_x}|}{|\mathrm{EPV_z}|} = \frac{\text{Baroclinicity}}{\text{vorticity+stratification+Coriolis}}$ **> 0.01 (Obs O(Ro))**

2. **Eddy core** $\left|\frac{\Delta \mathrm{EPV_z}}{\mathrm{EPV_x}}\right| > \beta$ with $\Delta\mathrm{EPV_z}(\sigma) = \mathrm{EPV_z}(\sigma) - \overline{\mathrm{EPV_z}}(\sigma)$, $\beta = 50$

If an eddy is *materially coherent* *(Béron-Vera & Haller Lagrangian definition)*

- **Its core is conserved over time** (McWilliams, *"coherent"* simply means **"long-lived"**)
- **Core water properties remain nearly unchanged**

Key question

- **What physical processes maintain this long-term coherence?**

Ocean Mesoscale Eddies: Are they coherent structures?

What we have determined so far : Ocean Observations & EPV equation

2D Vertical Sections:

$$\mathrm{EPV} = \mathrm{EPV_x} + \mathrm{EPV_z}$$

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If an eddy is *materially coherent* *(Béron-Vera & Haller Lagrangian definition)*

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- **Core water properties remain nearly unchanged**

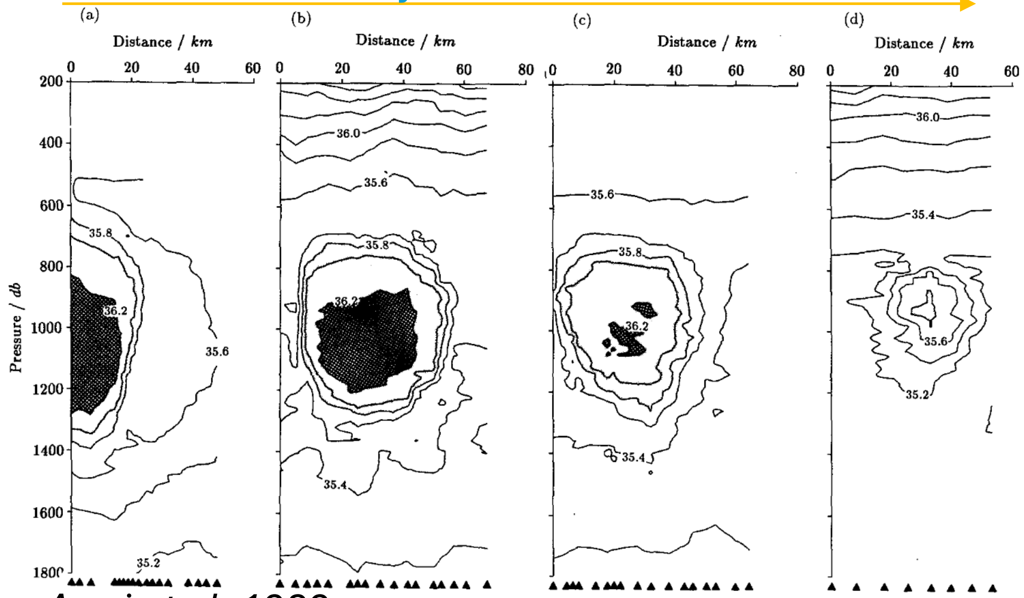
Key question

- **What physical processes maintain this long-term coherence?**

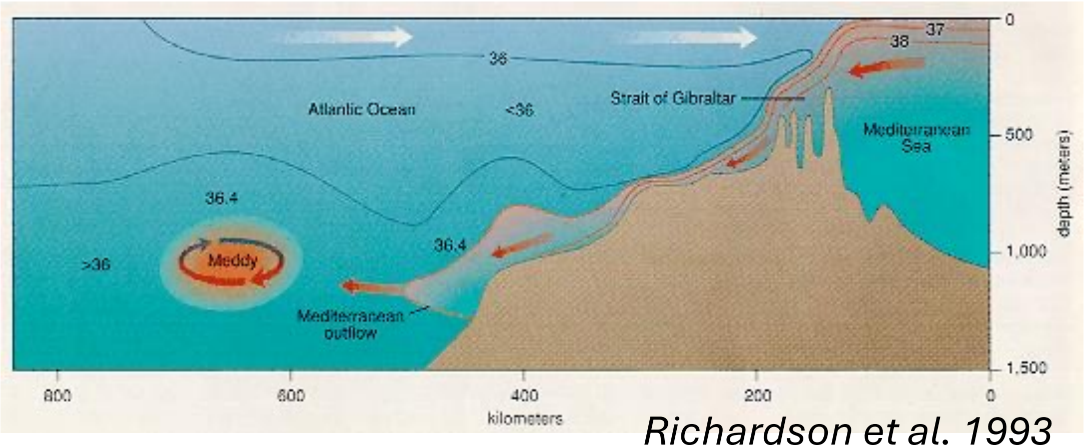
Mediterranean Water eddies (Meddies) are an example of Materially Coherent (MC) eddies

- Meddies = Mediterranean Water Eddies
  - Formation in the Gulf of Cadix, after passing the Gibraltar Strait
  - T
    c

