




## Eddy Tracking From In Situ and Satellite Observations

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### Key Points:

- Ship-based, autonomous, and remote sensing observations were combined to identify, characterize, and track a coherent anticyclonic eddy
- Estimates of the eddy center and spatial extent derived from altimetry and in situ observations had similar accuracy
- Constant or smoothly varying sea level anomaly thresholds better represent eddy spatial extent than other satellite-based methods

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### Citation:

Erickson, Z. K., Fields, E., Johnson, L., Thompson, A. F., Dove, L. A., D'Asaro, E., & Siegel, D. A. (2023). Eddy tracking from in situ and satellite observations. *Journal of Geophysical Research: Oceans*, 128, e2023JC019701. <https://doi.org/10.1029/2023JC019701>

Received 24 FEB 2023  
Accepted 7 AUG 2023

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**Abstract** Mesoscale eddies are a dominant source of spatial variability in the surface ocean and play a major role in the biological marine carbon cycle. Satellite altimetry is often used to locate and track eddies, but this approach is rarely validated against in situ observations. Here we compare measurements of a small (under 25 km radius) mode water anticyclonic eddy over the Porcupine Abyssal Plain in the northeastern Atlantic Ocean using CTD and Acoustic Doppler Current Profiler (ADCP) measurements from three ships, two gliders, two profiling floats, and one Lagrangian float with those derived from sea level anomaly (SLA). In situ estimates of the eddy center were estimated from maps of the thickness of its central isopycnal layer, from ADCP velocities at a reference depth, and from the trajectory of the Lagrangian float. These were compared to three methods using altimetric SLA: one based on maximizing geostrophic rotation, one based on a constant SLA contour, and one which maximizes geostrophic velocity speed along the eddy boundary. All algorithms were used to select CTD profiles that were within the eddy. The in-situ metrics agreed to 97%. The altimetry metrics showed only a small loss of accuracy, giving >90% agreement with the in situ results. This suggests that current satellite altimetry is adequate for understanding the spatial representation of even relatively small mesoscale eddies.

**Plain Language Summary** Rotating water masses called eddies are ubiquitous features in the ocean and are important because they can transport nutrients and heat and are often associated with enhanced biological activity. Eddies are accompanied by sea level anomalies (SLA), in the same way that atmospheric weather systems are associated with high or low pressure systems, and can therefore be observed and monitored by satellite altimeters. However, observations of SLA from satellite are relatively coarse compared with the spatial scales of eddies, and satellite-based algorithms are rarely rigorously tested against “ground truth” observations. We use data from a dense network of observations in the vicinity of a relatively small eddy in the northeastern Atlantic Ocean to track this eddy for several weeks from direct ocean measurements and satellite algorithms. We find widespread agreement between the in situ metrics and the satellite altimetry results, suggesting that satellite-based eddy tracking is sufficient to track even eddies that are relatively small compared with the resolution of SLA products.

## 1. Introduction

Upper ocean circulation is dominated by mesoscale eddies, coherent structures with scales of 10–200 km that have the ability to trap and retain water masses at their cores (Abernathey & Haller, 2018; Chelton et al., 2007, 2011; Goni & Johns, 2001; Richardson, 1993). Primary productivity and biogeochemical cycling in the upper ocean is impacted by these eddies primarily through injection of nutrients into the euphotic zone due to uplift of interior isopycnals (Falkowski et al., 1991; Martin & Pondaven, 2003; Siegel et al., 1999), enhanced vertical velocities caused by along-isopycnal motion through sloping isopycnals (Freilich & Mahadevan, 2019), and submesoscale instabilities, which can also lead to enhanced carbon export through small-scale subduction (Archer et al., 2020; Brannigan, 2016; Brannigan et al., 2017; Jing et al., 2021; Whitt et al., 2019). The “trapping” properties of mesoscale eddies make them natural laboratories to study the growth, evolution, demise, and export of carbon from phytoplankton blooms (e.g., Ellwood et al., 2020; Heywood & Priddle, 1987).

Studies that consider the evolution of a phytoplankton bloom in an Eulerian reference frame must deconvolve variability associated with horizontal advection from biological changes, which can make interpretation challenging (Bol et al., 2018; Dickey et al., 1991; Erickson & Thompson, 2018; Estapa et al., 2019). This is especially important for time series at fixed locations such as moorings that convolve spatial and temporal variability. Even

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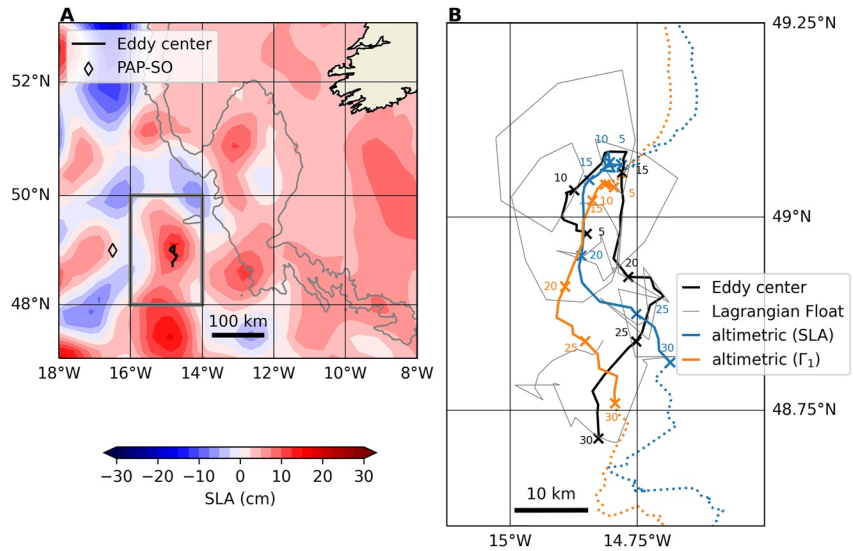
studies that are intended to be Lagrangian can run into difficulties when assets are initially placed in an area with high variability. For example, a significant part of the North Atlantic Bloom experiment in 2008 was challenging to interpret because of the advection of the reference frame through an eddy (Alkire et al., 2012), and the spreading of drifting instruments leads to difficulty in constraining water mass budgets. When the goal is to study the evolution of a phytoplankton bloom within a Lagrangian water mass, a good option is to site the measurements within a retentive feature such as a mesoscale eddy.

Mesoscale eddies (hereafter, “eddies”) in the ocean are associated with a sea level anomaly (SLA) and can therefore be studied using satellite altimetry (Chelton et al., 2007, 2011). Algorithms to track these eddies typically involve detecting and following contours of SLA (Chelton et al., 2011), geostrophic velocities calculated from first derivatives of SLA (Mason et al., 2014), or strain, shear, and vorticity terms calculated from higher-order SLA derivatives (Isern-Fontanet et al., 2003). These algorithms allow eddies to be tracked over their entire lifetime, and their temporally changing properties, such as size and eccentricity, to be studied. However, few satellite-based eddy tracking studies also include hydrographic information. Isern-Fontanet et al. (2004) found that altimetry-based metrics of the size of eddies in the Algerian Basin agreed well with the size of the same eddies using data from hydrographic transects, but that the boundaries of the eddies were difficult to accurately determine from satellite observations. Chaigneau and Pizarro (2005) similarly found good agreement between sea level height from satellite and derived from opportunistic in situ hydrographic measurements from a WOCE (World Ocean Circulation Experiment) cruise; however, the coarse station spacing of the cruise, of about 56 km, limited the ability of this study to precisely locate the eddy boundary from either method. Pascual et al. (2006) found good agreement between the path of a surface drifter in a cyclonic eddy in the Gulf Stream and velocity vectors derived from altimetry data using four satellite altimeters, although when products derived from only two altimeters were used the agreement was considerably worse between drifter trajectory and velocity vectors.

