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EXPORTS North Atlantic Eddy Tracking

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October 2022

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0. Summary

The EXPORTS North Atlantic field campaign (EXPORTS-NA) of May 2021 used a diverse array of ship-based and autonomous platforms to measure and quantify processes leading to carbon export in the open ocean. The success of this field program relied heavily on the ability to make measurements following a Lagrangian trajectory within a coherent, retentive eddy (Sections 1, 2). Identifying an eddy that would remain coherent and retentive over the course of a month-long deployment was a significant challenge that the EXPORTS team faced. This report details the processes and procedures used by the primarily shore-based eddy tracking team to locate, track, and sample with autonomous assets such an eddy before and during EXPORTS-NA.

In the months preceding the deployment, the eddy-tracking team developed metrics to identify and track eddies from sea surface altimetry products and predict the degree to which they would retain Lagrangian assets over the course of 30-60 days (Section 3). The most predictive metrics were found to be eddy size and past retentiveness, with larger and longer-lived eddies being more likely to remain coherent and retentive in the future. We planned how to use autonomous measurements from ocean gliders that were deployed approximately one month prior to the main EXPORTS-NA campaign (Section 4). We convened a series of “Dry Runs” using data from past years to assess our ability to use real-time altimetry to locate potential eddies, task gliders to optimally sample eddy candidates, and develop our eddy decision making procedures. This process highlighted the importance of dispersing gliders to multiple eddies. A numerical model was also employed to consider different glider sampling approaches. This model indicated that eddies in this region were often coherent features to at least 1000 m depth, accurately suggesting that we might find an eddy with a particularly retentive sub-surface core.

During March of 2021, the eddy-tracking team started formally meeting to look at real-time satellite altimetry, using the lessons from the Dry Runs to monitor candidate eddies (Section 5). Gliders were deployed in April and used to sample three different eddies. We recommended an anticyclone that was long-lived, predicted to be retentive, and had been well-sampled by a glider. We tracked this eddy throughout the course of the field deployment, providing daily updates of eddy location to guide ship-based sampling and the deployment of autonomous assets (Section 6). Satellite altimetry was too coarse for this application, so instead we used metrics derived from *in situ* depth-averaged-currents from gliders and ship-based ADCP. This analysis was made possible through clear communication channels between the ships and the shore team, transmitting data from ADCP measurements and CTD casts from the ships to the shore and permitting the exchange of figures and analyses between all scientific parties.

Following the successful completion of the EXPORTS-NA field deployment, we convened a group retrospective meeting to consider what went well, what could have been improved, and what lessons learned were learned (Section 7). A major conclusion of this group was the importance of shore-side support for eddy tracking and preliminary analyses, and the need to fund these activities in future field projects. Data access and communication channels between the ships and the shore were also identified as crucial to the success of this field program.

1. Introduction

The EXPORTS North Atlantic (EXPORTS-NA) Field Deployment was the second part of a NASA- and NSF-funded multi-year field program dedicated to understanding the mechanisms governing the export of fixed carbon out of the euphotic zone and ultimate fate within the twilight zone in two dissimilar oceanic regions: the relatively quiescent and one-dimensional North Pacific and the highly productive and energetic North Atlantic (Siegel et al., 2016). EXPORTS-NA utilized two research vessels, the *RRS Discovery* (DY131) and the *RRS James Cook* (JC214), and also partnered with the *R/V Sarmiento de Gamboa* (SG2105) cruise funded by the WHOI Ocean Twilight Zone (OTZ) project. This deployment took place in the vicinity of the Porcupine Abyssal Plains Sustained Observatory (PAP-SO). The main goals of EXPORTS-NA were to measure physical, chemical, and biological water properties associated with biological productivity and water mass transport during the demise of the annual phytoplankton bloom, and to obtain a Lagrangian time series of biological rates and carbon fluxes in the upper ocean. The main part of the field program occurred from 04 to 29 May 2021, and was supplemented by an earlier deployment of three ocean gliders, two Seagliders and one Slocum, from a preceding cruise on the *RRS Discovery* (DY130) in early April (Table 1). The purpose of the early glider deployment was to identify and map potential eddies that would be the focus of the ship-based field work.

Table 1. Platforms during EXPORTS-NA. Dates are during 2021.