2 years of measures

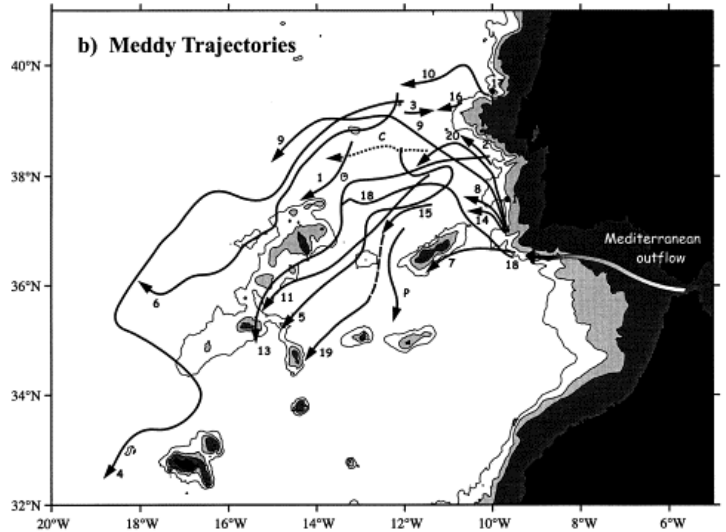


Armi et al. 1989



Richardson et al. 1993

Richardson et al. 2000



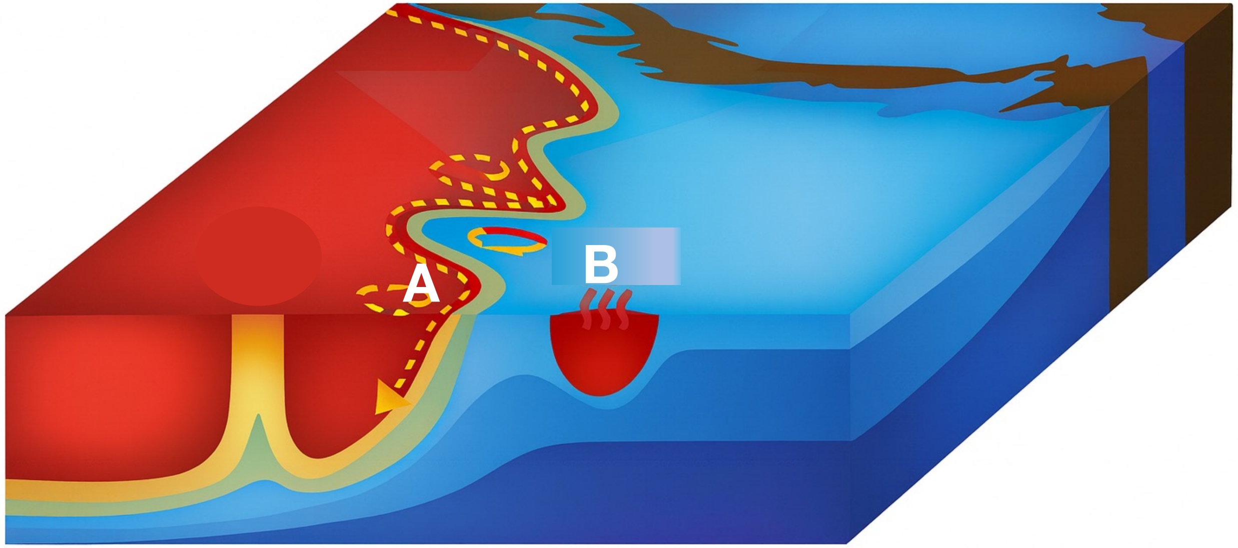
Eddies originating from distant regions have **properties** that **differ** from the surrounding environment

ENS PSL UNIVERSITÉ PARIS LMD Laplace

Ocean Mesoscale Eddies: Material Coherence

- **Material Coherence** requires **conservation of water properties**

- Hence **Thermohaline Coherence** can serve as an **observable equivalent of Material Coherences**



1) Let us consider two regions A and B of the ocean with constant salinity and temperature.
2) A materially coherent (MC) eddy forms and drifts from A toward B without dissipation.
3) The trapped fluid particles drift with it.
4) In region B, the eddy reaches hydrostatic equilibrium and remains at the surface.
5) In region B, for the same density, different (T, S) values can coexist

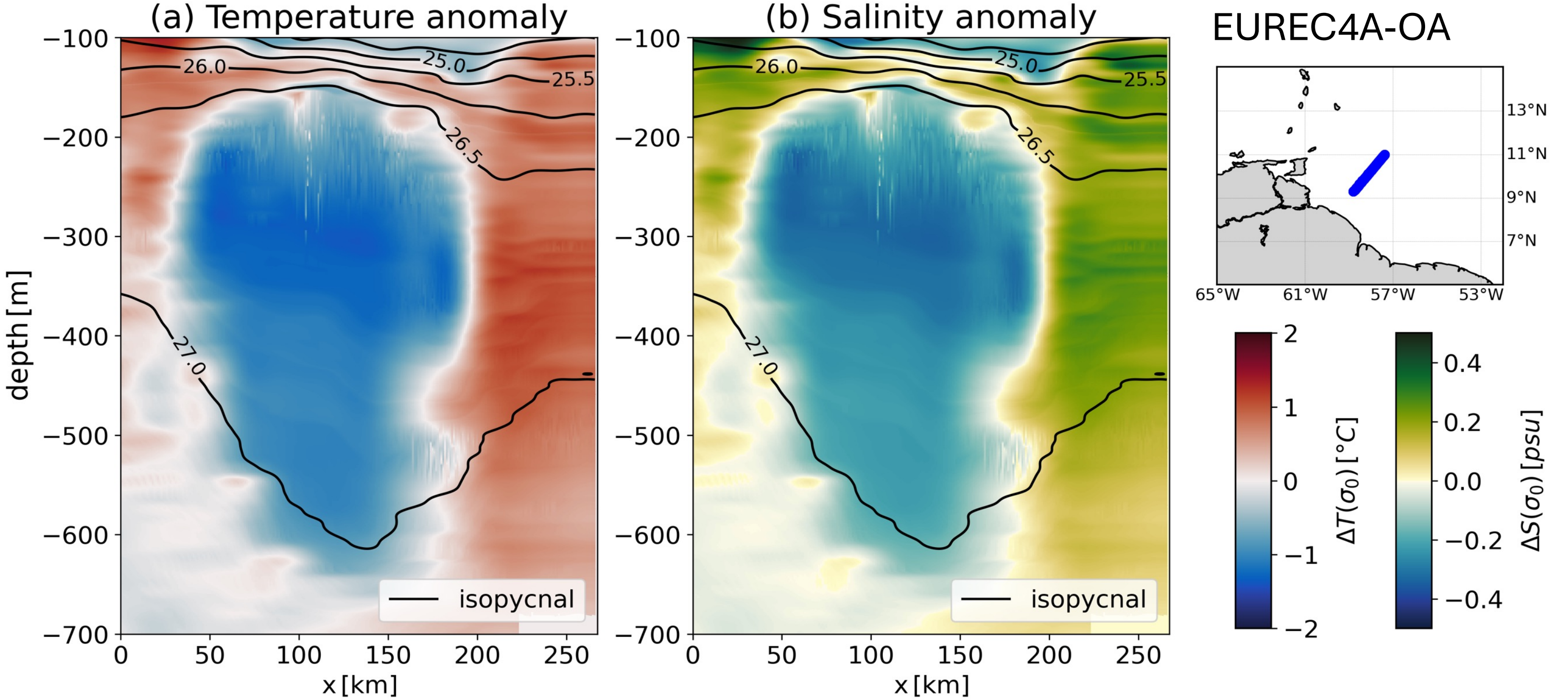
Thermohaline coherence: An eddy whose core water differs from the surrounding water (a direct consequence of material coherence)