The EXPORTS (EXport Processes in the Ocean from Remote Sensing) program was conducted in the North Atlantic (EXPORTS-NA) near the Porcupine Abyssal Plain (PAP) Sustained Observatory (Hartman et al., 2012) in May of 2021 (Figure 1a; Johnson et al., 2023). The goal of EXPORTS-NA was to survey biological properties during the demise of the North Atlantic spring bloom and to assess the major export flux pathways connecting the upper layers with the ocean interior (Siegel et al., 2016). The PAP region has high horizontal variability, with significant variation in water properties on small (<10 km) spatial scales (Damerell et al., 2016; Erickson et al., 2020; Johnson et al., 2023). Tracking of sinking particulates in a model suggests that particles at 3,000 m depth are sourced from up to 140 km away, with high interannual variability driven by changing currents and mesoscale variability (Frigstad et al., 2015). The scientific need to conduct field sampling in a Lagrangian reference frame, as well as the reality of managing and maximizing the science returns of over 40 drifting assets used as part of the EXPORTS-NA deployment, required locating the experiment in a retentive feature, such as an eddy (e.g., d’Ovidio et al., 2013; Della Penna & Gaube, 2019).

In the lead-up to EXPORTS-NA, a system of satellite and glider-based analyses was used to locate a retentive eddy in which to conduct the experiment (Erickson et al., 2022). A series of modeled particle release experiments, using satellite-derived geostrophic velocities, were conducted to test the retentiveness of eddies. Particle trajectories starting within eddies were tracked both forwards and backwards in time to determine the retentiveness of the eddy, defined as the average longevity of the particles within each eddy. This method, along with other characteristics such as size and shape, was used to determine four target eddies within the PAP region, which were then sampled by three gliders deployed in April 2021, one month before EXPORTS-NA. The eddy that was chosen was a relatively small and circular anticyclonic mode water eddy, with a radius of approximately 25 km and maximum edge velocities of about 20 cm s<sup>-1</sup> (Erickson et al., 2022).

The SLA associated with this eddy was smaller in magnitude than other nearby eddies (Figure 1a). Mode water eddies are characterized by a sub-surface region of low stratification (the “mode water”), resulting in a depression of isopycnals beneath the weakly stratified region and a shoaling of isopycnals above (McGillicuddy Jr., 2015). Geostrophic velocities at depth are anticyclonic and are primarily set by the slope of the deep isopycnals, typically representing the permanent pycnocline. Above the mode water layer, the doming of lighter isopycnals, typically representing the seasonal pycnocline, leads to a cyclonic shear in the geostrophic velocities that reduces the magnitude of the horizontal velocity associated with the eddy, suggesting that the sub-surface core of a mode water eddy is stronger than that of its near-surface waters. A consequence of the doming of these lighter isopycnals is that the SLA associated with a mode water eddy is reduced in comparison to non-mode water anticyclonic eddies of comparable strength.



**Figure 1.** (a) Sea level anomaly (SLA) in the North Atlantic at the start of the campaign, on 5 May 2021. Gray contours show the 1 and 3 km isobaths, the southwest coast of Ireland is shown in the upper right of the plot, and the gray box (16–14°W and 48–50°N) is the area shown in Figures 7 and 8 below. The trajectory of the eddy using in situ measurements (see text) is shown in black and is also in (b), where the blue and orange lines give the trajectory of the eddy using satellite methods and the light gray line is the path of the Lagrangian float. Numbers in (b) indicate the day in May (5–30 shown) and correspond with the ‘x’s every five days. Dotted colored lines in (b) extend the eddy center time series backwards (to the north) and forwards (to the south) in time beyond the campaign. PAP-SO = Porcupine Abyssal Plain-Sustained Observatory.

Field observations of biological processes over time benefit from the knowledge of which measurements are associated with waters retained within the core of the eddy, as opposed to those in an environment exposed to injection of other water masses and, potentially, outside fluxes of nutrients or biomass (Johnson et al., 2023). This paper introduces different metrics for in situ data to estimate whether a given measurement is taken from within or outside of the physically retentive core of the eddy. These metrics included distance from the eddy center and physical quantities derived from temperature and salinity. Satellite-based metrics using SLA and geostrophic velocities are also used to diagnose how well remote sensing products can predict whether a platform is inside or outside an eddy. While centered on one particular anticyclonic eddy in the North Atlantic, these methods can be applied to future field campaigns that are also targeting measurements following a Lagrangian trajectory.

## 2. Data

Three vessels collected observations within and around the target eddy during EXPORTS-NA (Table 1). The *RSS James Cook* tracked the evolution of eddy core water properties and fluxes, and remained primarily within the eddy. The *RSS Discovery* surveyed both within and outside the eddy to provide spatiotemporal context. The *R/V Sarmiento de Gamboa* was part of a different project measuring carbon flows and ecological distributions from the surface into the twilight zone but coordinated profiles with the EXPORTS-NA assets. Autonomous platforms were also deployed before and during EXPORTS-NA, including three gliders (SL305, SG219, and SG237) that scouted the region to find a suitable eddy in April of 2021 (Erickson et al., 2022), a Lagrangian float (D’Asaro, 2003) that was deployed near the center of the eddy at the beginning of the field deployment, two Biogeochemical (BGC) floats (Claustre et al., 2020) initially deployed outside of (1902303) and within (1902304) the eddy, and over 40 drifting platforms, primarily surface drifters, that are not considered here.

Temperature and salinity data from each of these platforms were inter-calibrated against nearby profiles from the *RSS Discovery*, revealing

**Table 1**  
Platform Profiles

Platform	# Profiles	# Deep	# Within eddy	# Outside eddy
<i>RSS James Cook</i>	67	27	27	0
<i>RSS Discovery</i>	109	18	12	6
<i>R/V Sarmiento de Gamboa</i>	10	8	7	1
SL 305	285	259	112	147
SG 219	311	291	287	4
BGC 1902303	15	15	0	15
BGC 1902304	26	26	26	0
All	823	644	471	173

*Note.* Number of profiles are those that are located within the dashed box shown in Figure 1a and were made during the main part of the deployment (5–30 May 2021). Deep profiles are those that extend to a potential density of at least 27.2 kg m<sup>-3</sup>. SL = Slocum. SG = Seaglider. BGC = Biogeochemical float.

temperature offset adjustments of 0.001–0.01°C and salinity adjustments of 0.001–0.01 PSU. No time or pressure dependence was noted in any of the comparisons. The conductivity sensor on SG237 developed uncorrectable issues early in its deployment and is not used here. For the remainder of this paper, temperature and practical salinity from these platforms have been converted (Wright et al., 2011) into conservative temperature ( $\Theta$ , °C) and absolute salinity ( $S_A$ , g kg<sup>-1</sup>). These profiles are smoothed using a Gaussian window with a 5 m standard deviation and then used to calculate potential density ( $\sigma_\theta$ ) and spice, the variation in  $\Theta$  and  $S_A$  that does not contribute to variation in  $\sigma_\theta$  (McDougall & Krzysik, 2015). Both potential density and spice are referenced to 0 db.

A subset of available profiles was used, including only profiles taken during the main part of the EXPORTS-NA deployment (5–30 May) near the eddy (within 14–16°W and 48–50°N, see gray box in Figure 1a) that profiled to densities of at least 27.2 kg m<sup>-3</sup>, or approximately 600 m. This sub-selection of data was necessary to allow all eddy metrics, defined below, to be utilized, and to not include data from profiles within other nearby eddies. From an initial 823 profiles (not including SG237 or profiling instruments such as the Lagrangian float that never reached the 27.2 kg m<sup>-3</sup> isopycnal) this sub-selection process resulted in 644 “deep” profiles (Table 1).