Platform	Abbreviation	Start	End
RRS Discovery	DY130	25 March	14 April
Slocum 305	SL305	03 Apr	29 May
Seaglider 219	SG219	01 Apr	29 May
Seaglider 237	SG237	04 Apr	29 May
RRS Discovery	DY131	01 May	29 May
RRS James Cook	JC214	04 May	29 May
R/V Sarmiento de Gamboa	SG2105	05 May	19 May

Because this region of the Atlantic is dominated by eddies, a central component of EXPORTS-NA was to survey the core of a coherent eddy where Lagrangian platforms would be retained. Our goal was to find a biologically productive and physically retentive eddy, such that changes in biological or chemical properties over time would be dominated by local changes rather than advective processes. This document describes the process used to choose an eddy in which to locate the EXPORTS-NA Field deployment.

2. Definition of a “Good Eddy”

The criteria for defining and choosing a “good eddy” was based on physical, biological, and geographical factors (summarized in Table 2 below). Physically, the eddy needed to be long-lived and retentive, such that deployed assets and the biological community alike would remain trapped inside the eddy for the duration of the deployment. This would help to minimize changes in properties within the eddy core from entrainment of different waters from outside the eddy. Biologically, it was vital that the eddy was co-located with a phytoplankton bloom, or the recent demise of one, so that carbon export processes could be measured during the deployment. Geographically, there were scientific and logistical considerations. From a scientific perspective, the eddy should not interact with the continental shelf, since this could affect the ability to extrapolate scientific results to an open ocean eddy. A location close to the continental shelf could also complicate the interpretation of deep backscattering particles (as was seen in past North Atlantic observations; Briggs et al., 2011). Eddies close to the Porcupine Abyssal Plains Sustained Observatory (PAP-SO; 49˚N, 16.5˚W) were preferred because this long-term time series would aid in scientific interpretations and interannual comparisons (Hartman et al., 2021). Logistically, we preferred an eddy closer to the UK because that would require less transit time for the ships, and an eddy close to PAP-SO because gliders monitoring the area before the field deployment were launched from near PAP-SO (see Table 1 and Section 5C). These geographical considerations led us to consider an area from 23 - 15˚W and 46 - 52˚N (Figure 1). A final consideration was that our chosen eddy may disperse during the deployment, and we would need to move the assets to another location. Therefore, was also weakly preferred an eddy that was near another prospective eddy.

Although all three main types of criteria – physical, biological, and geographical – were important, the majority of this memorandum concerns the physical issue of eddy retention and longevity. The geographic issues primarily involved describing the ocean region wherein we would search for a suitable eddy, although we did consider all of the geographical concerns in choosing the eddy, as will be described in the text below. Biological considerations only became meaningful in the last phases of choosing an eddy, since plankton blooms develop over timescales of days.

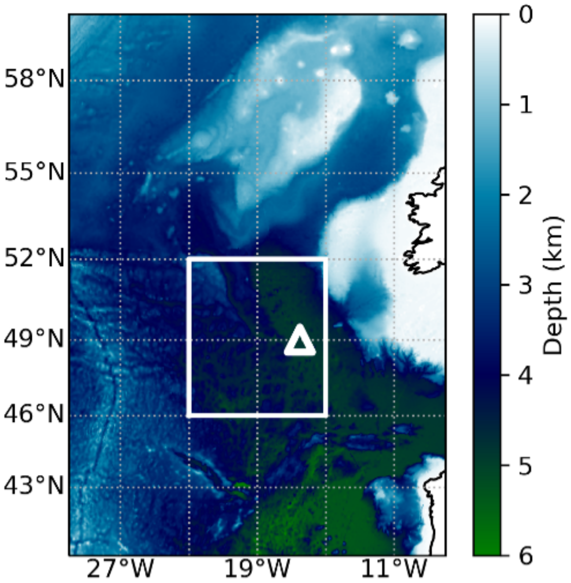

Figure 1. Bathymetry in the study region (white box). White denotes the PAP-SO.

Table 2. Summary of eddy criteria.

Physical Factors	Biological Factors	Geographical Factors
- Long-lived (exist throughout deployment) - Retentive (no exchange between waters inside and outside the eddy)	- Substantial phytoplankton biomass	- Far from the continental shelf - Close to PAP-SO - Close to the UK - Close to another suitable eddy

