Thermo-haline Surface signatures of the Gulf Stream Eddies: Statistics based on historical Satellite SSS data

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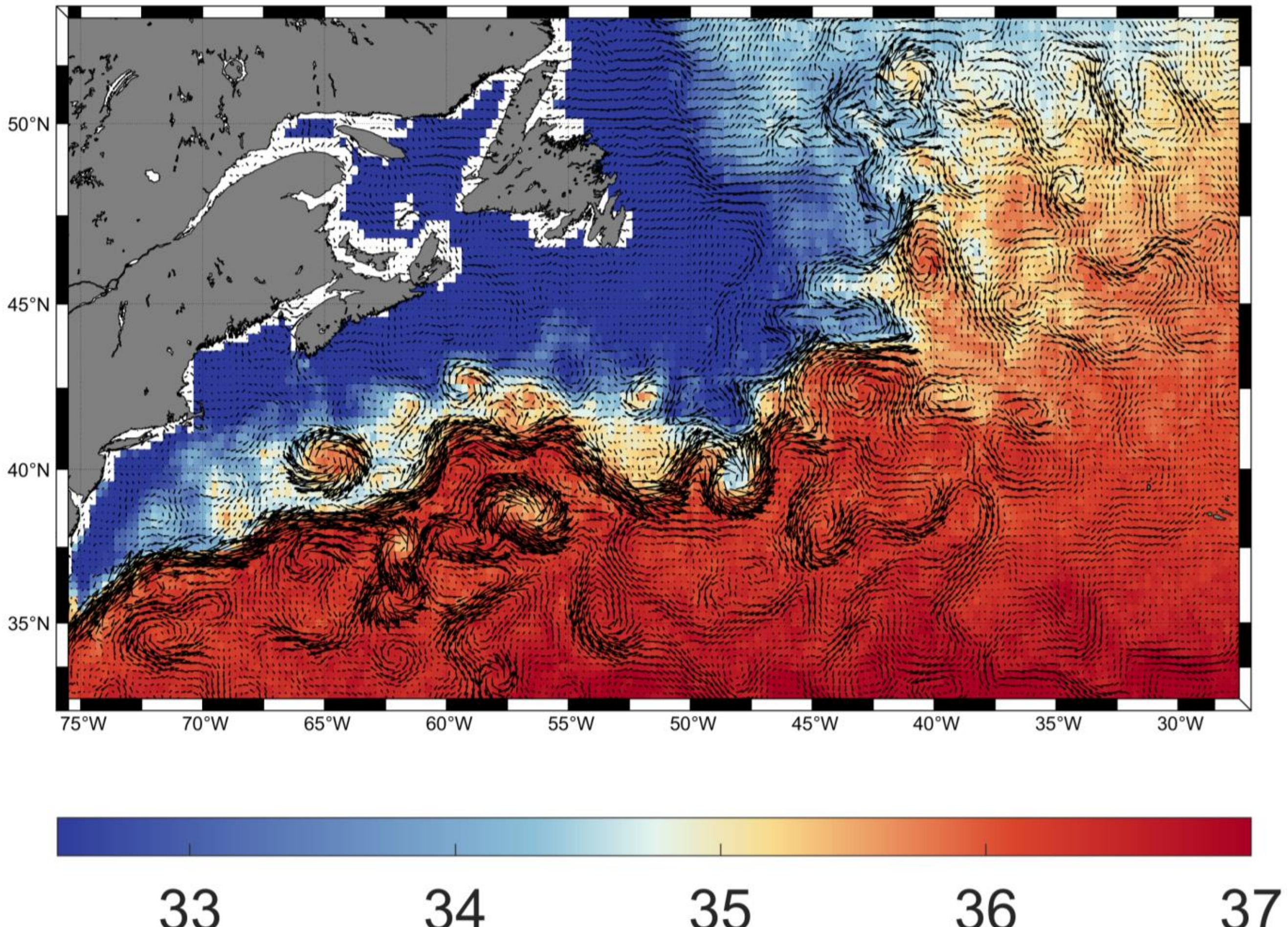


The Gulf Stream: a boundary current for all key oceanic variables

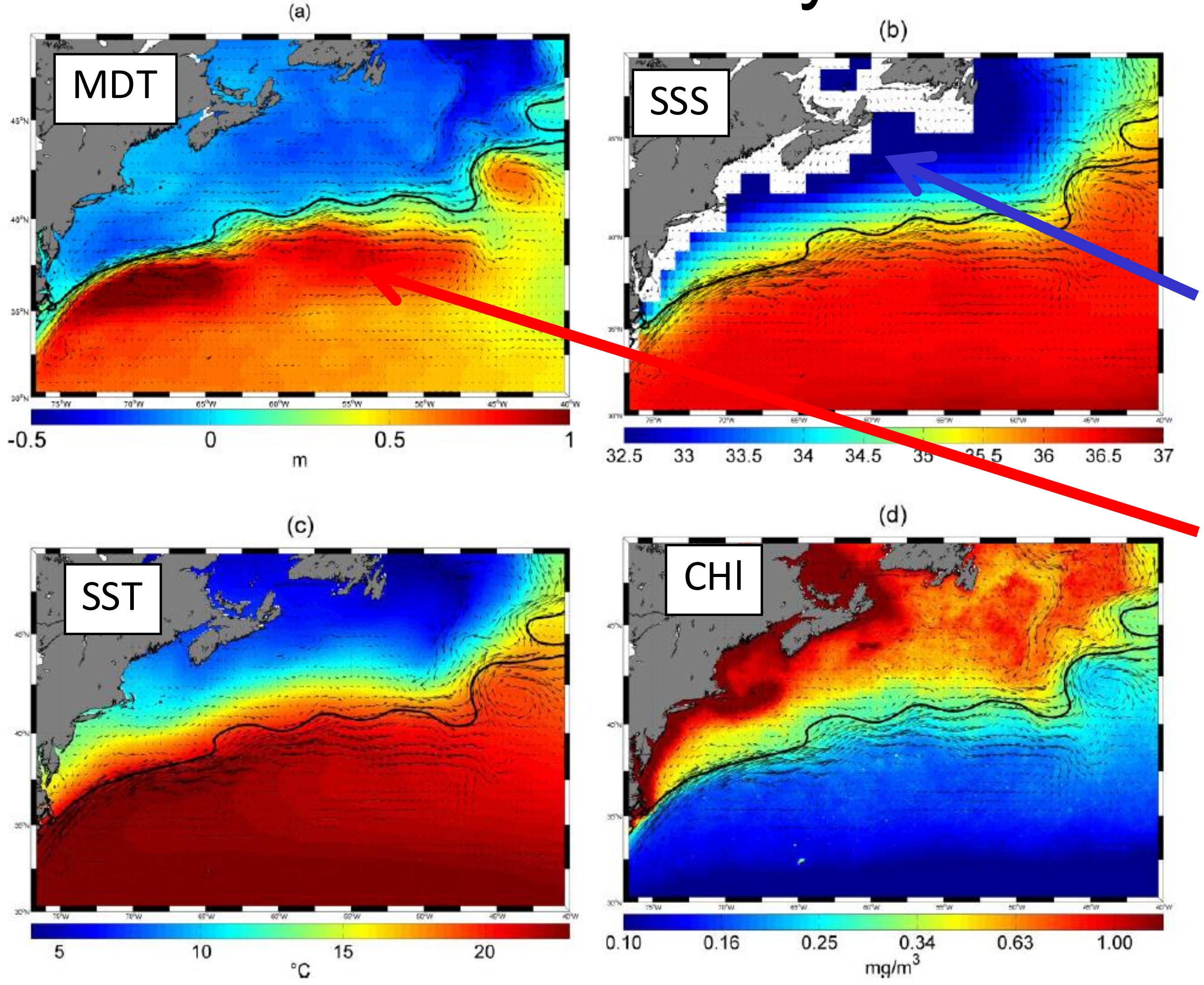


Figure 2: *Climatologies of (a) the Mean Dynamic Topography (color) and geostrophic currents (arrows) (Rio, 2009); (b) World Ocean Atlas SSS; (c) Pathfinder SST (Casey) and (d) SeaWIFS 1997-2007 Chlorophyll. The black curve extending across the North Atlantic is the separating streamline estimated from the steady atltimer-based streamfunction.*

In the North-Western Atlantic, the Gulf Stream flows at the boundary between two distincts water masses:

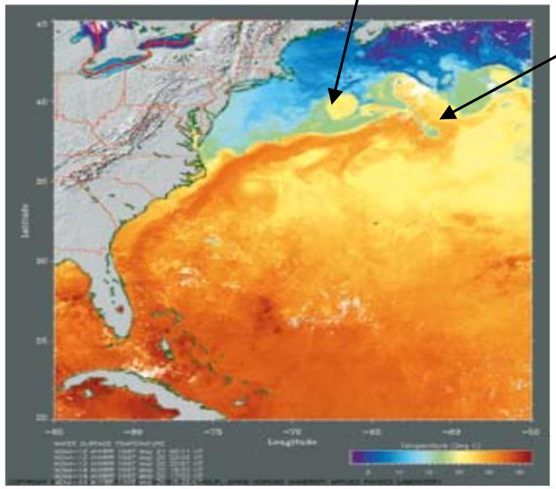
1) **The cold & Fresh waters from the Labrador Sea** advected South Westerly by the Labrador Current and which spread **North of the GS main path** (so-called « Slope and Shelf waters »)

2) **The warm and Salty waters from the subtropical gyre** which spread **South of the GS main path** (Sargasso sea)

Large scale Strong Frontal Boundaries in
⇒SSH (~25 cm jump)
⇒SSS
Zonal Gradients> 5 pss/10°
⇒SST
Zonal Gradients> 10°C/10°
⇒Chl
...