Horizontal velocities were also used (Section 3.1) to define and track the eddy. Each ship was equipped with a narrow beam ADCP (Acoustic Doppler Current Profiler) measuring current velocities using acoustic signals at 75 and 150 kHz. ADCP-derived velocities were processed using the University of Hawaii Data Acquisition System (UHDAS) to a gridded data product at 5 min resolution, with valid data down to about 400 m at 75 kHz and 150 m at 150 kHz. Only small differences were observed between the 75 and 150 kHz instruments, and the 150 kHz is used here. ADCP-derived horizontal velocities can be unreliable near the surface because of noise from bubbles injected under the ship’s hull (Firing & Hummon, 2010) and at depth because of insufficient signal strength. 130 m was found to be a convenient trade-off between these two effects (not shown). ADCP data were only used while the ship was in motion, using a threshold speed of 0.5 m s<sup>-1</sup>, or roughly 1 knot.

Finally, satellite altimeters provided SLA data, which are optimally interpolated onto a daily, 1/4° gridded product using spatial scales of 100–200 km and temporal scales of 10–45 days (Pujol et al., 2016). Ballarotta et al. (2019) estimate that this data product captures wavelength scales down to 150–200 km in the study region, equivalent to an effective spatial resolution of about 30–40 km (Chelton et al., 2011). For comparison with a common eddy detection algorithm described below, a filtered SLA product was also calculated,  $SLA_{\text{filt}}$ , to remove larger-scale variability in the data. This filtered product is constructed by removing the large-scale SLA signature, estimated by filtering the SLA through a two-dimensional first-order Lancos filter with a half maximum of 700 km.

### 3. Eddy Detection Methods

Eddies are typically defined as rotating volumes of water that are distinct from their surrounding environments. Horizontal velocities around the eddy are associated with horizontal gradients of SLA. Each of these properties—rotational velocities, SLA, horizontal interior density gradients, and a distinct water mass—can be used as a metric to understand the location, spatial extent, and strength of an eddy.

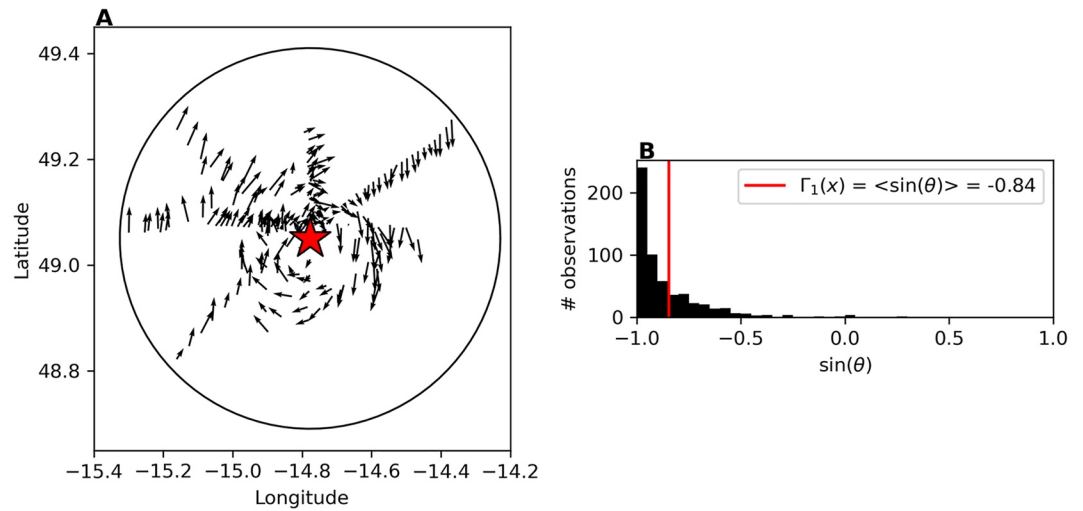
#### 3.1. Rotational Metrics

Horizontal velocities surrounding an eddy center will be predominantly tangential to the eddy center, rather than in a radial direction. Graftieaux et al. (2001) describe a method for determining the location of an eddy center from horizontal velocity measurements by calculating the local rotational metric  $\Gamma_1(\mathbf{x})$ , where  $\mathbf{x} = (x, y)$  is a geographical location surrounded by horizontal velocity measurements  $\mathbf{u}(\mathbf{x}_i)$  (where  $\mathbf{u} = (u, v)$ ) at locations  $\mathbf{x}_i$  within a given radius of  $\mathbf{x}$ , here chosen as 40 km. Here two-dimensional (horizontal) vectors are denoted in bold-face text.  $\Gamma_1(\mathbf{x})$  is calculated as

$$\Gamma_1(\mathbf{x}) = \langle \sin \theta \rangle, \quad (1a)$$

$$\sin \theta = \frac{\mathbf{r} \wedge \mathbf{u}}{|\mathbf{r}| \cdot |\mathbf{u}|} = \frac{v \cdot \delta x - u \cdot \delta y}{(u^2 + v^2)^{1/2} (\delta x^2 + \delta y^2)^{1/2}}, \quad (1b)$$

where  $\langle \cdot \rangle$  represents a spatial average and  $\theta$  are angles between  $\mathbf{u}(\mathbf{x}_i)$  and the positional vector  $\mathbf{r} = (\mathbf{x}_i - \mathbf{x})$ .  $\Gamma_1(\mathbf{x})$  is unitless and varies between  $-1$ , denoting measurements that are purely tangential in an anticyclonic direction, and  $1$ , representing tangential flow in a cyclonic direction. Fronts, by contrast, would result in a roughly



**Figure 2.** (a) Example of calculating  $\Gamma_1(x)$  from in situ Acoustic Doppler Current Profiler (ADCP) velocity measurements (see Equation 1a) within 40 km (circle) of the calculated center position ( $x$ , red star). (b) Histogram of  $\sin(\theta)$  about the center, with a red vertical line showing the average value,  $\Gamma_1(x)$ .

uniform distribution of  $\theta$  and therefore a  $\Gamma_1(x)$  near 0. An eddy center is therefore determined as the location with maximum  $|\Gamma_1(x)|$ ; that is, the area where the horizontal velocity measurements within a 40 km radius are most uniformly tangential/rotational.

Advection of an eddy can substantially reduce the magnitude of  $\Gamma_1(x)$  within an eddy when the advection speed becomes comparable to the eddy's rotational speed. The local rotational metric  $\Gamma_2(x)$ , calculated similarly to  $\Gamma_1(x)$  but with the mean horizontal velocities  $\mathbf{u}_m = \langle \mathbf{u} \rangle$  subtracted, corrects for the influence of eddy advection:

$$\Gamma_2(x) = \langle \sin\theta_m \rangle, \quad (2a)$$

$$\sin\theta_m = \frac{\mathbf{r} \wedge (\mathbf{u} - \mathbf{u}_m)}{|\mathbf{r}| \cdot |\mathbf{u} - \mathbf{u}_m|} = \frac{(v - v_m) \cdot \delta x - (u - u_m) \cdot \delta y}{((u - u_m)^2 + (v - v_m)^2)^{1/2} (\delta x^2 + \delta y^2)^{1/2}}. \quad (2b)$$

Graffieux et al. (2001) show that waters with  $|\Gamma_2(x)| > 2/\pi$  are influenced primarily by rotation and can therefore be considered within the confines of an eddy. This suggests  $|\Gamma_2(x)| = 2/\pi \approx 0.64$  as an appropriate threshold for the boundary of an eddy.