Ocean Mesoscale Eddies: Material Coherence

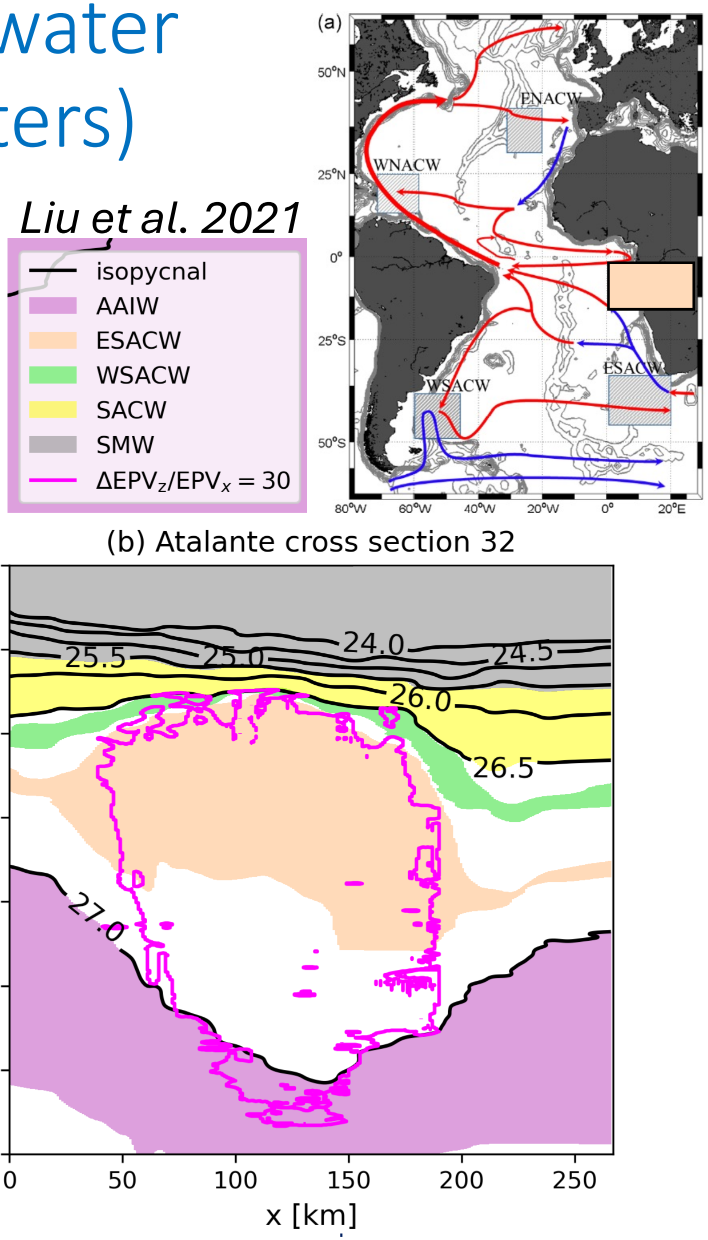
An EUREC4A-OA subsurface Anticyclone contained water masses of the Southeast Atlantic (Agulhas Rings waters)

- Computing from observations thermohaline anomalies on density surface
  - $\Delta T, S(\sigma) = T, S(\sigma) - \overline{T, S}(\sigma)$

Barabinot et al., 2025b



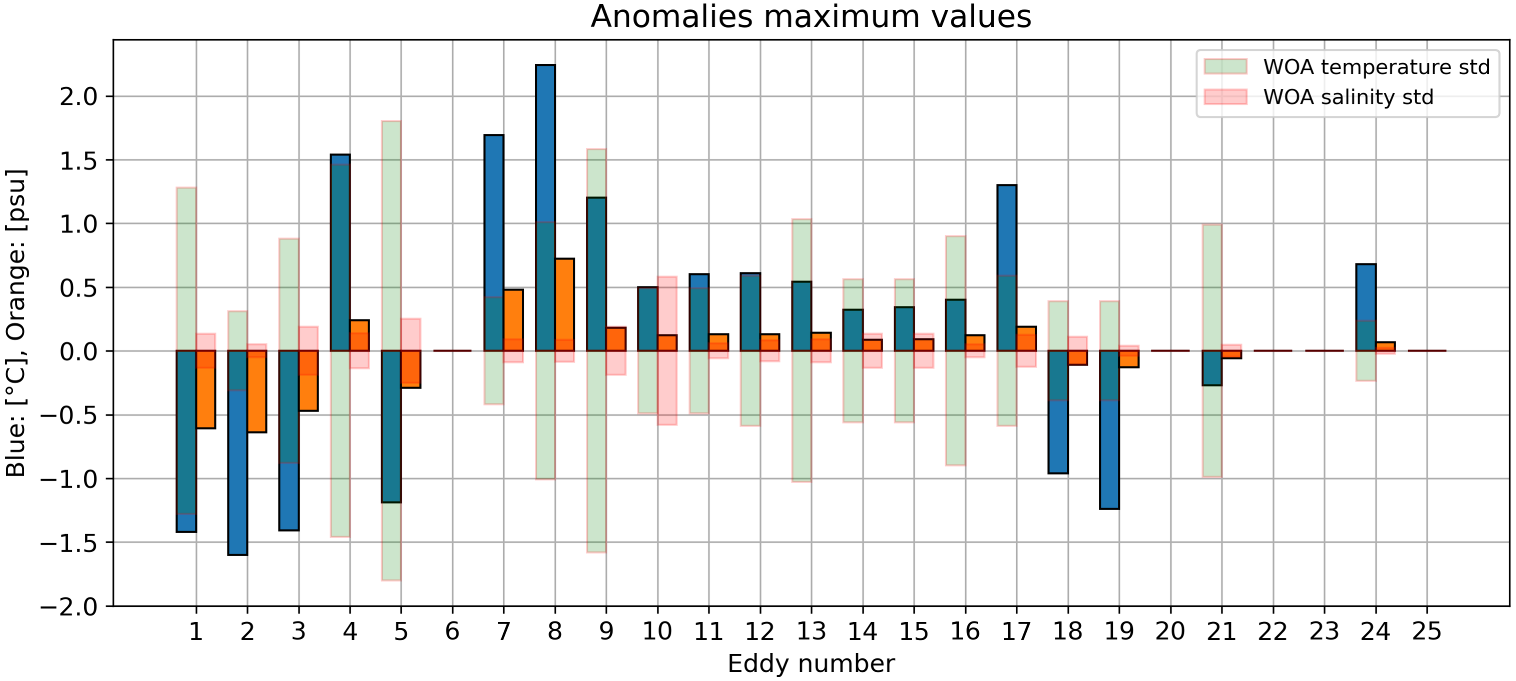
Liu et al. 2021



Ocean Mesoscale Eddies: Material Coherence

What about the other 25 anticyclones we have studied

- **Task**: Computing the **Proportion of TC (hence MC) eddies among the 25 eddies we have studied**