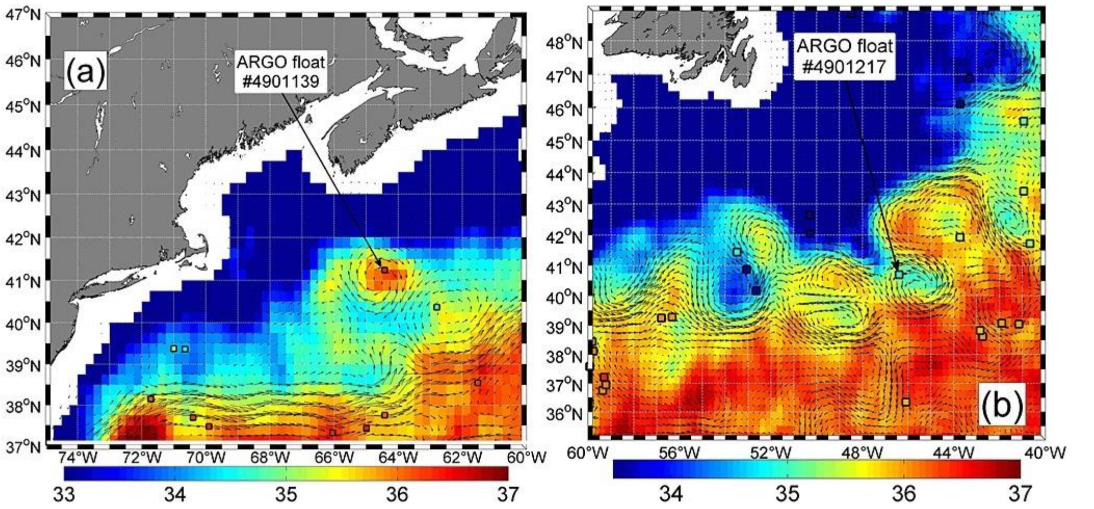
Meso-scale SST & SSS Structures along the path of the Gulf Stream after separation at Cap hateras are well detected from Space

Warm Core Ring (WCR) and **Cold Core Rings (CCR)**



SST IR image of the Gulf Stream Rings

Salty Core Ring (SCR) and **Fresh Core Rings (FCR)**



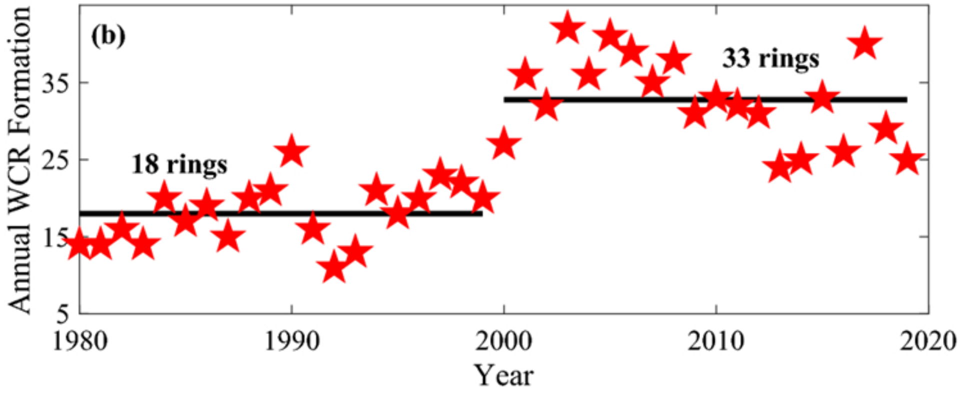
SMOS SSS images of the Gulf Stream Rings **Reul et al., 2014**

- **The stark difference in temperature and salinity between the warm, salty waters of the Gulf Stream and the cold, fresher waters of the western Atlantic Ocean means that the Gulf Stream is inherently unstable.**
- The contrast causes the Gulf Stream to follow a meandering path, and roughly **15 to 30 times each year a loop of salty or fresh water breaks off as an independent, wandering, rotating eddy. most common size for these rings is between 40 km and 50 km.**
- **SMOS reveals SSS structure of the Gulf Stream with an unprecedented resolution (Reul et al., 2014)**
- **Cold rings are better captured by SSS observations than by SST during summer (better surface contrasts)**

Recent scientific results about GS eddies

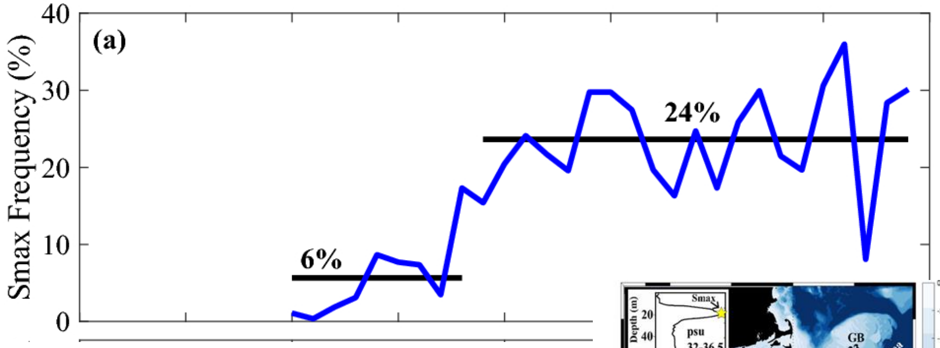
- Silver et al., Nature Scientific Report (2021)

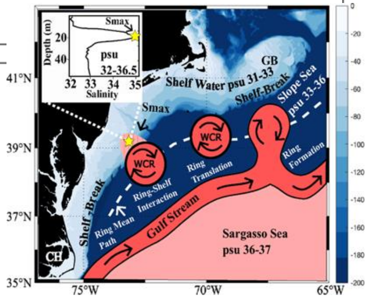
After a regime-shift in 2000, 15 more Warm Core Rings have been forming yearly compared to 1980–1999. In contrast, there have been **no changes in the annual formation rate of the Cold Core Rings.**



- Silver et al., Nature Scientific Report (2023)

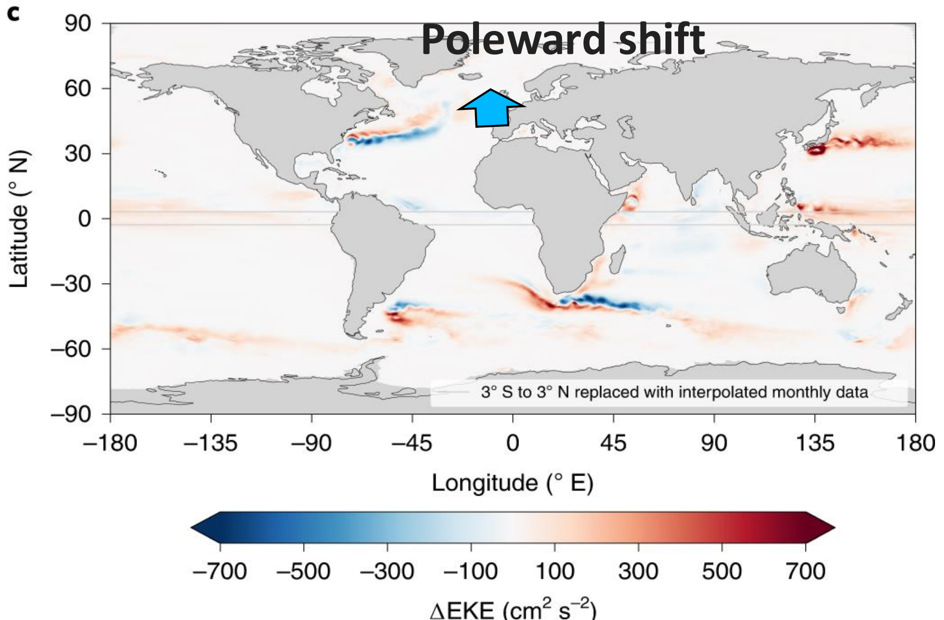
Increasing WCR formation contributes to an observed increase In salinity maximum intrusion in the NE shelf