3. Eddy and Retention calculations

While planning for the EXPORTS-NA Field Deployment, we primarily used multi-satellite merged satellite altimetry (doi:10.48670/moi-00149) from Copernicus Marine Environment Monitoring Service (CMEMS) to define and diagnose eddies. We used the method of Graftieux et al. (2001) to calculate the location and extent of each observed eddy. This approach uses two rotational metrics, $\Gamma_1(x)$ and $\Gamma_2(x)$. $\Gamma_1(x)$ represents the rotation about a point x (Figure 2) and $\Gamma_2(x)$ is a similar measure of rotation after removing the mean flow. These metrics are calculated as

$$\Gamma_1(x) = \frac{1}{N}\sum_N \frac{r \wedge U}{|r|\cdot|U|} \quad \text{and} \qquad \text{(Eq. 1)}$$

$$\Gamma_2(x) = \frac{1}{N}\sum_N \frac{r \wedge (U - U_S)}{|r|\cdot|U - U_S|} \quad , \qquad \text{(Eq. 2)}$$

where *N* represents a range of data points near *x*, *r* is the (2-D) vector from *x* to each of *N* points, *U* is the (2-D) velocity at each of *N* points, and ∧ is the exterior product operator; that is, $r \wedge U$ represents the "area" of a parallelogram defined by r and U. $\Gamma_2(x)$ is calculated with the mean velocity, $U_S = \frac{1}{N}\sum_N U$, removed. $\Gamma_1(x)$ and $\Gamma_2(x)$ are bounded within the range $(-1,1)$ and are unitless.

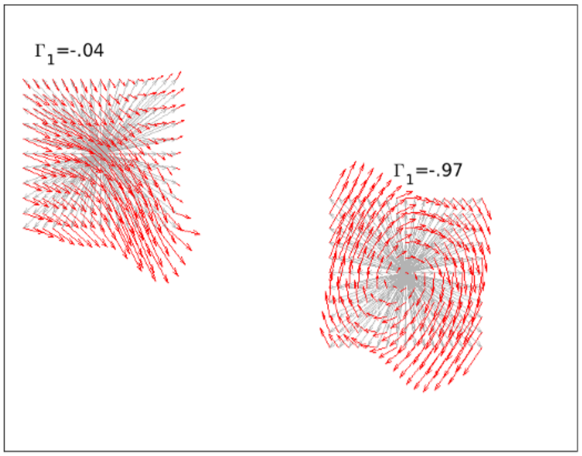

Figure 2. Example of Γ_1 calculated for a front (left) and an anticyclone (right).

For use with altimetry measurements, *N* was defined as those points within a number of grid cells from *x* corresponding to about 100 km. The error associated with calculating as a number of grid cells in both spatial directions, rather than within a radius around *x*, is small. However, $\Gamma_1(x)$ and $\Gamma_2(x)$ can vary significantly depending on the length scale over which they are calculated. During the field deployment we also calculated these metrics from in situ observations (see Section 6), in which case *N* was often the total number of velocity measurements from

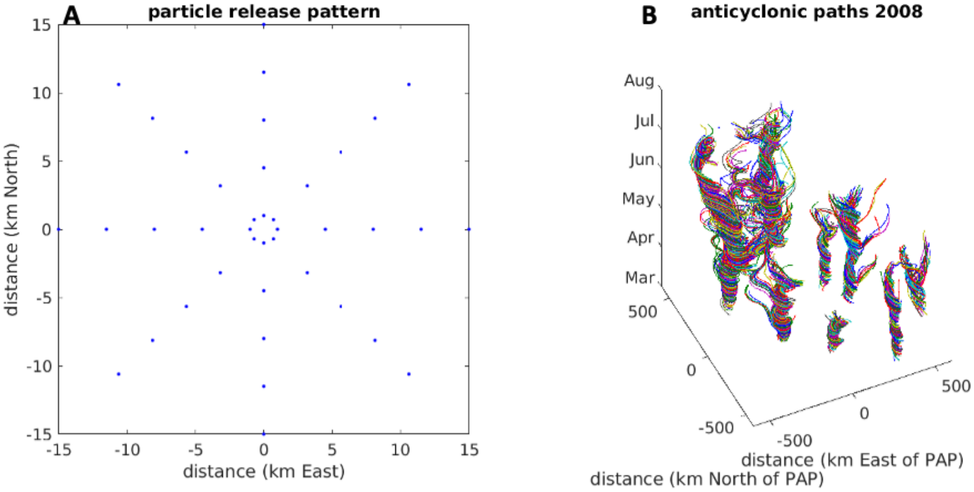

Figure 3. Map of particle release experiments. (A): Particle release pattern, with distances referenced to each eddy center. (B): Particle tracking for an example set of eddies over 4 months in 2008.

in situ platforms within a given time range and distance, typically 3-5 days and 60-100 km. In that case, measurements of U_S were highly uncertain and in general we only used $\Gamma_1(x)$.