Maximum Temperature Anomaly

Maximum Salinity Anomaly

18/25 TC → **72%**
Within the limits of the study (eddy center positions + resolution + climatology)

- **Comparaison** with Liu et al. (2019): MITgcm → **< 50%**

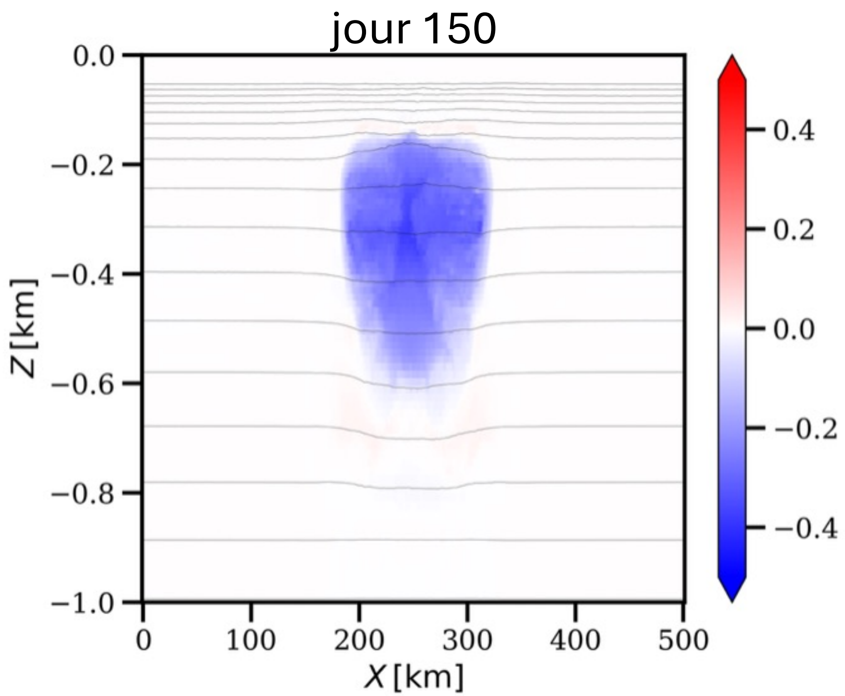
But this depends on the integration time window…

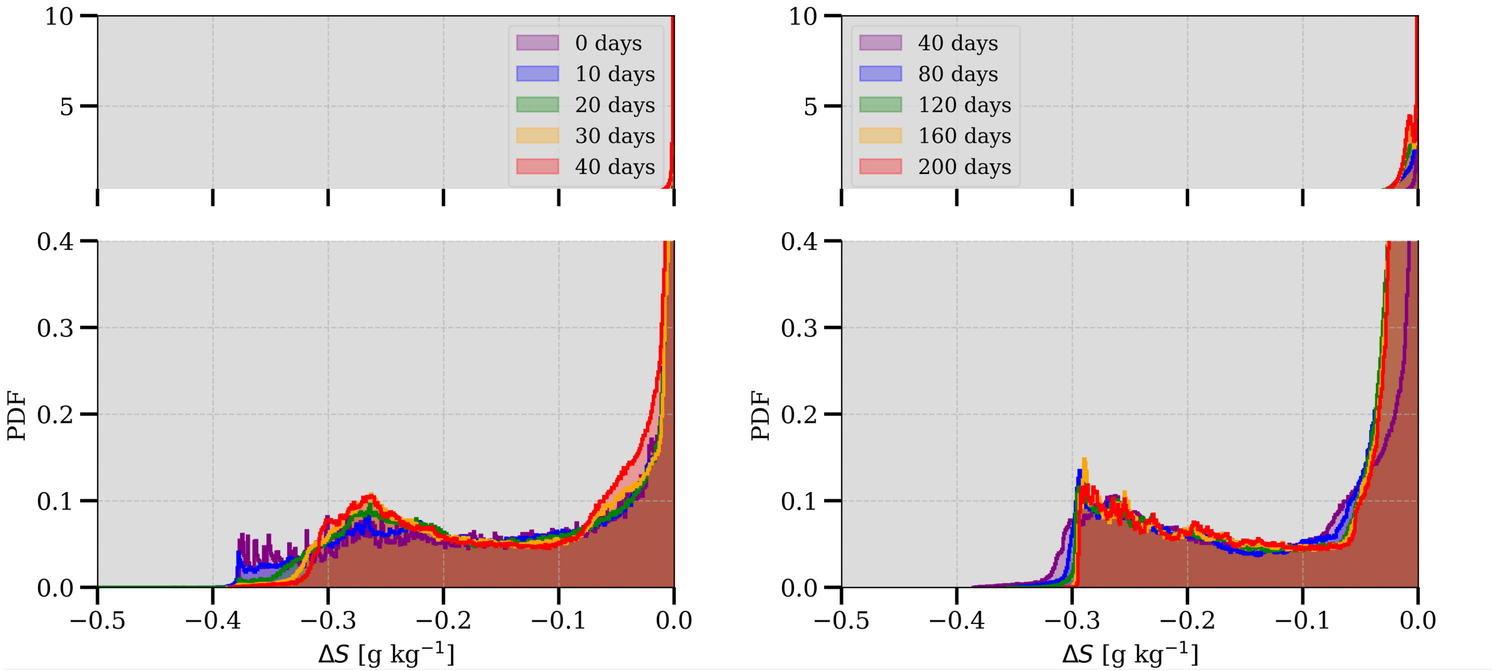
$$LAVD_{t_0}^{t_1}(\boldsymbol{x}) = \int_{t_0}^{t_1} |\omega(\boldsymbol{x}, s) - \overline{\omega}(\boldsymbol{x})|\, ds$$

It is difficult to compare …

Barabinot et al., 2025c

What do **Numerical Simulation** provide as evidence of Material versus Thermohaline Coherence ?