- Beech et al., Nature Clim Change, (2022)

Eddy kinetic energy is projected to shift poleward in most eddy-rich regions, to intensify in the Kuroshio Current, Brazil and Malvinas currents and Antarctic Circumpolar Current **and to decrease in the Gulf Stream.**



Science Questions:

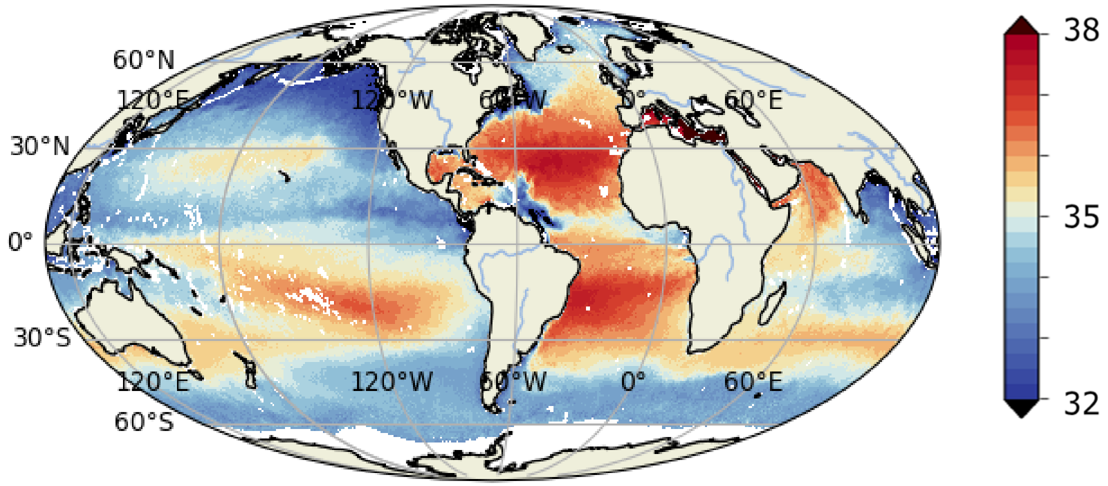
1) **How SMOS/Aquarius/SMAP data complement SST & SSH informations to better track meso-scale features of the Gulf Stream** ?

2) What is the **spatial distribution & temporal evolution of the thermo-haline surface-transport across the GS induced by anticyclonic (& cyclonic) eddies** ?

3) What is the **surface density signature of Gulf-stream rings and their temporal evolution as function of season & eddy aging** ?

4) What is **the respective contribution of SST & SSS to surface density in the core of GS Eddies and their evolution as function of seasons & eddy aging ?**

CCI Salinity



New version Released 2025

- **CCI V5.5: 2010 – 2023**
- **Weekly and monthly fields of SSS and their uncertainty**
- **Global (0.25° grid) and Polar (N and S EASE polar grid) products**
- **Daily 7-day average running window product**

Data available at CEDA : https://dx.doi.org/10.5285/f2ca631f29a24c47a7e98654ddf2c7d9
ESA News: https://climate.esa.int/en/news-events/new-sea-surface-salinity-record-released/

Boutin, J. et al. (2024). ESA Sea Surface Salinity Climate Change Initiative (Sea_Surface_Salinity_cci): Weekly and monthly sea surface salinity products, v04.41, for 2010 to 2022. NERC EDS Centre for Environmental Data Analysis. https://dx.doi.org/10.5285/f2ca631f29a24c47a7e98654ddf2c7d9

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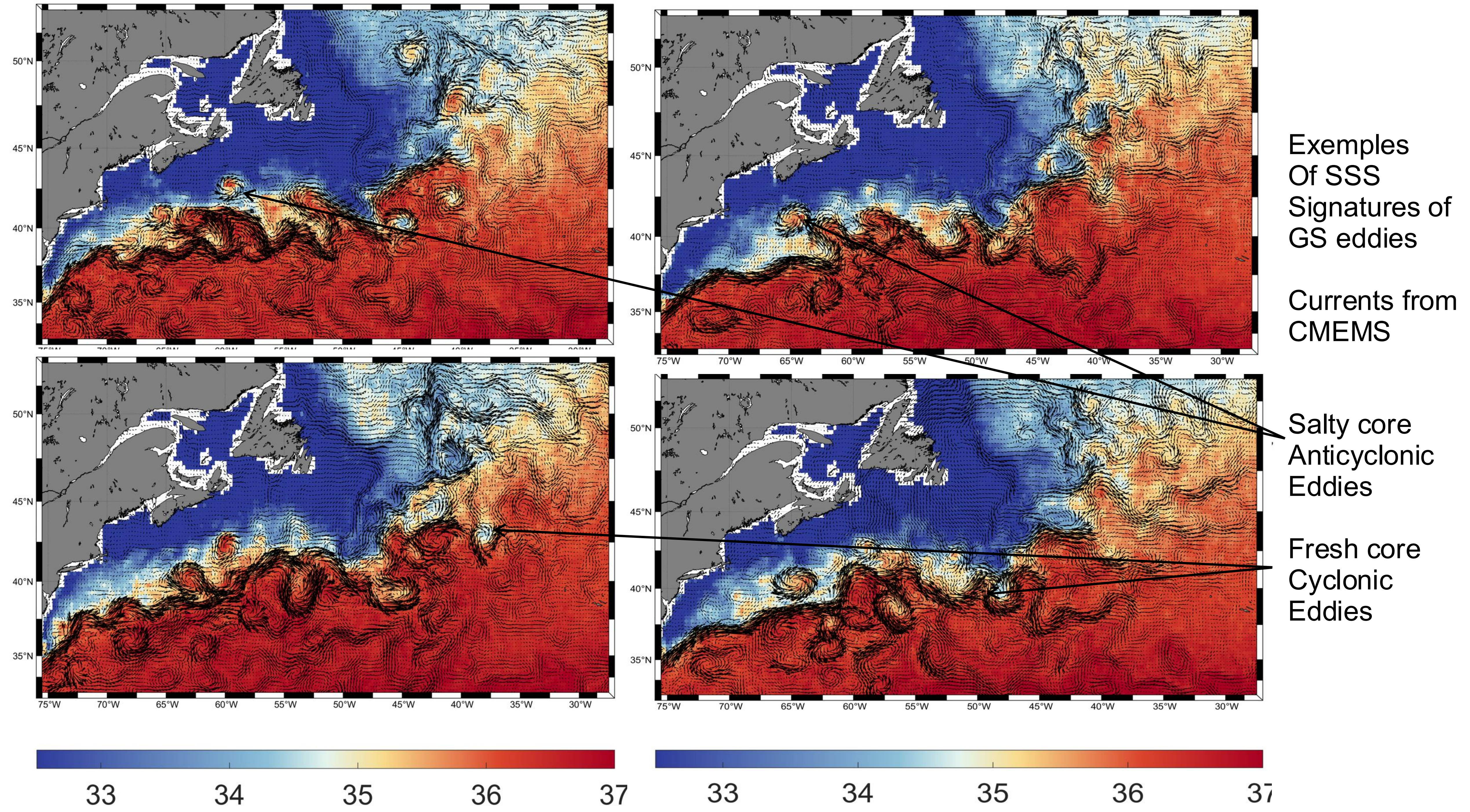
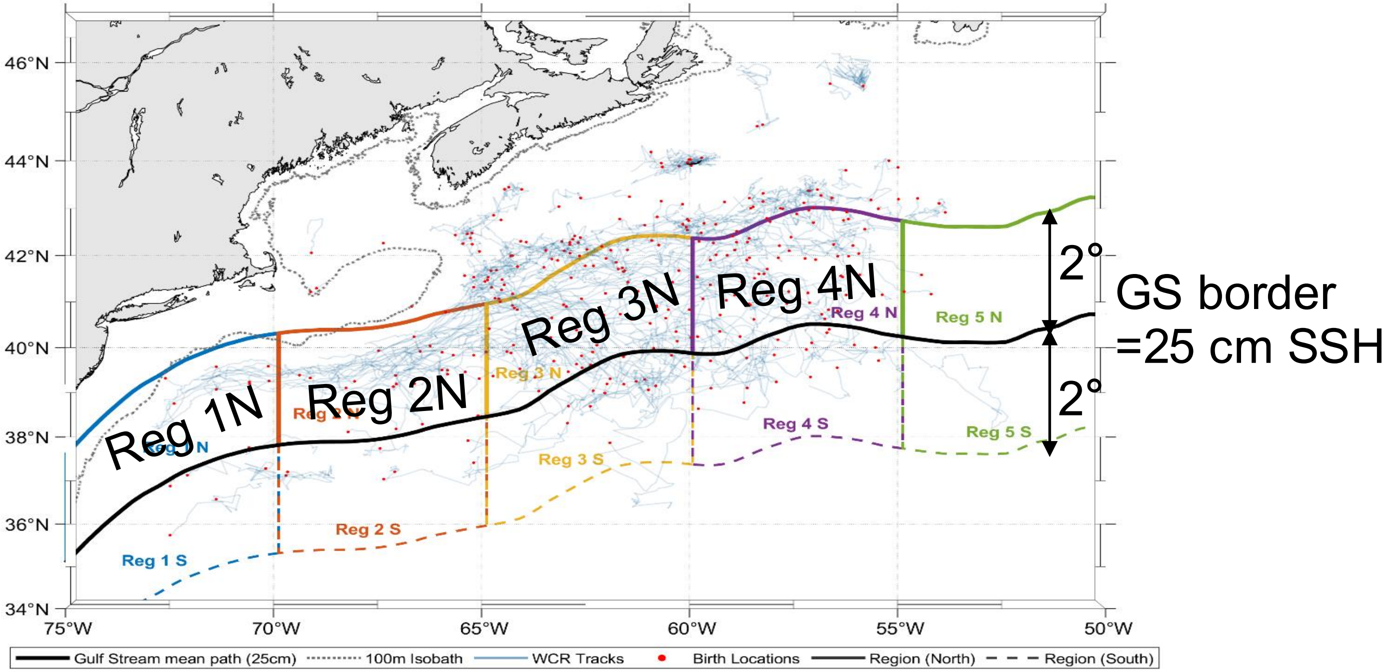