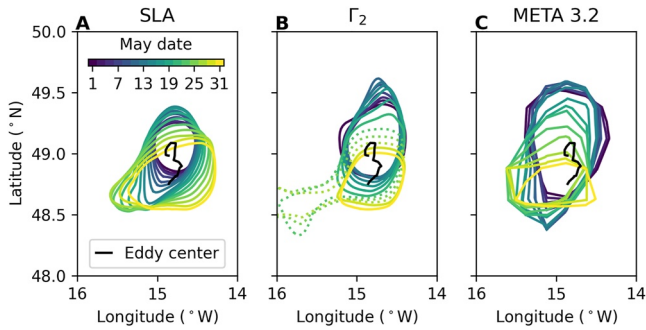
Horizontal velocities derived from ADCPs mounted on the *RSS James Cook* and *RSS Discovery* were used to calculate  $\Gamma_1(x)$  using a moving time window of  $\pm 2$  days (e.g., Figure 2). The location of minimum  $\Gamma_1(x)$  is calculated every 12 hr and defined as the eddy center (Figure 1). This method is possible due to the mapping strategies employed by both vessels, with large numbers of measurements within the core of the eddy (*RSS James Cook*) and surveys ranging outside of the eddy core in all directions (*RSS Discovery*). However, even with two vessels dedicated to this task there were limitations in our ability to map the shape of the eddy throughout the EXPORTS-NA deployment; see Section 5.4. Satellite-based measurements were calculated similarly every day from gridded  $1/4^\circ$  maps of geostrophic horizontal velocities, further interpolated using a cubic spline to  $1/40^\circ$  for the calculation of  $\Gamma_{1,2}(x)$ .

### 3.2. Sea Surface Height Metrics

Anticyclonic eddies are associated with positive SLA on the order of tens of centimeters. Remote sensing of oceanic eddies from constellations of orbiting altimeters have built up a census of eddy properties and statistics throughout the global ocean over the past decades (Chelton et al., 2007, 2011; Faghmous et al., 2015). These approaches involve detecting peaks (or valleys, for cyclones) in SLA and defining a SLA contour about each peak that properly defines the boundary of the eddy.

Here we extend the  $\Gamma_2$  approach above to define a matching SLA contour that has the most overlap with the effective eddy boundary  $\Gamma_2$  contour of  $-2/\pi$  (Figures 3a and 3b). This proposed contour for  $\Gamma_2$ , however, occasionally





**Figure 3.** Eddy shape over the month of May (colors) for the (a) sea level anomalies (SLA) (a), (b)  $\Gamma_2$ , and (c) Mean Eddy Trajectory Analysis (META) 3.2 methods. Dotted contours in (b) denote circularity metrics less than 0.6, as described in the text.

conjoins with other nearby eddies to form highly irregular eddy boundaries. Therefore, only  $\Gamma_2 = -2/\pi$  contours with a circularity of at least 0.6 were used to define the appropriate SLA contour, where the circularity is defined as the fraction of the given area that falls within a perfect circle with the same area. Using this approach, the SLA contour best defining the eddy was 11.0 cm (Figure 4).

Other approaches incorporate horizontal gradients in SLA, or geostrophic velocities, into the eddy boundary definition. The Mean Eddy Trajectory Analysis (currently version 3.2; META3.2) is used as a comparison here (Mason et al., 2014) (Figure 3c). This approach first looks for the largest area, or the  $SLA_{fit}$  contour with the smallest magnitude, about each  $SLA_{fit}$  maximum or minimum, while requiring an area of between 8 and 1,000 pixels (at  $1/4^\circ \times 1/4^\circ$  resolution) and a  $SLA_{fit}$  amplitude of at least 1 cm, as the outermost extent of the eddy. It then estimates the  $SLA_{fit}$  boundary best representing the eddy itself as the contour within this area that maximizes the

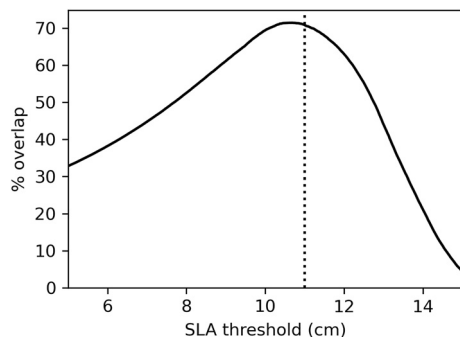
average geostrophic velocity along the eddy boundary, or equivalently the  $SLA_{fit}$  contour that is associated with the largest horizontal SLA gradient (Mason et al., 2014; Pegliasco et al., 2022).

A number of other metrics are not considered here, but also rely on the relevant dominance of rotation about the eddy center. The Okubo-Weiss method (Isern-Fontanet et al., 2003), which measures the difference between rotational flow and shear/strain, is commonly used to determine eddies from altimetry. However, this method, which relies on multiple derivatives of SLA, is generally coarsely resolved when using  $1/4^\circ$  data. At the scale of the EXPORTS-NA eddy, this method predictably gave poor results (not shown). Another method, the Lagrangian-averaged vorticity deviation approach, advects particles along (geostrophic) velocities and calculates their individual vorticities, defining an eddy as a region where individual Lagrangian particles show high levels of vorticity (Haller et al., 2016). This method is essentially a Lagrangian version of the Eulerian  $\Gamma_2$  method, but is considerably more computationally expensive to calculate.

### 3.3. Seawater Property Metrics

Glider SL305 was used to map waters within and outside of the target eddy and is therefore an ideal platform to construct a definition of interior water properties associated with distinct core eddy waters. Potential densities from SL305 indicate shoaling of waters near the eddy center lighter than about  $27.15 \text{ kg m}^{-3}$  when the platform was near the eddy center, whereas isopycnals greater than about  $27.2 \text{ kg m}^{-3}$  deepen, creating the signature widening of interior isopycnal layers characteristic of an anticyclonic mode water eddy (Figure 5). The thickness, or height, of the core isopycnal layer  $27.15\text{--}27.2 \text{ kg m}^{-3}$ ,  $h_{iso}$ , can therefore be used as a metric for the eddy extent.

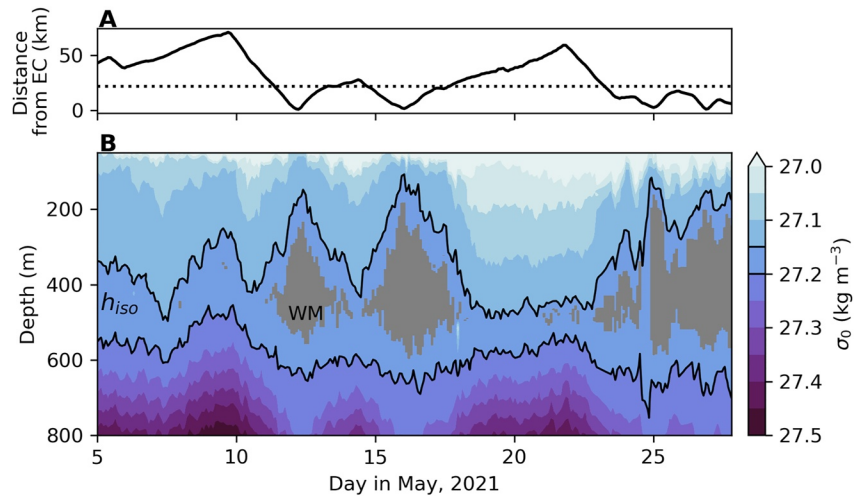
Water mass characteristics can also define waters that are retained within the eddy. Temperature and salinity are relatively homogeneous at densities of about  $27.17 \text{ kg m}^{-3}$  for those profiles with  $h_{iso}$  greater than 275 m (Figure 6), suggesting that water mass (WM) properties with  $\Theta$  of about  $10.83^\circ\text{C}$  and  $S_A$  near  $35.63 \text{ g kg}^{-1}$  designates that profile as passing through the interior eddy core. Potential density and spice thresholds were found to more precisely define these waters, and here we define the amount of core WM in each profile as the integral of waters with potential density from  $27.16$  to  $27.18 \text{ kg m}^{-3}$  and spice from  $1.74$  to  $1.76 \text{ kg m}^{-3}$  (gray area in Figure 5b; see also Johnson et al., 2023).



**Figure 4.** Percent overlap between  $\Gamma_2$  and sea level anomalies (SLA) thresholds, calculated as the areal ratio where both  $\Gamma_2 < -2/\pi$  and  $SLA > SLA_{thres}$ , over a region where either  $\Gamma_2 < -2/\pi$  or  $SLA > SLA_{thres}$ .