- **Persistence** of the anomaly over time
  - Despite filaments and BC/BT instabilities, the core remains materially coherent.
  - Diffusion alone is not sufficient to cancel the effects of material coherence.
  - The lower part of the eddy is more affected.

Barabinot et al., 2025c

Ocean Mesoscale Eddies: They are, in majorty, coherent structures

What we have determined so far : Ocean Observations & EPV equation

2D Vertical Sections:

$$\mathrm{EPV} = \mathrm{EPV_x} + \mathrm{EPV_z}$$

$$\mathrm{EPV} = -\frac{\partial b}{\partial r}\frac{\partial V_o}{\partial z} + (\zeta + f_0)\frac{\partial b}{\partial z}$$

1. **Eddy boundaries** $\alpha = \frac{|\mathbf{EPV_x}|}{|\mathbf{EPV_z}|} = \frac{\text{Baroclinicity}}{\text{vorticity+stratification+Coriolis}}$ **> 0.01 (Obs O(Ro))**
2. **Eddy core** $\left|\frac{\Delta \mathrm{EPV_z}}{\mathrm{EPV_x}}\right| > \beta$ with $\Delta \mathrm{EPV_z}(\sigma) = \mathrm{EPV_z}(\sigma) - \overline{\mathrm{EPV_z}}(\sigma)\ and\ \beta = 50$

If an eddy is *materially coherent* *(Béron-Vera & Haller Lagrangian definition)*

- **Its core is conserved over time** (McWilliams, *"coherent"* simply means **"long-lived"**):

  yes (70%)

- **Core water properties remain nearly unchanged:**

  yes

Ocean Mesoscale Eddies: What is the physical processes driving eddy coherence?

What we have determined so far : Ocean Observations & EPV equation

2D Vertical Sections:

$$\mathrm{EPV} = \mathrm{EPV_x} + \mathrm{EPV_z}$$

$$\mathrm{EPV} = -\frac{\partial b}{\partial r}\frac{\partial V_o}{\partial z} + (\zeta + f_0)\frac{\partial b}{\partial z}$$

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If an eddy is *materially coherent* *(Béron-Vera & Haller Lagrangian definition)*

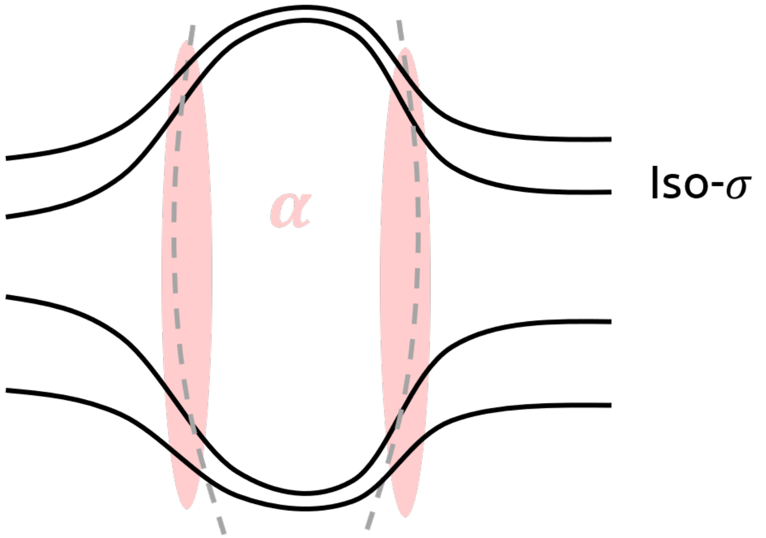
- **Its core is conserved over time** (McWilliams, *"coherent"* simply means **"long-lived")**:
  yes (75%)
- **Core water properties remain nearly unchanged:**
  yes (75%)

Key question

- **What physical processes maintain this long-term coherence?**

Physical Interpretation

- **Outside** the eddy:
  - $\partial_r b = 0$, $\partial_z b = d_z \bar{b}$ and the velocity is zero
- The eddy locally **modifies the ocean stratification** :
  - $|\partial_r b| \uparrow$, $|\partial_z b| \downarrow$
- From the Thermal Wind, the velocity gradients change:
  - $|\partial_z V_O| \uparrow$, $|\zeta| \downarrow$
- Conclusion : $|\mathrm{EPV_x}| \uparrow$, $|\mathrm{EPV_z}| \downarrow$ at the eddy boundary:
  - **The slope of the isopycnals governs the eddy boundary.**
  - The boundary becomes stronger as the slope increases



- Régions $|\mathrm{EPV_x}|/|\mathrm{EPV_z}|$ coincide with inflection point of isopycnal surfaces:

$$\frac{\mathbf{d^2 z_b}}{\mathbf{dr^2}} = \mathbf{0}, \qquad f_0 \partial_z v_\theta = \partial_r b\,, \qquad \left|\frac{\partial v_\theta}{\partial z}\frac{\partial b}{\partial r}\right| - \alpha \left|(\zeta + f_0)\frac{\partial b}{\partial z}\right| = 0,$$