Exemples
Of SSS
Signatures of
GS eddies
Currents from
CMEMS
Salty core
Anticyclonic
Eddies
Fresh core
Cyclonic
Eddies
50°N
45°N
40°N
35°N
75°W
70°W
65°W
60°W
55°W
50°W
45°W
40°W
35°W
30°W
33
34
35
36
37

Eddy Composite approach

<u>Data collected over 2010-2022</u>

- **SSS daily ¼°x1/4° from ESA CCI v5.5**
- **SST daily OI MW/IR REMSS** 9 km resolution
- **Currents from CMEMS** (1/4° res, daily)
- **Eddy database from The Eddy Census (thermal) database (Porter et al., 2022;Silver et al., 2025)**



<u>Methods:</u>

For **Each sub-regions**

1) Treated **separatly Anti-cyclones & Cyclones** with center position & speed radius found at each location during eddy lifetime

2) **gathered SSS & SST data in 400 km x 400 km boxes centered on the eddy center at time t**

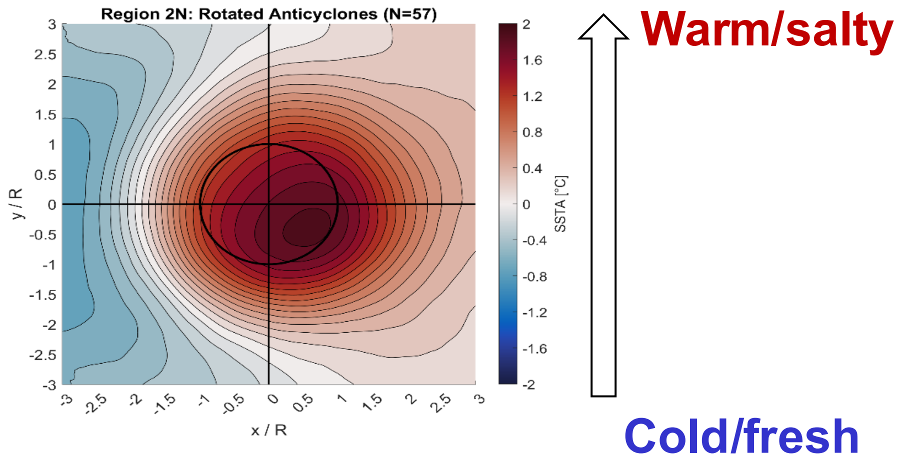
3) **Normalized the distance with respect the eddy radii Ls** (speed radius)

4) Evaluated **the SSS (& SST) anomalies by high pass filtering**
   - **in time the 120 days signals**
   - **in space the 6°X6° SSS (& SST) fields**

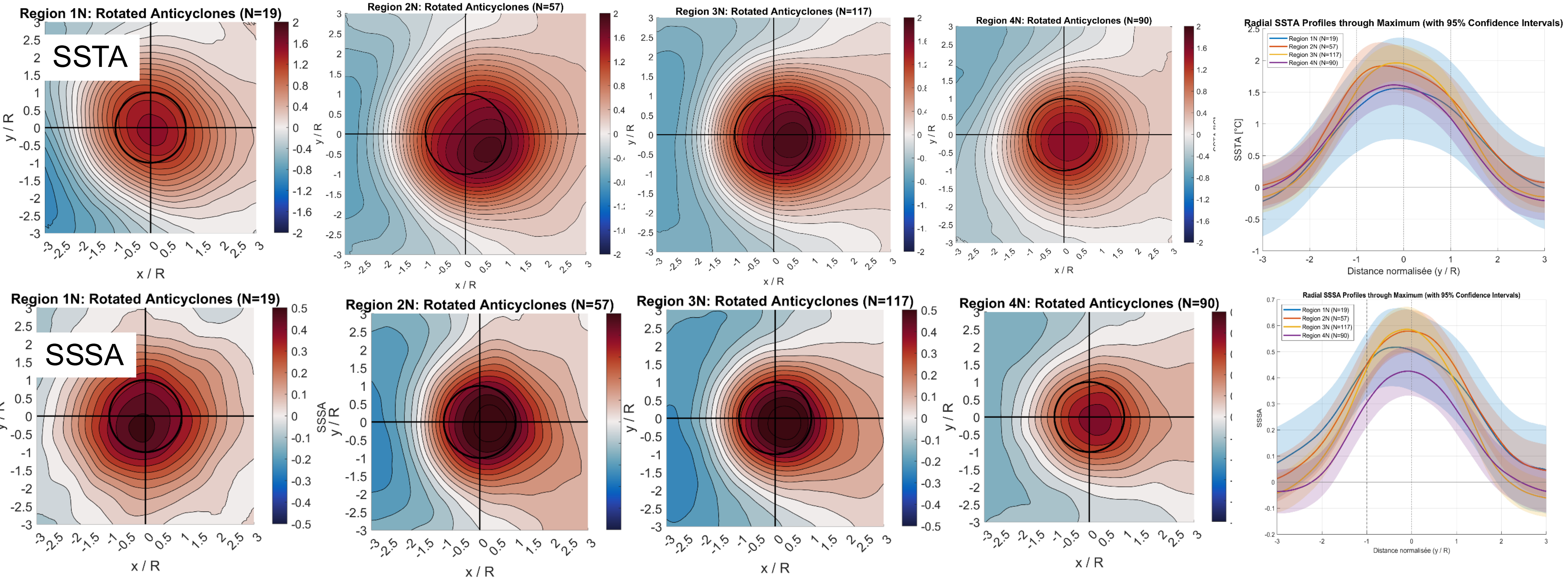
5) We **rotate the SSSA & SSTA with respect the the smooth thermal/haline background gradients**

6) **Build up SSSA & SSTA averaged composites for each region and each structure polarity** (cyclonic vs anti-cyclonic)