### 3.4. Validation

The core isopycnal layer thickness was defined as the reference metric defining the eddy core, with profiles having a core thickness of over 275 m assumed to be within the eddy ( $n = 471$ ), and outside of the eddy otherwise ( $n = 173$ ; Table 1). Then, each method described above, along with the distance from the eddy center, is calculated and given a threshold value. The results present



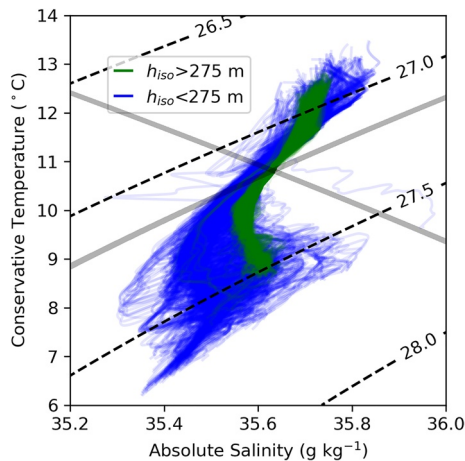
**Figure 5.** Data from ocean glider SL305 during the campaign. (a) Distance from SL305 to the eddy center, with 22 km marked. (b) Potential density  $\sigma_0$ , with isopycnals involved in the calculation of  $h_{iso}$  (27.15 and 27.2 kg m<sup>-3</sup>) in black. Gray filled region within  $h_{iso}$  denotes core WM, with  $\sigma_0$  between 27.16 and 27.18 kg m<sup>-3</sup> and spice between 1.74 and 1.76 kg m<sup>-3</sup>.

the number of true positive and true negative predictions, where a given metric correctly diagnosed a profile as being within and outside of the eddy, respectively, and the number of false positive and false negative predictions, where the metric incorrectly diagnosed a profile as being within or outside of the eddy, respectively.

## 4. Results

### 4.1. Eddy Center

Calculation of  $\Gamma_1(\mathbf{x})$  from ADCP horizontal velocities at 130 m depth was used to estimate the location of the anticyclonic eddy center, defined as the location with a minimum value of  $\Gamma_1(\mathbf{x})$ . Over the month of May, the eddy center translated southward from about 49.1 to 48.7°N (Figure 1). The Lagrangian float, drifting at a parking depth of about 100 m, transcribed a circular motion about this eddy center, with an approximate radius of 5–10 km and a period of about 4 days.

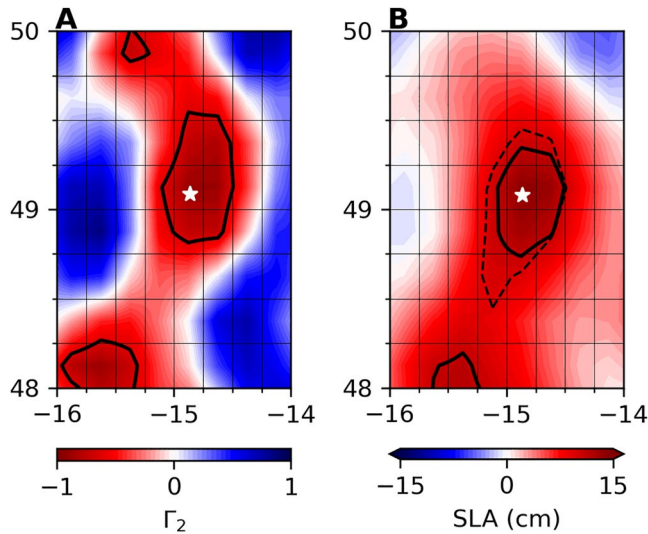


**Figure 6.** Profiles of  $S_A$  and  $\Theta$  for profiles within (green) and outside (blue) the eddy, determined by a  $h_{iso}$  threshold of 275 m. Black dashed contours show potential density. Gray lines show values used to define core waters, with potential density from 27.16 to 27.18 kg m<sup>-3</sup> and spice from 1.74 to 1.76 kg m<sup>-3</sup>.

Satellite approaches were also used to calculate the eddy center and compare with the in situ result. The  $\Gamma_1$  and SLA metrics give predictions of the eddy center as the minimum  $\Gamma_1$  and maximum SLA, respectively (see Figure 7). The satellite-derived eddy centers were always within 16 km of the in situ eddy center, with an average distance of about 7 km (Figure 1b), which is well within the resolution of the gridded satellite altimetry product. This result is in spite of the reduction in SLA associated with mode water eddies, as interior isopycnals are partially compensated near the surface, making it more difficult to locate this eddy from altimetry. The eddy center from the META3.2 algorithm closely matches the SLA-based eddy center location shown here, since the only difference in the underlying altimetry data is a low-pass spatial filter, and is therefore not independently shown. Using satellite altimetry also enables tracking of the eddy before and after the EXPORTS-NA deployment, showing a slow and steady drift southward of the eddy over time (Figure 1b).

### 4.2. Eddy Spatial Extent

The in situ metrics clearly show the eddy as an area around the eddy center with a weakly stratified interior (large  $h_{iso}$ ) and large amounts of core waters (Figure 8). These eddy-like waters are also confined within a distance from an apparent eddy center, suggesting the use of a simple distance metric. Each



**Figure 7.** Snapshot of (a)  $\Gamma_2$  and (b) sea level anomaly (SLA) from 11 May 2021 calculated from satellite data, with grid lines representing the resolution of the gridded product. In each panel, the black contour represents a proposed threshold ( $-0.64$  for  $\Gamma_2$  and  $11$  cm for SLA) and the white star is the eddy center according to each product. In (b), the dashed black line gives the eddy edge from the Mean Eddy Trajectory Analysis (META) version 3.2 data product (along a given  $SLA_{filt}$  contour).

of these metrics can be compared to a suitable threshold value to determine if a given profile is within, or outside of, the eddy.

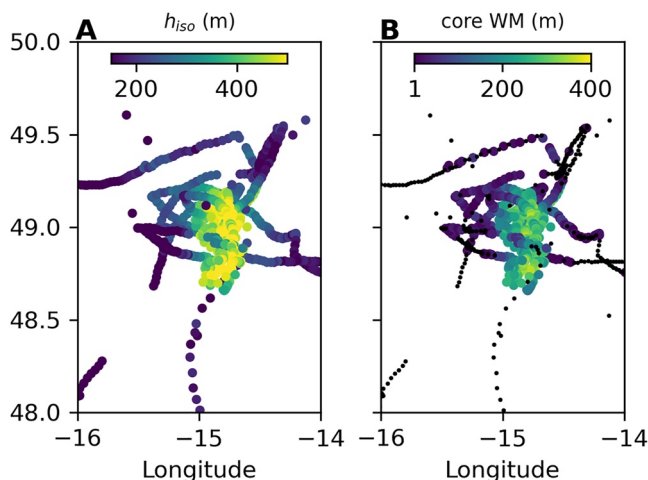
Out of the 644 profiles used here, 456 were within 20 km of the eddy center, and all but two of those had a core isopycnal thickness of over 275 m, designating them as within the eddy. Similarly, all 156 profiles farther than 25 km from the eddy center were designated as outside of the eddy. A threshold value of 22 km minimized the sum of false positive and false negative results and was chosen as the threshold value. This distance threshold correctly classifies 99% (466/471) of the profiles within the eddy, and 97% (168/173) of the profiles outside of the eddy (Figure 9a).

The existence of at least 40 m of core WM in a given profile, defined using potential density and spice thresholds, is another relatively simple metric that correctly identified 98% (461/471) of profiles within the eddy, and 83% (169/173) of profiles outside of the eddy (Figure 9b). This approach therefore has similar skill as compared with the distance metric.