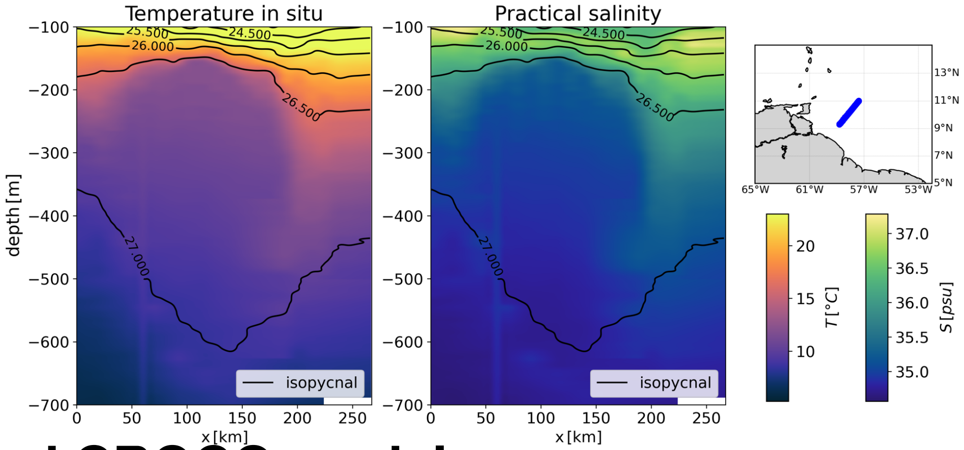
$$\alpha = Ro = \frac{V}{f_0 R}$$

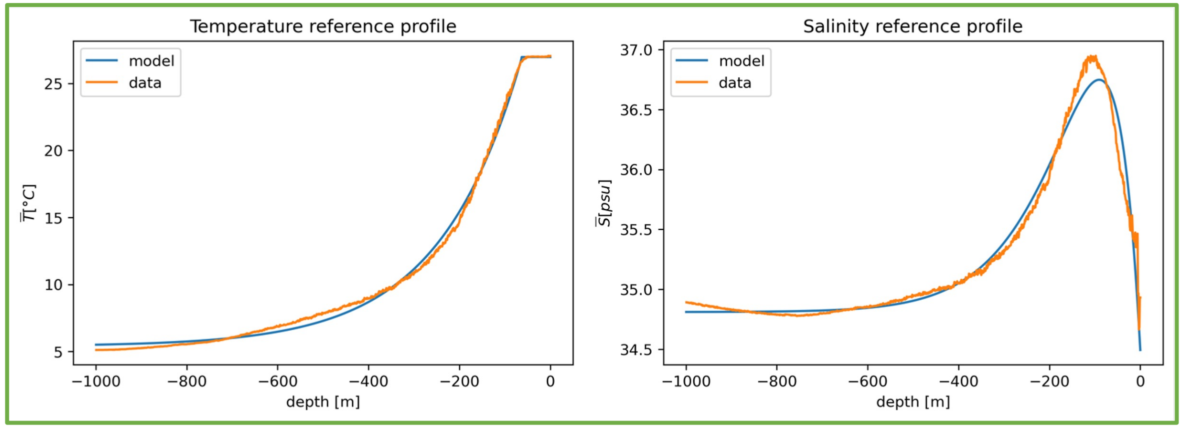
Barabinot et al., 2025c

Ocean Mesoscale Eddies: What is the physical processes driving eddy coherence?

What do **Numerical Simulation** suggest as the physical terms responsible of robust, impermeable, eddy boundaries ?

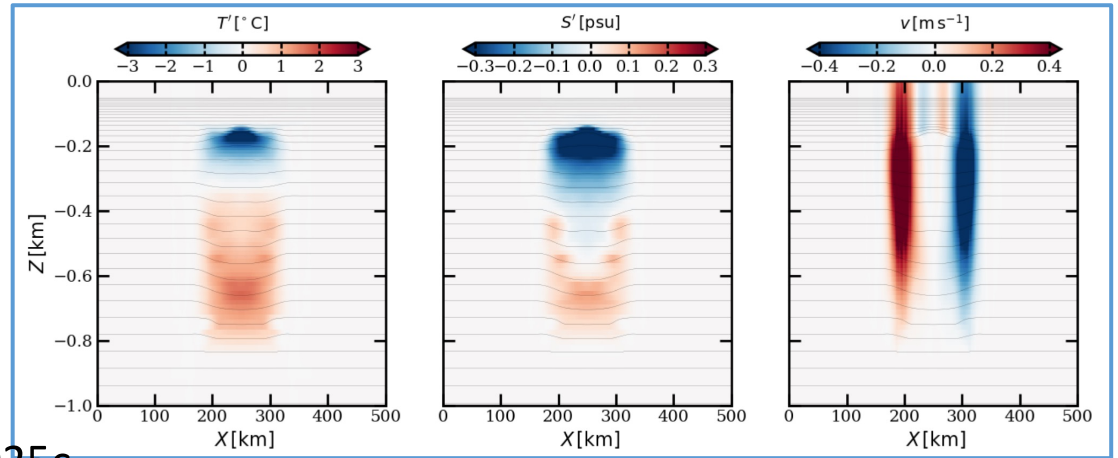
- **Simulation of a Subsurface Antucyclone (EUREC4A-OA like)** pendant EUREC4A





Idealized CROCO model

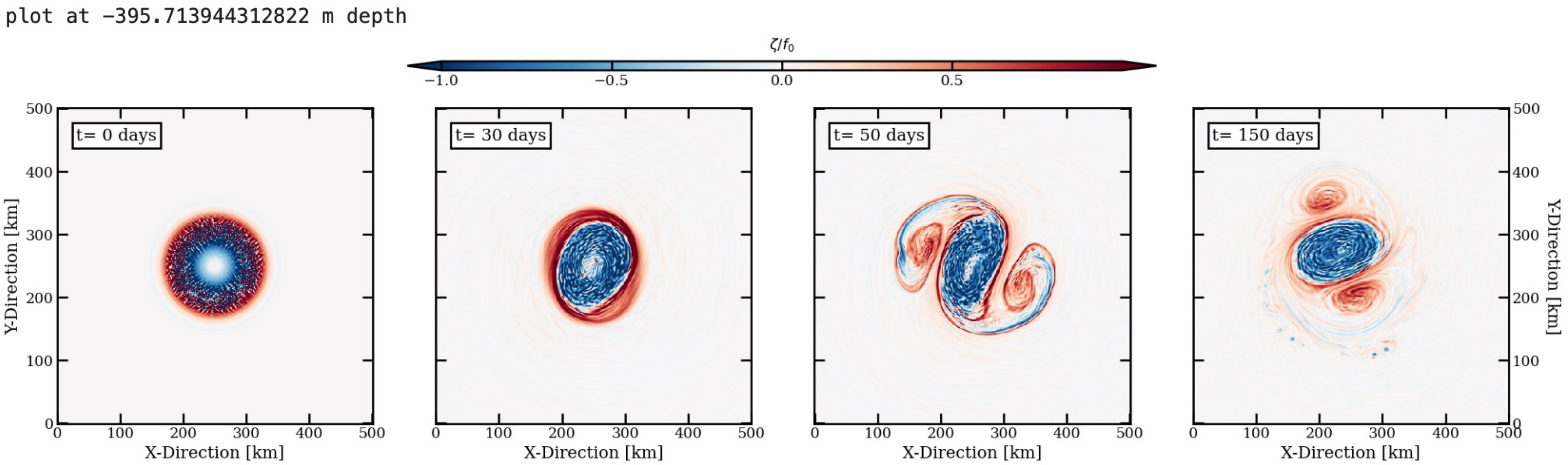
- Configuration already published (de Marez et al., 2020)
- Flat bottom at –2000 m, open boundary conditions, 500×500 km box
- No forcing, vertically uniform levels
- Resolution: dx = 1 km, dz ≈ 15 m, dt = 90 s
- Background: climatological T and S profiles
- Initialization: in situ T and S anomalies



Barabinot et al., 2025c

What do **Numerical Simulation** suggest as the physical terms responsible of robust, impermeable, eddy boundaries ?