Rotation of the eddy SSTA/SSSA
With respect the background SST/SSS gradients

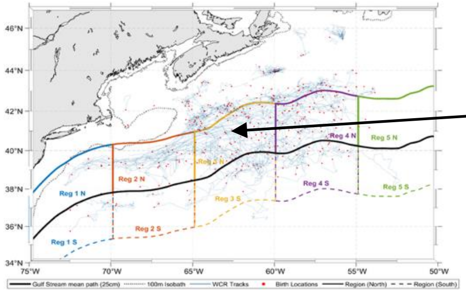


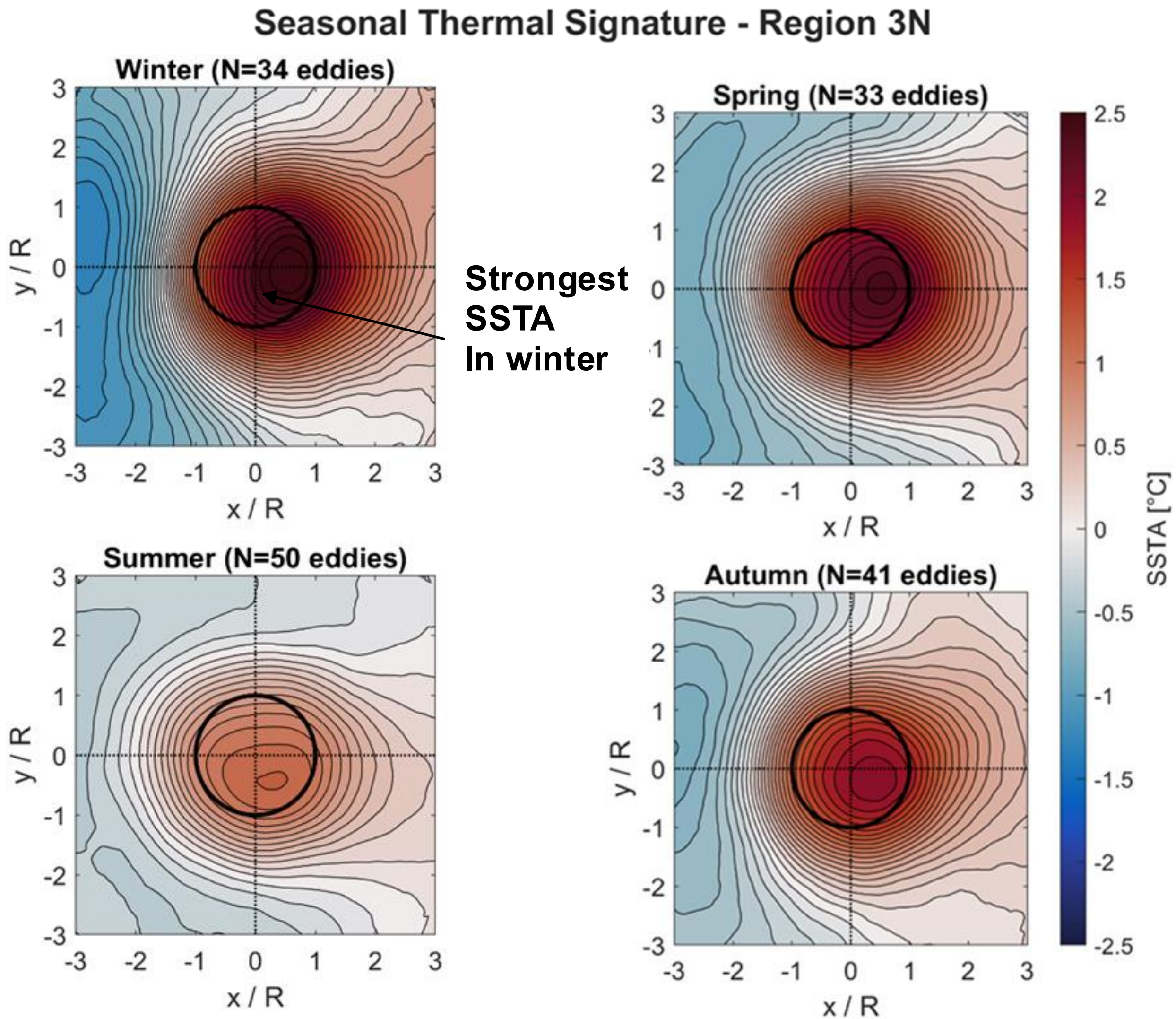
All period **SSTA & SSSA composites for Anti-Cyclonic Eddies Warm Core Rings** (WCR) **or Salty Core Ring**(SCR)

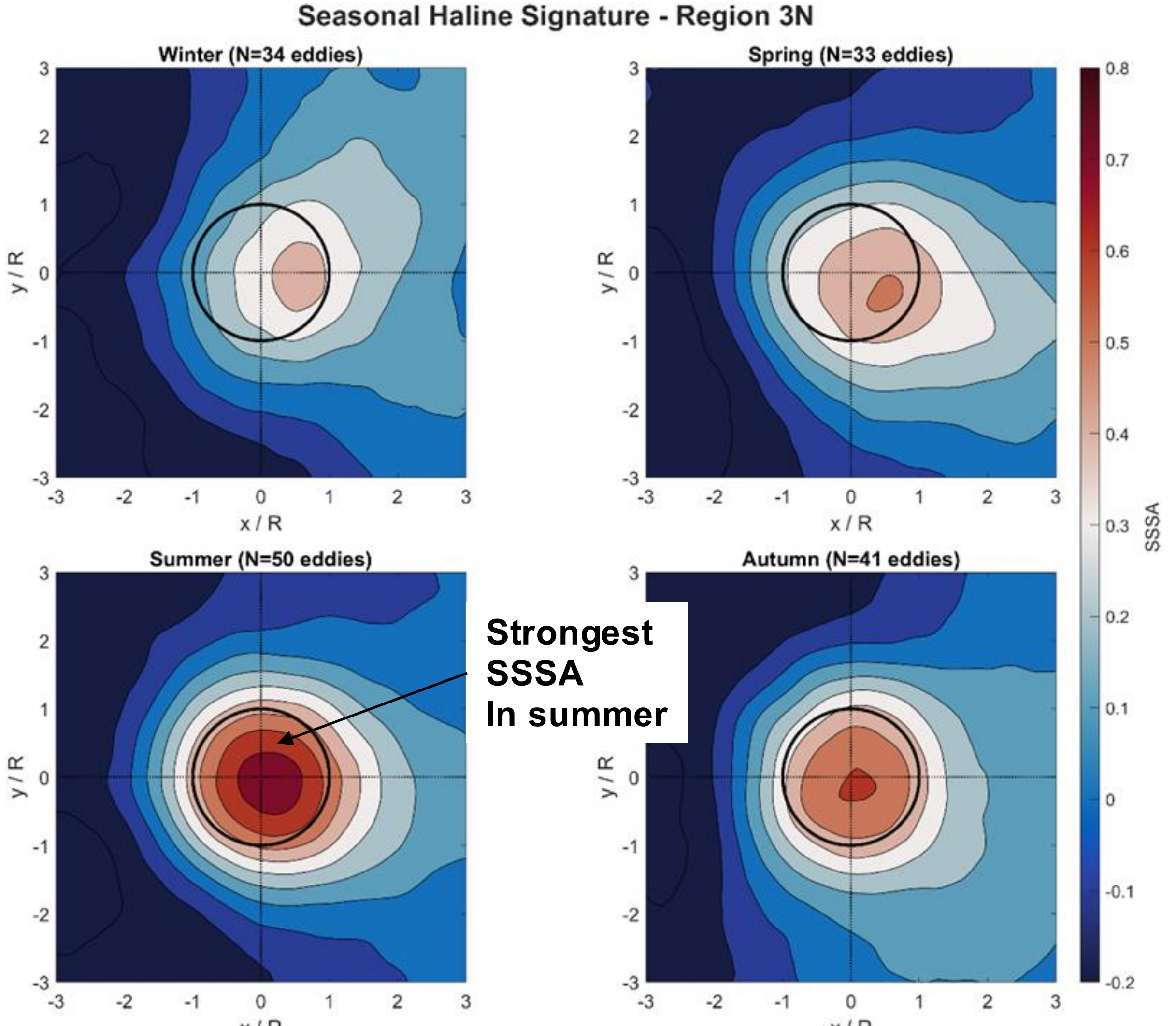


- Mostly monopole SSTA & SSSA structures with small N/S asymetries
- Strongest SSTA/SSSA found in the 2N & 3N regions in the coldest/freshest background (the slope sea)

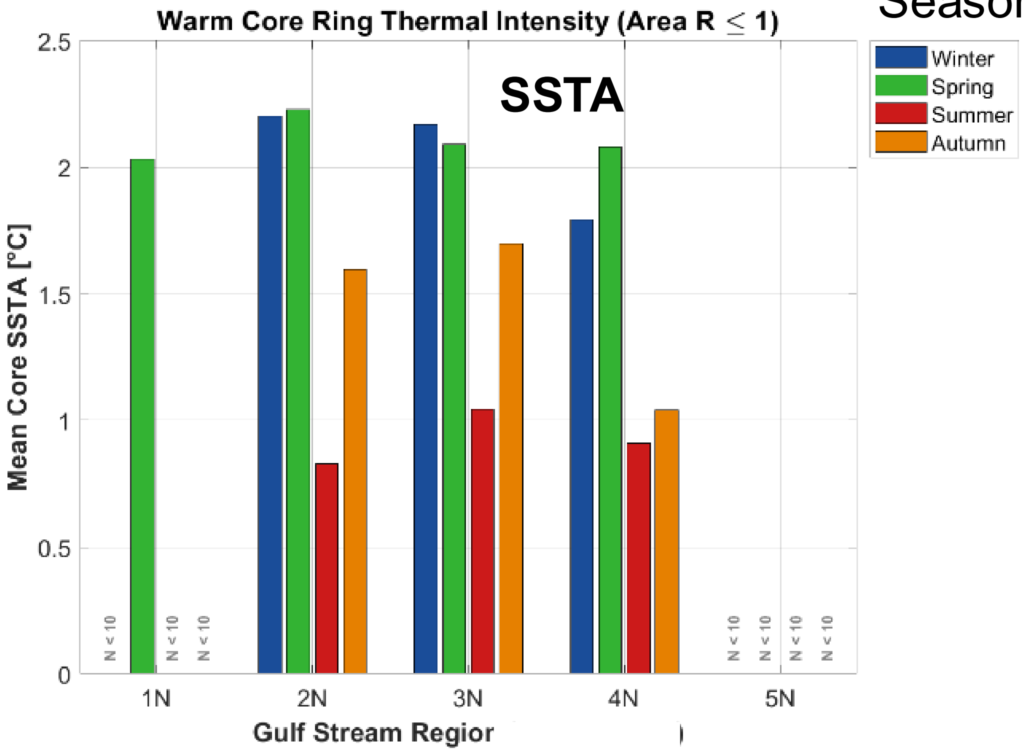
Seasonal Variations of surface thermo-haline averaged signatures In Anticyclonic eddies in: Region 3N