The satellite metrics showed comparable skill at diagnosing when a profile was in an eddy compared with the in situ metrics. The rotational metric  $\Gamma_2$  indicates the local dominance of anticyclonic rotation, rather than shear, at values less than  $-2/\pi \approx -0.64$ . This threshold value correctly identifies 100% (471/471) of profiles from within the eddy and 62% (106/171) of profiles outside of the eddy (Figure 9c). The SLA method was more accurate than the  $\Gamma_2$  approach, with 100% (471/471) of profiles within the eddy accurately predicted, as well as 77% (132/171) of profiles outside the eddy (Figure 9e).

In contrast to the in situ metrics defined above, the satellite-based thresholds employing  $\Gamma_2$  and SLA were not optimized for the highest accuracy. Optimizing  $\Gamma_2$  and SLA thresholds, as was done for the in situ metrics, would have resulted in only 25 incorrect predictions from  $\Gamma_2$  (threshold level of  $-0.75$ ), and 26 from SLA (threshold value from 11.8 to 12 cm), which represents approximately equivalent skill to the core WM metric and distance metrics.

The META3.2 algorithm is about as accurate as the  $\Gamma_2$  method, with 100% (471/471) accuracy on profiles within the eddy and 63% (107/171) for those outside the eddy (Figure 9e). This approach uses a time-varying threshold on  $SLA_{filt}$  data (see above), ranging from 5.8 to 7.6 cm. The upper limit on this threshold, 7.6 cm, roughly corresponds to the SLA threshold used in Figure 9e of 11 cm, indicating a static, rather than time varying, approach would have resulted in higher accuracy for this eddy.



**Figure 8.** (a) Core isopycnal thickness  $h_{iso}$  and (b) width of core water mass (WM) for each profile (see Table 1). Black dots in panel B indicate waters with no core WM present.

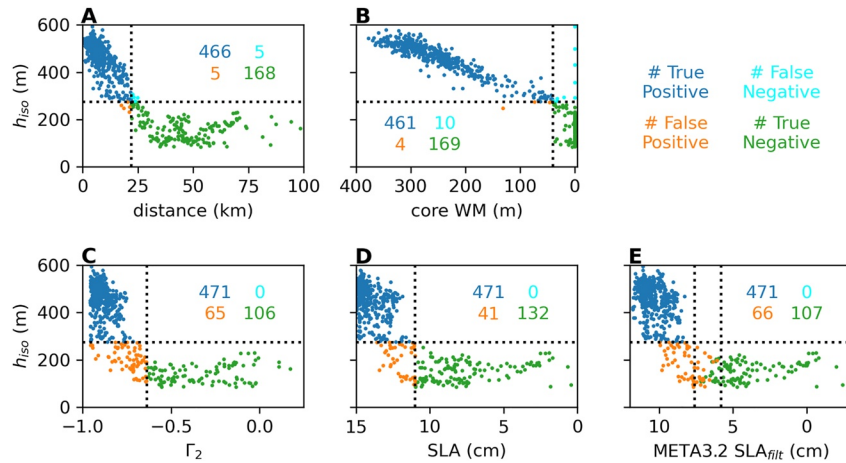
## 5. Discussion

This study compares and contrasts methods for determining the location and spatial extent of an anticyclonic eddy in the North Atlantic during May of 2021. Methods using in situ metrics are able to directly capture features of the subsurface ocean where the eddy core is located (Johnson et al., 2023). Satellite-based products are more coarsely resolved, due to the limited number of observations in space and time by nadir-looking satellite altimeters, and can only estimate geostrophic currents. However, they provide a more complete picture of the water surrounding the eddy, rather than only where in situ assets were located, and can track the target eddy for a longer period of time.

### 5.1. Eddy Center From in Situ and Satellite Metrics

Satellite and in situ metrics differed only slightly on where the center of the eddy was located, with the satellite metrics placing the eddy center on





**Figure 9.** Scatter plot of eddy metrics with respect to the reference of  $h_{150}$  for all profiles ( $n = 644$ ) from 5 to 30 May that reach at least  $27.2 \text{ kg m}^{-3}$  and are located between  $48$  and  $50^\circ\text{N}$  and  $14$ – $16^\circ\text{W}$ . Metrics (proposed thresholds as black dotted lines) are: (a) distance from eddy center ( $<22 \text{ km}$ ), (b) vertical extent of core water mass (WM;  $>40 \text{ m}$ ), (c) satellite-based  $\Gamma_2$  ( $<-2\pi$ ), (d) satellite-based sea level anomaly (SLA;  $>11 \text{ cm}$ ), and (e) the Mean Eddy Trajectory Analysis (META) version 3.2 algorithm, with threshold values of  $\text{SLA}_{\text{fit}}$  from  $5.8$  to  $7.6 \text{ cm}$ . Colors and numbers are associated with true positive (blue), false negative (cyan), false positive (orange), and true negative (green) predictions, where the truth is determined by the threshold metric  $h_{150} > 275 \text{ m}$ .

average within about  $7 \text{ km}$  of the in situ observations. Satellite and in situ metrics alike generally remained within the approximate trajectory of the Lagrangian float (Figure 1b), which remained within the eddy throughout the deployment (Johnson et al., 2023). For the EXPORTS-NA eddy considered here, satellite-based estimates of the eddy center were therefore accurate enough to follow the retentive core of this relatively small eddy. These results also suggest more generally that satellite approaches which locate eddy centers from SLA extremes are adequately able to represent eddy locations to within the retentive centers of the eddies.

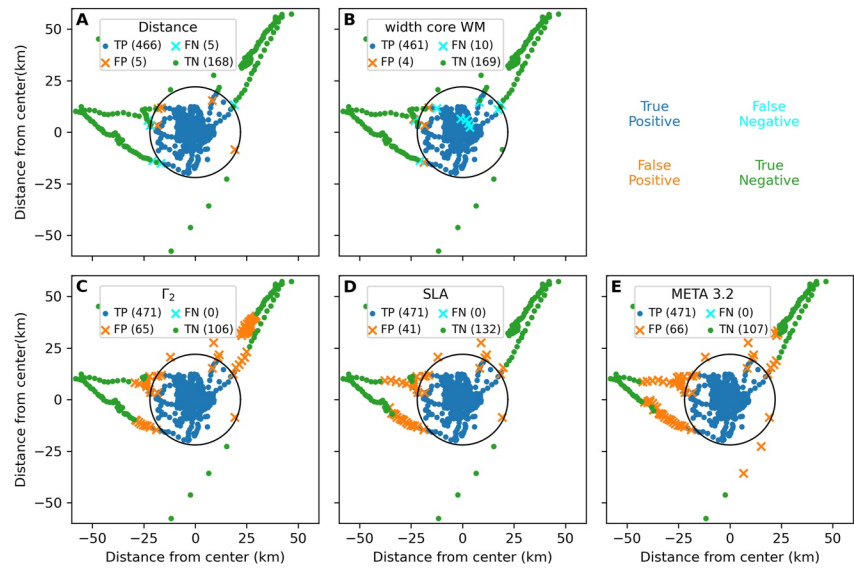
Eddy centers defined here correspond to the eddy core at approximately  $400 \text{ m}$  depth, defined primarily by the  $27.15$  and  $27.2 \text{ kg m}^{-3}$  potential density surfaces (Figure 5). However, eddy centers can shift laterally with depth, linked to the baroclinicity of the eddy (e.g., Kurczyn et al., 2013; Li et al., 2022; Roemmich & Gilson, 2001; Tang et al., 2020), potentially leading to significant discrepancies between the eddy center at depth and at the surface. While not directly measured here, this effect could be important for experiments such as EXPORTS-NA that seek to understand connections between the surface and interior ocean. For this eddy, wind stress from periodic storm events played a major role in setting the density structure and horizontal velocity field of the eddy near the surface, and Lagrangian particles advected along streamlines set by geostrophic and Ekman effects trace significantly different paths than those advected only geostrophically around the eddy (Johnson et al., 2023).