- f − plan; integrated over 300 days



Axysymmetric

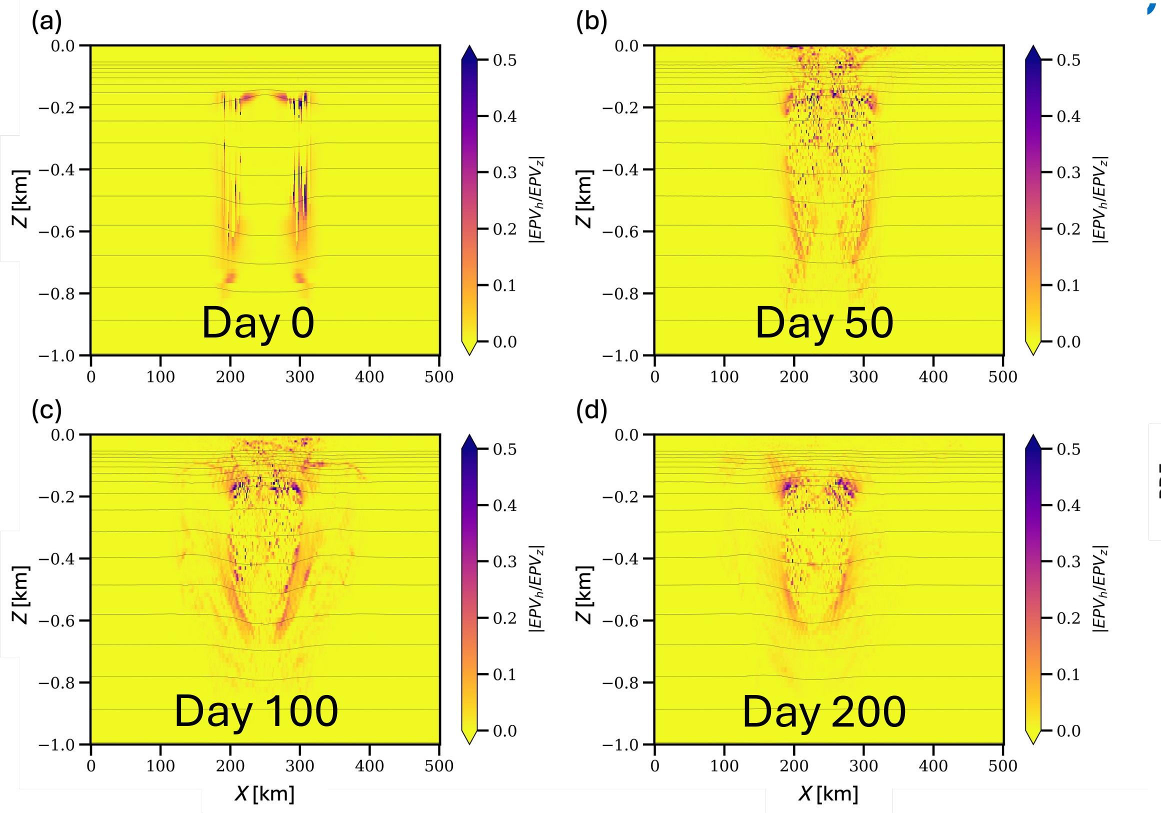
Mixed barotrope and baroclinic instabilities (de Marez et al. 2020)

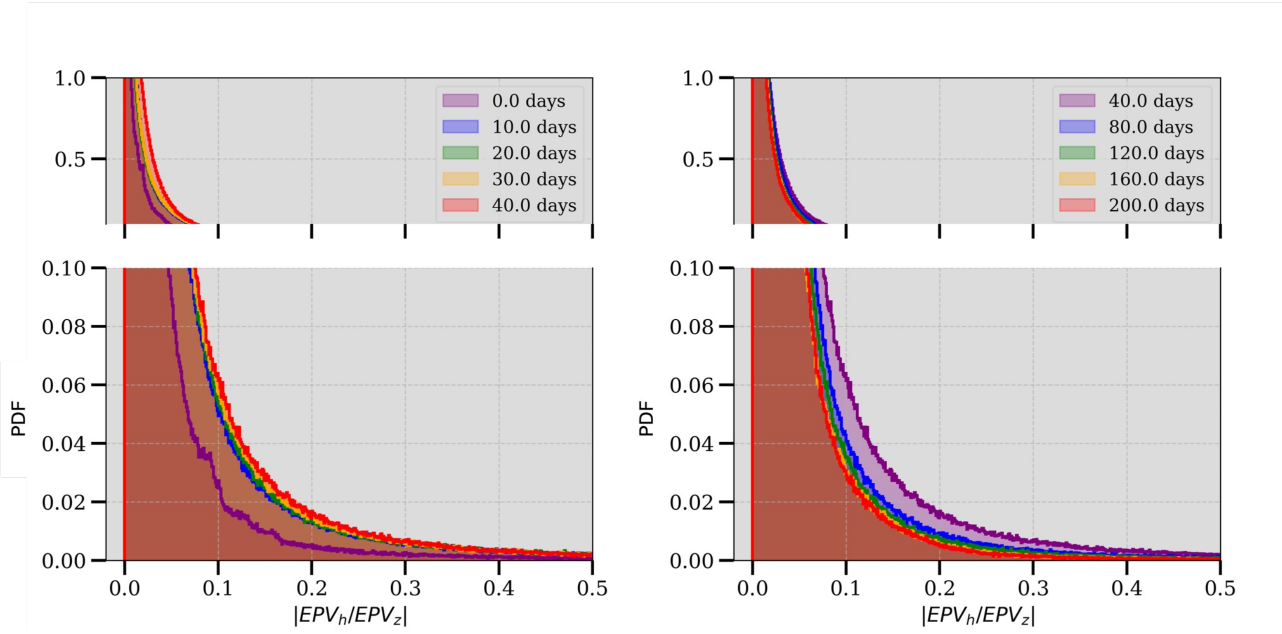
Stable tripole

Barabinot et al., 2025c

Ocean Mesoscale Eddies: What is the physical processes driving eddy coherence?