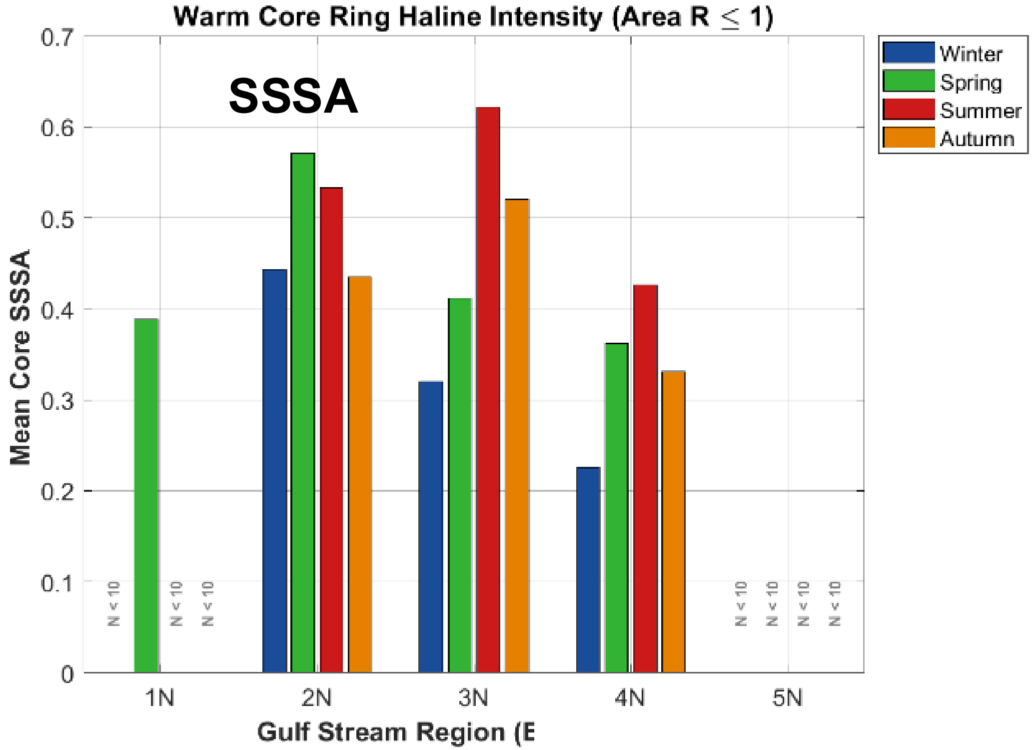






Seasonal Variations





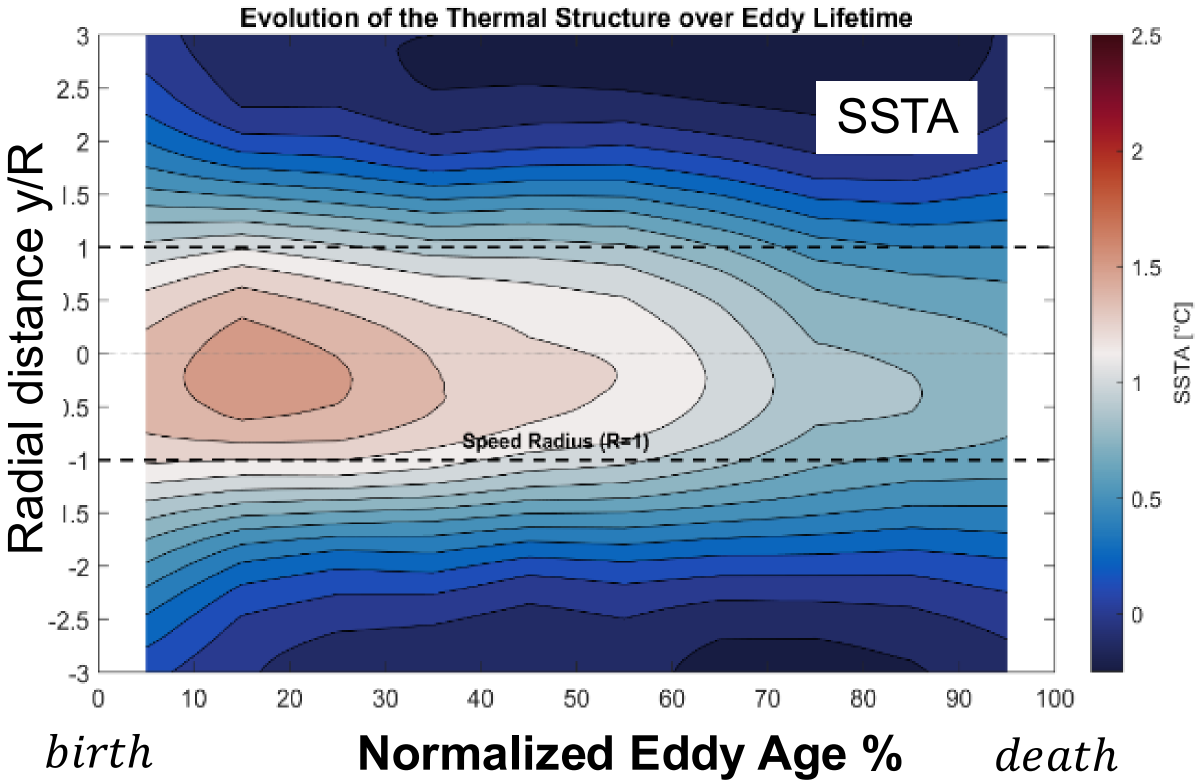
=> sharp contrast between how surface temperature (SSTA) and salinity (SSSA) behave as eddies propagate westward through the seasons:

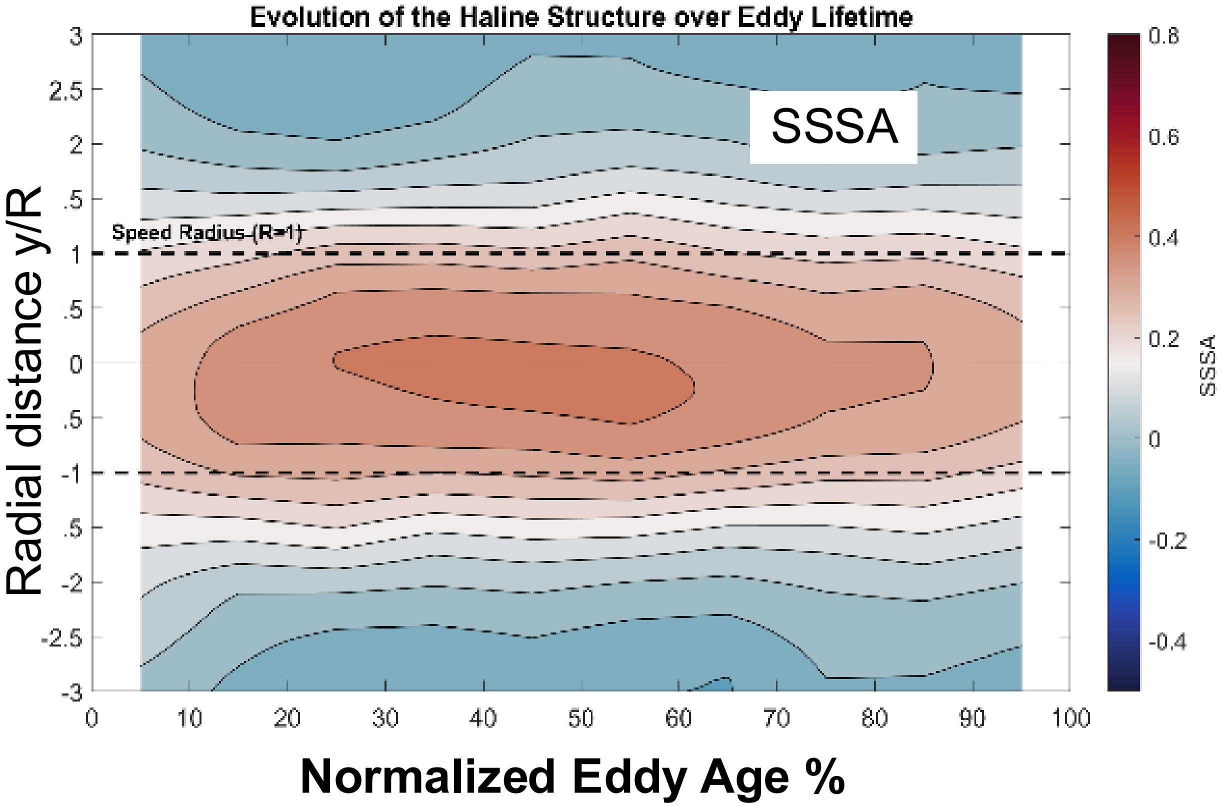
- ❑ **Thermal signature of WCRs is primarily driven by air-sea heat flux**, **leading to rapid decay and high seasonal sensitivity.**
  - ⇒ **Highest thermal intensity in Winter and Spring**, frequently exceeding **2°C**.
  - ⇒ **Summer** thermal signatures are the weakest, often dropping below **1°C** due to solar "masking" that reduces the temperature gradient between the eddy and the surrounding water.