### 5.2. Eddy Size From in Situ Measurements

Six different methods for determining the extent of the eddy were compared, of which three were based on in situ measurements and three were from satellite altimetry. The three in situ metrics agreed with each other well for the available deep profiles:  $459$  of the  $471$  (97%) of the profiles within the eddy were identified as such for all in situ metrics, as were  $166$  of  $173$  (96%) of profiles outside of the eddy, for a combined accuracy of all in situ metrics of 97%. False eddy predictions for the in situ metrics based on distance and core WM are distributed throughout the region, indicating that there is no significant spatial bias in this prediction (Figures 10a and 10b).

While the predictions from each of the metrics are similar, they each provide distinct information about the eddy and individually have different advantages. The thickness method,  $h_{150}$ , defined here as the reference method, classifies profiles with low interior stratification as within the eddy. The threshold chosen here, a minimum thickness of  $275 \text{ m}$  over  $0.05 \text{ kg m}^{-3}$ , imposes a maximum Brunt-Väisälä frequency within the eddy core of

$$N_2 = b_z = \frac{g}{\rho_0} \frac{\Delta\sigma}{\Delta z} \approx 1.7 \times 10^{-6} \text{ s}^{-2}, \quad (3)$$



**Figure 10.** Scatter plot of every “deep” profile (see Table 1) during EXport Processes in the Ocean from Remote Sensing (EXPORTS)-North Atlantic (NA), colored by the prediction (Positive/Negative) of being within the eddy from (a) distance from eddy center, (b), width of core waters, (c) satellite-derived  $\Gamma_2$ , (d) satellite-derived sea level anomalies (SLA), and (e) Mean Eddy Trajectory Analysis (META) 3.2, and whether or not that prediction was accurate (True/False) based on a  $h_{iso}$  threshold. Black circle in each panel is the 22 km distance threshold.

where  $g = 9.8 \text{ m s}^{-2}$  is the gravitational acceleration and  $\rho_0 = 1,027 \text{ kg m}^{-3}$  is a reference density. The maximum Ertel potential vorticity (PV) within the eddy core can be approximated as

$$PV = fN^2 \approx 2 \times 10^{-10} \text{ s}^{-3}, \quad (4)$$

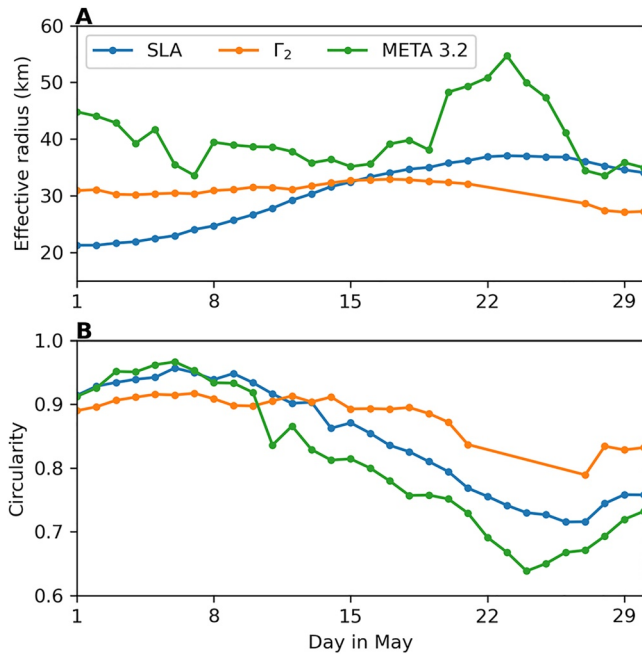
where  $f = 1.1 \times 10^{-4} \text{ s}^{-1}$  is the planetary vorticity. This definition assumes that the relative vorticity is small compared to  $f$ . Assuming an average eddy radius of 22 km and a speed of  $20 \text{ cm s}^{-1}$  at the eddy edge, the relative vorticity is approximately  $-0.09 \times 10^{-4} \text{ s}^{-1}$ , or less than 10% of the planetary vorticity. This PV threshold aligns well with previous observations of subthermocline eddies in the region (cf. Figure 5 of Thompson et al., 2016).

Another in situ metric is the existence of core waters, which are defined here by potential density and spice thresholds. Assuming minimal mixing of waters over time, this definition can be used to trace this water mass back in time and find outcropping locations of waters with these characteristics at the surface. This method is also conceptually straightforward, as it directly equates being within an eddy to waters with given physical characteristics.

A critical distinction, however, exists between the spatial extent of the eddy core, considered here, and the spatial extent of the surface waters most identified with this particular eddy. In contrast to the results presented here, Johnson et al. (2023) find a much more diffuse temperature and salinity signal identifying core eddy surface waters, and suggest a smaller radius of 15 km about the eddy center. This difference poses a significant limitation to current eddy tracking efforts: the interior core of the eddy may be distinct from the volume of water trapped by the eddy at the surface, due primarily to wind stress, notably from a series of storms during the deployment (Johnson et al., 2023). This is especially important for Lagrangian deployments such as EXPORTS-NA that aim to measure biological processes occurring primarily within the euphotic zone.

### 5.3. Eddy Size From Satellite Observations

The EXPORTS-NA deployment provides an excellent opportunity to evaluate how well satellite altimetry-based algorithms, and especially the widely distributed META3.2 method (Mason et al., 2014), perform at estimating the extent of one anticyclonic eddy. In general these methods compare well with in situ metrics, despite not being optimized for this particular eddy. False predictions for the satellite metrics are spatially concentrated in a region to the west of the eddy (for  $\Gamma_2$ , SLA, and META 3.2) and to the northeast (for  $\Gamma_2$ ; Figures 10c–10e).



**Figure 11.** Changes in satellite-based eddy effective radius (a) and circularity (b) for the  $\Gamma_2$  (orange), sea level anomalies (SLA) (blue), and Mean Eddy Trajectory Analysis (META) 3.2 (green) algorithms. Gaps in the  $\Gamma_2$  metric indicate when this approach incorrectly merged the study eddy with another nearby eddy, as indicated by a circularity below 0.6 (see text).

This suggests two possibilities: either the satellite data on the western edge of the eddy is biased due to lack of altimetry data and/or a coarsely resolved data product, or the satellite algorithms accurately depict a western region of the eddy that has similar SLA and is encircled by rotating waters, but nevertheless contains waters with different properties. This second possibility is supported by steric height data calculated from in situ profiles (not shown here), which also suggest a region to the west of the eddy with high SLA. This area to the west of the eddy core has also been shown to have anomalous surface water properties, possibly indicating injection of different waters into the eddy (Johnson et al., 2023). In contrast, the incorrect predictions on the northeast side of the eddy from the  $\Gamma_2$  method were due to the apparent merging (only shown in this metric) of this feature with another eddy to the north.

Satellite-based methods for eddy detection and tracking provide the ability to diagnose changes in eddy properties, such as effective radius and circularity or eccentricity over time. The SLA metric shows a gradual increase in the effective radius from 22 to 37 km over the course of the month of May (Figure 11a). This increase is not clearly seen in the other metrics,  $\Gamma_2$  and META3.2, which show either no overall change ( $\Gamma_2$ ) or are highly variable (META 3.2). Near the beginning of the month the  $\Gamma_2$  method displaced the eddy toward the northeast as a result of the influence of a nearby eddy in the region, likely contributing to the slightly larger size predicted from this method. However, the difference between the SLA and  $\Gamma_2$  methods are small compared to the underlying resolution of the satellite altimetry. The high variation in eddy size from META 3.2 is a direct result of the way META3.2 determines the threshold  $SLA_{fit}$  value, which is to maximize the geostrophic velocity around the eddy edge. This method does not take into account past threshold levels, potentially resulting in large variations from day-to-day,

which will affect the size and shape of the eddy. For example, the increase in apparent eddy size from 19 to 23 May for this algorithm is due to a decrease in the threshold value of  $SLA_{fit}$  from 7.25 cm to about 6 cm over this period. These changes in satellite-based  $SLA_{fit}$  do not smoothly vary with time and likely will contribute to overestimating variance in eddy parameters using this method. All three methods, however, agree that the circularity of the eddy, defined as the fraction of area within the eddy that is also within a perfect circle encompassing the same area, decreased from a nearly circular eddy at the beginning of May to a more eccentric eddy, with a circularity of 0.7–0.85, by the end of the month (Figure 11b).