Following Graftieux et al. (2001), we defined regions where $|\Gamma_1(x)| > 0.9$ as defining the core of a strong eddy, with positive values cyclonic and negative values anticyclonic, and the extent of the eddy was the region where $|\Gamma_2(x)| > 2/\pi \sim 0.6$.

To diagnose the retentiveness of each eddy, defined as having a core region with $|\Gamma_1(x)| > 0.9$, we advected particles with geostrophic currents deployed in an axially symmetric pattern within a 15 km radius around each eddy center as determined by AVISO altimetry for 60 days (Figure 3). The retentiveness of each eddy was expressed as the amount of time (up to 60 days) that each particle remained in a location where $|\Gamma_2(x)| > 2/\pi$.

A reasonable metric for “mission success” was to find an eddy that retained particles over a 30-day timescale, as this was the length of the EXPORTS-NA field deployment. Using past years' data, we could evaluate what percentage of anticyclones and cyclones succeeded by this metric. Using only eddies that fulfilled a set of thresholds (such as having a core $|\Gamma_1(x)| > 0.9$ and an effective radius of at least 9 km), we found that approximately two thirds of anticyclones and cyclones were “successful” at retaining particles over a 30-day window (Figure 4).

To increase our predictive capabilities beyond this, we gathered a number of other metrics for each eddy to determine how well each of them predicted retentiveness (Figure 5). These other metrics were:

- longitude (*lon*; degrees)
- latitude (*lat*; degrees)
- *time* (yearday)
- *area* (km^2)
- eccentricity (*ecc*; unitless)

- average Γ_2 within the eddy region (*G2*; unitless)
- average Okubo-Weiss parameter within eddy region (*OW*; s^{-2}; Isern-Fontanet et al., 2003)
- backwards retentiveness (*RTback*; days)
- nearest anticyclone (*nearestA*; km)
- nearest cyclone (*nearestC*; km)
- bathymetric *depth* (km)
- translational speed (*trans_sp*; m s^{-1})

Multilinear regression using these metrics resulted in a r^2_{adj} of 0.35 and 0.30 for anticyclones or cyclones, respectively; that is, only about one third of the variance in retentiveness could be predicted using this method. Of all of the metrics, the two that had the highest correlation were area (correlation of 0.23 for anticyclones and 0.09 for cyclones) and backwards retentiveness (0.23 for anticyclones and 0.16 for cyclones). These metrics also contributed the most uniquely to the multilinear regression. This was diagnosed by re-calculating the regression without each metric in turn and evaluating the change in r^2_{adj}. The added variance (that is, the increase in r^2_{adj} when each variable was added back in to the regression) for area was 0.06 for anticyclones and 0.03 for cyclones, and for backwards retentiveness was 0.05 for anticyclones and 0.05 for cyclones; no other variable had more than about 1% unique predictiveness.

For these reasons, operationally we only used *area* and *RTback* to predict forward retention. Using just these two parameters, we were able to predict 33% of the variance for anticyclones and 21% for cyclones. However, this simple two-variable model (and the version with all variables) failed to capture the spread of results; essentially, all eddies were predicted to be good at our 30-day metric (Figure 6).

One way to get more information was to consider which ranges of variables gave any predictive power. For our two predictive variables (area and backwards retention time), we split up the eddies into different ranges of these two variables to consider whether there were threshold values that were better predictors than a

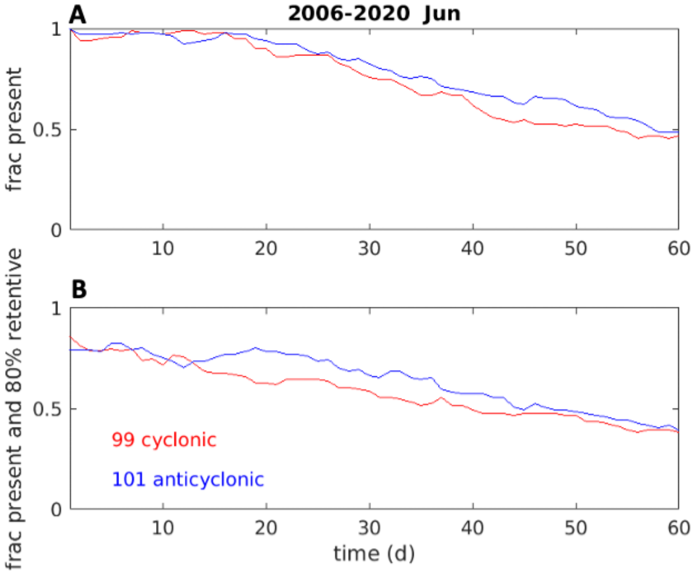

Figure 4. Analysis of eddy retentiveness for eddies present in the study region. Analysis was run from 01 March to 19 July from 2006-2020, and retentiveness is shown during June of each year (A) Rate of eddy disappearance over time, from the first date a given eddy was detected (or from 01 March). (B) Eddy retentiveness over time, where retentiveness here denotes the continued existence of the eddy and at least 80% of the particles (see Figure 3A) retained within.