- ❑ Unlike temperature, **haline intensity is often highest in Summer and Autumn**. This is **particularly evident in Region 3N, where Summer SSSA peaks above 0.6 PSU**. This occurs because coastal freshening in summer increases the contrast between the salty WCR core and the surrounding Slope Water.

Thermo-haline surface signature evolution in Anticyclonic eddy core as aging

For every snapshot of an eddy, we calculate $Age_{\{normalized\}} = \frac{T_{\{snapshot\}} - T_{\{birth\}}}{T_{\{death\}} - T_{\{birth\}}} \times 100$

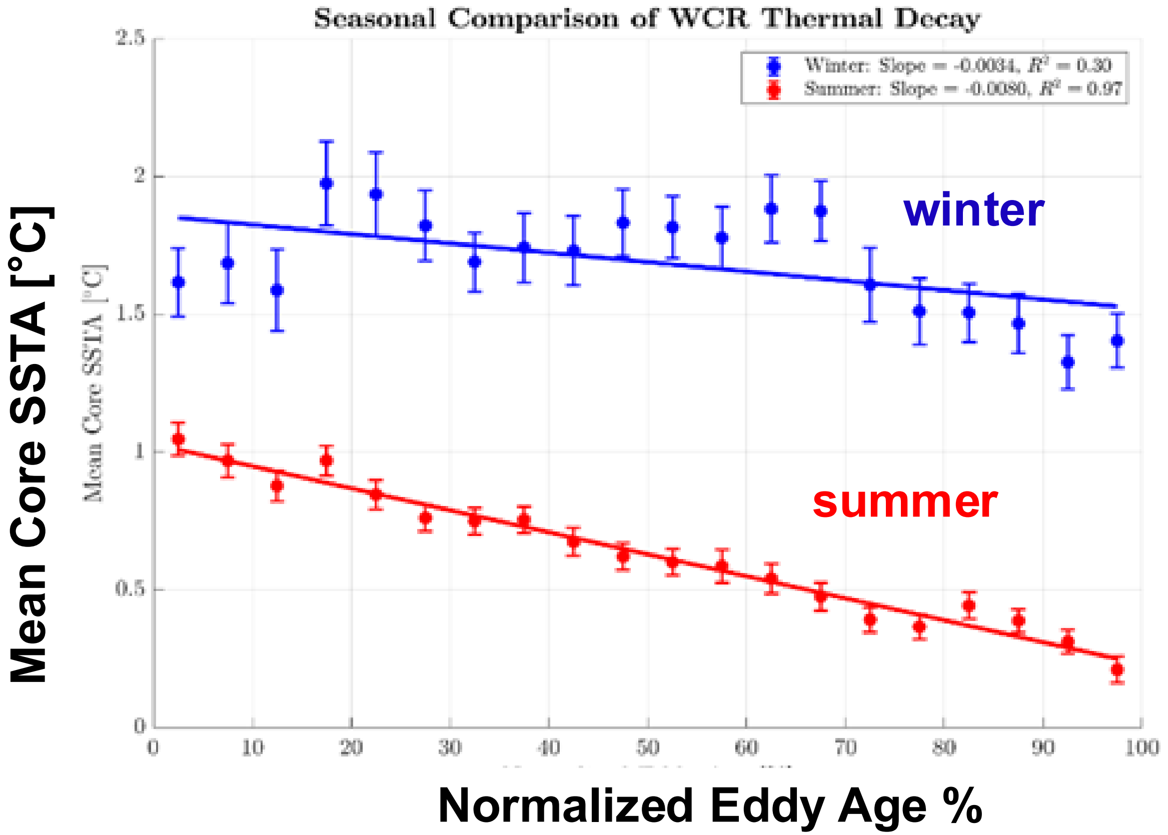


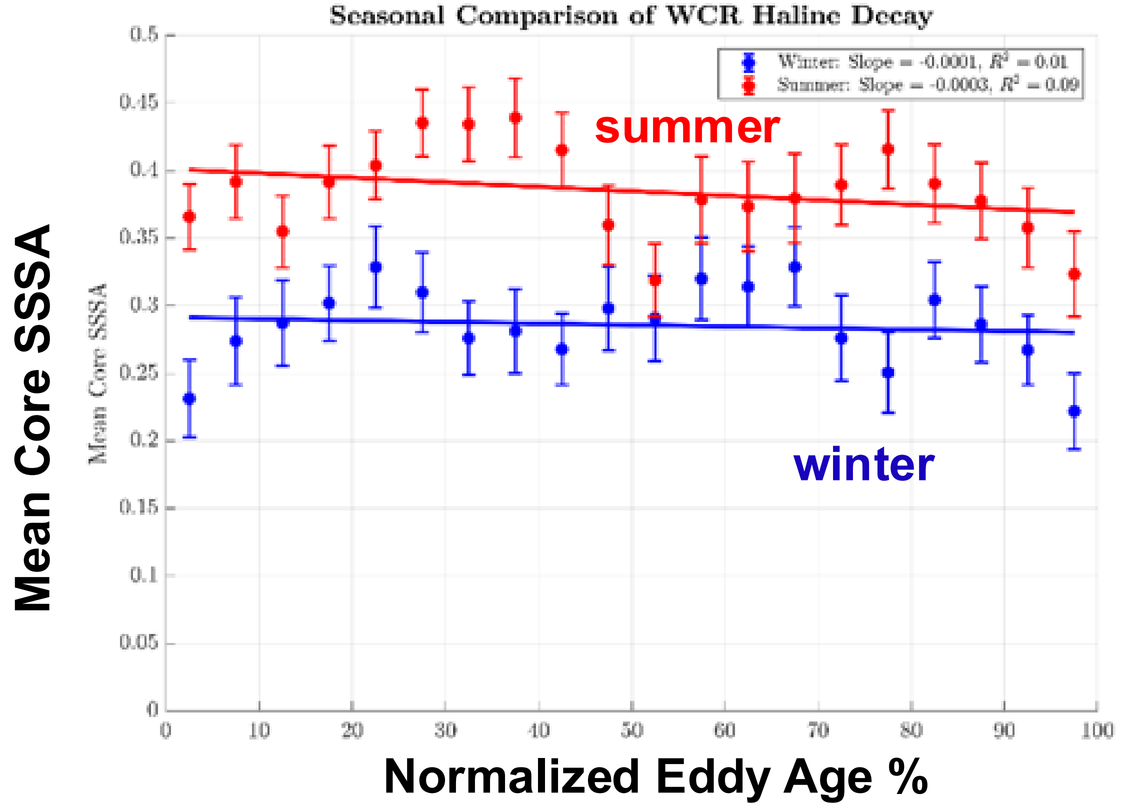


- ❑ **SSTA peak at ~10-20% lifetime.**The **rings are then subject to a near-constant cooling rate, likely driven by the persistent temperature contrast between the trapped Sargasso Sea water and the cooler Slope Water background**