The central altimetry product used here was a daily SLA field utilizing five satellite altimeters, gridded at  $1/4^\circ$  intervals. Gridded SLA was then interpolated using a cubic spline to the positions of the assets. Which altimetry fields are used, how they are gridded, and how that grid is interpolated are all factors that will influence local SLA values at the positions of the assets. For example, use of a two-altimeter data product, produced to provide a consistent long-term time series of altimetry, severely and detrimentally affected the accuracy of all of the satellite-based predictions, an effect also seen by Pascual et al. (2006). Other gridding procedures have been developed, although not yet implemented for the North Atlantic during EXPORTS-NA. For example, Ubelmann et al. (2015) developed a dynamical mapping algorithm which improves on the standard linear interpolation used here by including nonlinear temporal propagation of sea surface height anomalies. This product has improved skill at accurately estimating sea surface height products (Ballarotta et al., 2020). These newer products are precursors to operational sea surface height data that will be available from the recently launched Surface Water and Ocean Topography (SWOT) satellite (Morrow et al., 2019).

Machine learning may also lead to improvements in SLA estimation and therefore eddy identification and tracking even from coarser satellite-derived data products. Martin et al. (2023) show that incorporating higher-resolution sea surface temperature (SST) measurements into sea surface height gridding algorithms can significantly increase the final accuracy and possible resolution of these final products. For the EXPORTS-NA data set, the mean SST, here estimated as the average conservative temperature of the upper 20 m from in situ profiles, is significantly different ( $p < 0.01$ ) for the false positive regions ( $12.79 \pm 0.31$ ) than for the true positive ( $12.46 \pm 0.16$ ) and true negative ( $12.60 \pm 0.123$ ) regions with respect to the satellite-derived SLA predictions (Figure 10d), suggesting

that a product incorporating SST may improve the accuracy of satellite-derived SLA for eddies with distinct surface warm or cold cores.

#### 5.4. Lessons Learned From Mapping an Eddy

One of the primary challenges in mapping an eddy from in situ measurements is to resolve the depth variability. The core of the EXPORTS-NA eddy was located at about 400 m, and measurements down to at least 800 m were required to fully characterize this feature (Figure 5). Since the EXPORTS-NA deployment was primarily concerned with the biological pump, many of the ship-based profiles did not extend to this depth, and were therefore not used here (Table 1). Part of the challenge is that surface water characteristics were modified during the course of the deployment by several large storms that entered the region (see Johnson et al., 2023), meaning profiles only near the surface, or underway data from the ships, were less useful in determining the eddy extent.

Transects across the edge of the eddy were also important to distinguish interior water masses from those outside of the eddy, which were used to determine threshold values for isopycnal thickness and the temperature and salinity characteristics that went into characterizing the core WM (e.g., Figure 5). However, in situ characterization of the eddy edge came primarily from three glider transects: two on the western edge and one to the northeast (Figure 10). The lack of knowledge of the eddy boundary to the southeast from in situ measurements limited our ability to fully distinguish between the different satellite metrics. This also highlights the utility of satellite-derived eddy boundaries, which are able to provide estimated values for the entire edge of the eddy (e.g., Figure 7), despite the trade-offs associated with their coarse resolution.

The results here indicate that even for a relatively small eddy, standard satellite-based methods of deriving eddy boundaries, such as META3.2, perform well. However, the EXPORTS-NA eddy was not necessarily a good representative candidate. This eddy was carefully chosen to represent a stable and coherent feature over the course of the field deployment (Erickson et al., 2022), which may have resulted in its being better represented in satellite products than an average eddy. The PAP region is also an area of low variability in sea surface height (Ballarotta et al., 2020) and low error in derived velocities as compared with drifter data (Taburet et al., 2019) compared with, for example, more energetically active western boundary current regions. On the other hand, as a mode water eddy, it had a smaller associated SLA due to interior compensating isopycnal gradients, challenging satellite altimetry algorithms that rely on SLA. A study focused on only one eddy can only provide suggestive evidence on the utility of altimetry methods for determining eddy boundaries, and a more comprehensive survey of eddy edges from in situ and satellite measurements is needed.

## 6. Conclusions

The EXPORTS-NA field program was conducted within and around an anticyclonic mode water eddy. Profiles of temperature and salinity from ships, gliders, and BGC floats deployed as part of this project allow different methods of detecting eddies from in situ and satellite methods to be tested. A key characteristic of an anticyclonic mode water eddy is shoaling lighter isopycnals and deepening denser isopycnals, motivating the use of the thickness of the  $27.15\text{--}27.2\text{ kg m}^{-3}$  layer as a metric for the eddy, along with a water mass characteristic determined by the temperature and salinity, or equivalently the potential density and spice, of measured waters. Each of these metrics did well at accurately predicting the eddy. Velocity-based metrics from in situ measurements and from satellite-based altimetry give similar results, suggesting that even comparably low satellite resolution can accurately track even relatively small eddies, with radii on the scale of the gridded data product itself.

For this eddy, the data collected here support the use of algorithms based on satellite altimetry in future eddy tracking studies. Satellite altimetry is able to provide information on changes in eddy properties over time and space that are not possible even with hundreds of in situ profiles taken as a result of the EXPORTS-NA deployment. However, there are challenges to these altimetry-based methods. At least for this eddy, these challenges related less to the coarse resolution of altimetry maps, and were more related to the ability of sea level contours to reliably demarcate eddy boundaries. In addition, a commonly used algorithm, META3.2, re-calculates the SLA contour associated with the eddy edge each day, leading to significant jumps in eddy size that are likely unphysical. Here we therefore suggest a constant, or perhaps smoothly time-varying, SLA contour approach that was shown to more accurately represent the edge of the eddy, as compared with in situ measurements. This SLA contour can be found using a method that calculates the average rotation about each point in space, and calculates



the eddy center as the point associated with the maximum level of rotation. This approach is generalizable to any other eddy using satellite altimetry measurements, and in future work will be applied to a variety of other datasets sampling eddies throughout the ocean.

### Data Availability Statement

The in situ data collected by the EXPORTS-NA project can be found at Siegel et al. (2021). Satellite altimetry was provided by Copernicus Climate Change Service (2018), and the META3.2 analysis was provided by AVISO (2022). Code to process ADCP measurements was provided by the University of Hawaii Data Acquisition System (UHDAS) (2021). Figures were made using Matplotlib version 3.7.1 (Hunter, 2007).

### Acknowledgments

The authors would like to gratefully acknowledge the efforts of the captains and crews of the *RRS Discovery*, *RRS James Cook*, and *R/V Sarmiento de Gamboa*, as well as those of the entire EXPORTS science team. This field deployment was funded by the NASA Ocean Biology and Biogeochemistry program and the National Science Foundation Biological and Chemical Oceanography programs. Initial gliders deployments were performed by the *RRS Discovery* and the authors thank the Porcupine Abyssal Plain – Sustained Observatory of the Natural Environment Research Council (NERC, UK), which is principally funded through the Climate Linked Atlantic Sector Science (CLASS) project supported by NERC National Capability funding (NE/R015953/1) and by IFADO (Innovation in the Framework of the Atlantic Deep Ocean) EAPA\_165/2016. Technical assistance with the Slocum glider deployment and quality control was provided by Filipa Carvalho (NOC) and Marine Autonomous Robotic Systems (NOC). Assistance and quality control of the Seagliders was provided by Geoff Shilling (UW) and Craig Lee (UW). Z.K. Erickson would like to thank Scott Martin (UW) for valuable conversations about satellite altimetry products. This is PMEL Contribution Number 5444.

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