What do **Numerical Simulation** suggest as the physical terms responsible of robust, impermeable, eddy boundaries ?

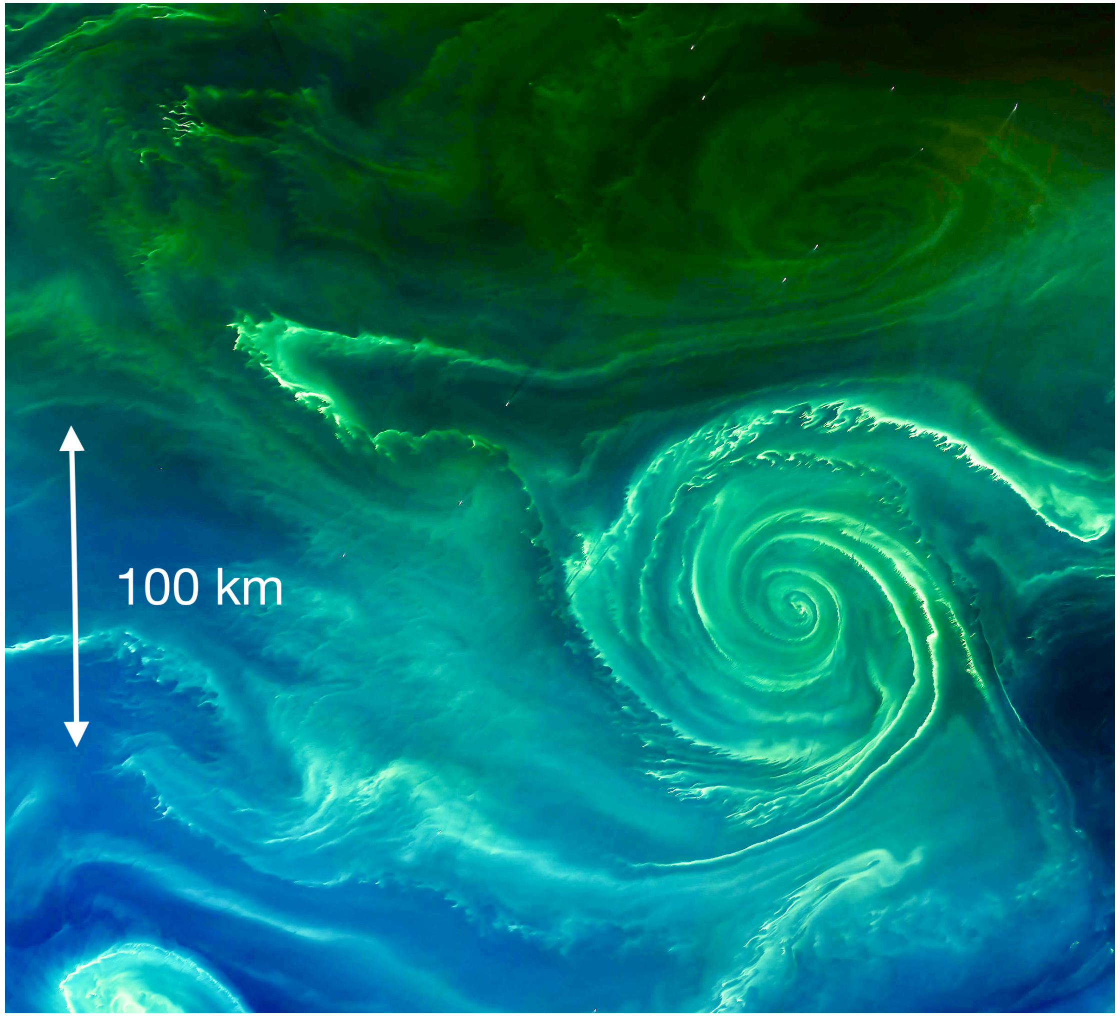




- The ratio $\alpha = \frac{EPV_h}{EPV_z}$ characterizes the boundary in 3D, with the same order of magnitude as the observations.
- During the BC/BT instability (~day 30), α increases
- Then α decreases and stabilizes once the tripole becomes stable.

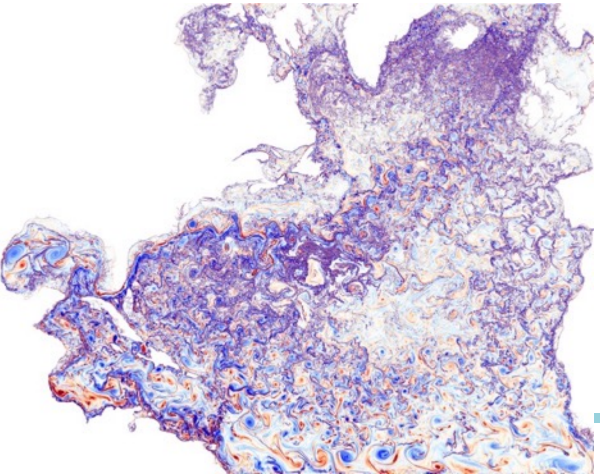
Ocean Mesoscale Eddies:
What we have understood so far from HR in-situ observations

- **Thermohaline coherence** is evidence of **material coherence.**
- Our results suggest that the **majority of ocean mesoscale eddies are thermohaline coherent**
- **Eddy boundaries** are **frontal regions,** the dynamical barriers where trapped water and surrounding water meet.
- The **slope of the isopycnals** and **the thermal wind** determine their strength.
- The **boundaries are potentially unstable**. However, **small-scale instabilities do not affect thermohaline coherence** for an isolated eddy (< 300 days).



Conclusions

- **Mesoscale eddies** are **ubiquitous** features of the turbulent upper ocean.
- Their **evolution is complex**: **eddies frequently split, merge, and form network of trajectories** (i.e., they have a complex life-tree).
- **Lifespans range from months to years**, often with **long-distance transport of water-mass properties**.
- **Eddies can be surface- or subsurface-intensified** and **may subduct water into the thermocline**.
- **Subtropical anticyclones** **contribute to Mode Water formation and ventilation**.
- **Most eddies** exhibit **strong thermohaline (material) coherence** despite boundary instabilities.
- **Eddy boundaries** are **intense dynamical fronts set by isopycnal slopes and thermal-wind balance**.




Thank you !

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