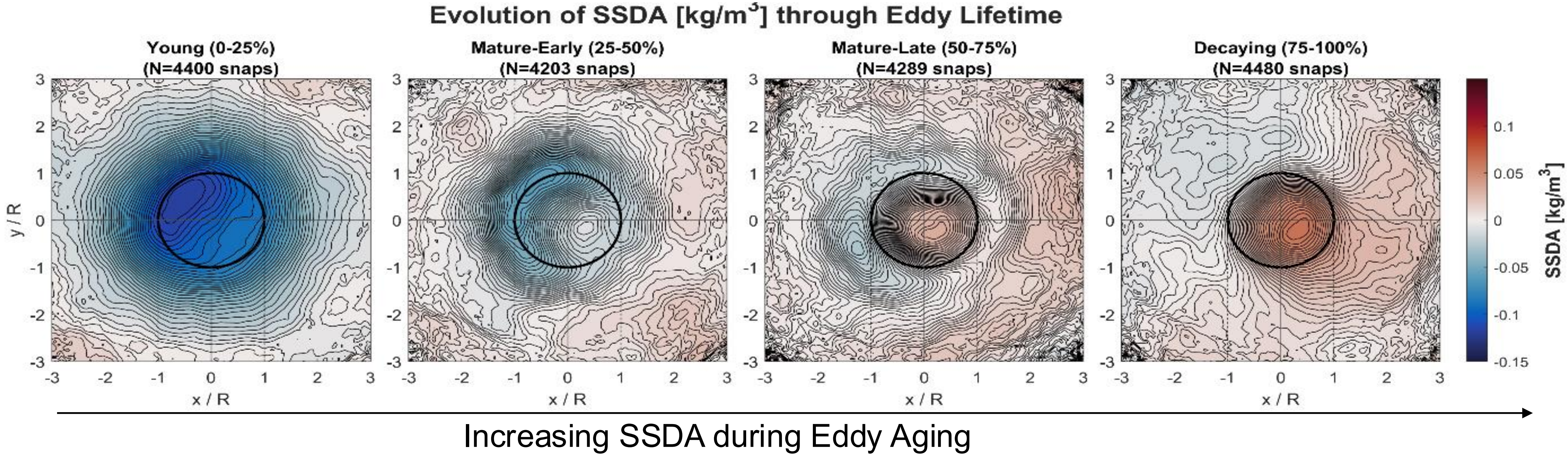
- ❑ **SSSA signatures are reaching a max from 30% to 60% lifetime but are much more stable with eddy aging than SSTA**

Anticyclonic Thermo-haline signature aging as a function of seasons





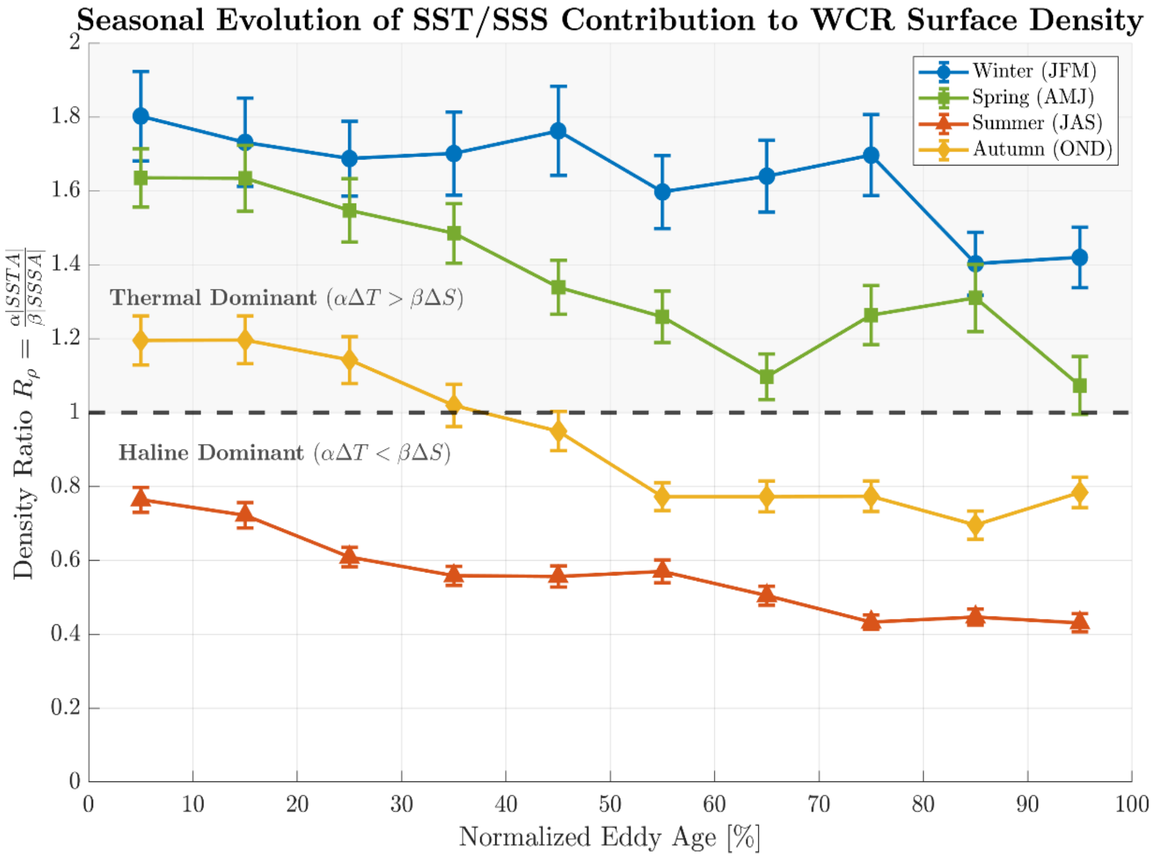
Feature	Surface Thermal Intensity (SSTA)	Surface Haline Intensity (SSSA)
Origin (Reg 5/4)	**Maximum Intensity. Strongest contrast as the ring pinches off from the Gulf Stream**.	High Salinity core signature from Sargasso Sea, **Stonger by ~0.1 in summer than winter**
Propagation (westward, Reg 3 & 2)	**Rapid Linear Decay in summer**. Heat is lost to the atmosphere continuously as the ring travels west.	**High Persistence in both seasons**. Salinity remains trapped within the core despite the long journey.
Final Stage (Reg 1)	**Minimum Intensity. Often "masked" or dissipated by the time it reaches the western boundary**.	**"Double Modulation" Fluctuations**. Salinity only drops when the structural integrity fails.



The **evolution of Sea Surface Density Anomaly (SSDA) provides a window into the ring's stability**:

- **The decreasing SSTA and rather stable SSSA is** leading to a **significant increase in core density as the ring ages**

Physical drivers of the AC eddy's buoyancy at the surface: the density ratio $R_\rho = \alpha\text{SSTA}/\ \beta\text{SSSA}$



- **Summer and Autumn:** these seasons are consistently **Haline Dominant** (R_ρ< 1) throughout their lives. This suggests that in the warmer months, the salinity "ballast" of the Gulf Stream water is the primary factor keeping the ring distinct from surrounding waters.
- **Winter and Spring:** These seasons remain **Thermal Dominant** (R_ρ >1) In literature, this is often attributed to the ring being significantly warmer than the very cold winter background water, making the temperature difference the most powerful buoyancy driver.
- **Transition Points:** Autumn crossing the threshold R_ρ=1 around **35-40% of its lifetime**, which is a high-precision observation of when a ring transitions its physical identity.

To quantify the physical drivers of the eddy's buoyancy, we use the **Density Ratio (R_ρ)**:

- If R_ρ >1 : The density anomaly is **Temperature-driven** (Thermal dominance).
- If R_ρ <1 The density anomaly is **Salinity-driven** (Haline dominance).

Summary

- **Merged Satellite SSS data** (SMOS, SMAP & Aquarius, CCI SSS) combined with Altimetry & SST **now allows to well monitor the statistical characteristics & evolution of the R~50 km meso-scale features** (Eddies) generated by the Gulf stream instabilities

- **Monopole positive SSTA & SSSA found in meso-scale Anticyclonic structure centers**
- Anticyclonic salty eddies **show maximum anomalies westward in region 3.**
- We found a **sharp contrast between how SSTA and SSSA behave as eddies propagate westward through the seasons**:
  - $\Rightarrow$ **Highest thermal intensity in Winter and Spring, frequently exceeding 2°C**.
  - $\Rightarrow$ Summer thermal signatures are the weakest, often dropping below 1°C due to solar "masking" that reduces the
    temperature gradient between the eddy and the surrounding water.
  - $\Rightarrow$ **Unlike temperature, haline intensity is often highest in Summer and Autumn.**
    This is particularly evident in Region 3N, where Summer SSSA peaks above 0.6 PSU.
- We **characterized the thermo-haline surface signature evolution in Anticyclonic eddy core as they are aging**: **SSTA peak at ~10-20% lifetime.The rings are then subject to a near-constant cooling rate**, likely driven by the persistent temperature contrast between the trapped Sargasso Sea water and the cooler Slope Water background in summer. **SSSA signatures** are reaching a max from 30% to 60% lifetime but **are much more stable with eddy aging than SSTA**

- The evolution of Sea Surface Density Anomaly (SSDA) provides a window into the ring's stability:

• **In Winter , SSTA dominates the density budget and evolution of the increasing SSDA**

• **In summer, the density anomaly remains more stable but is dominated by SSS changes :** the salinity "ballast" of the Gulf Stream water is the primary factor keeping the ring distinct from surrounding waters.
local buoyancy.