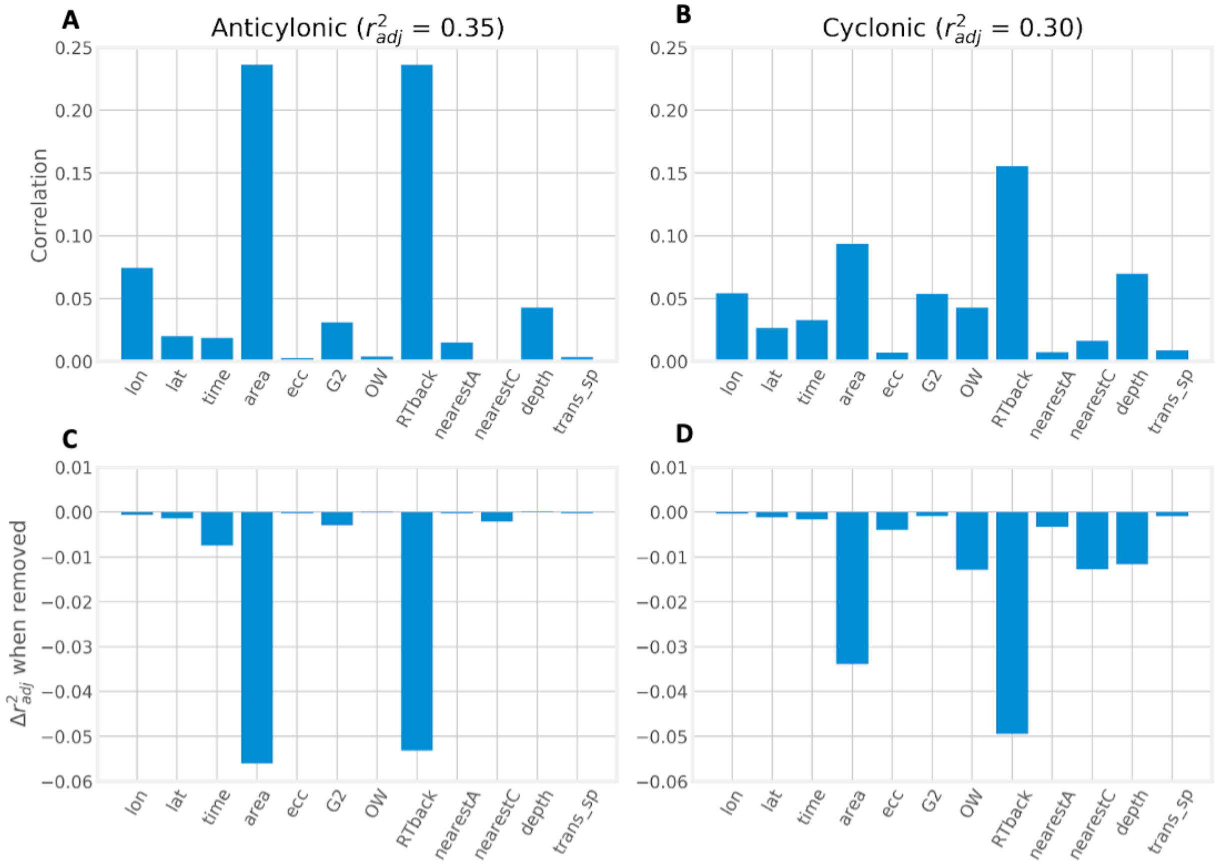

Figure 5. Correlation coefficients for (A) anticyclones and (B) cyclones for each of the 12 parameters. The total correlation when all 12 parameters are included is shown in the title of each panel. The change in the total correlation when each parameter is removed is given in the bottom panels for (C) anticyclones and (D) cyclones.

linear regression (Figure 7). We found that very small eddies (<2000 km^2, equivalent to 25 km effective radius) were likely to be non-retentive, although this may partly be due to the choice of particle locations (Figure 3A), and slightly larger eddies (2000-4000 km^2, 25-35 km effective radius) showed little predictive power. Larger eddies (>6000 km^2, or 45 km effective radius) were likely to be more retentive. For backwards retentive time, there was very little predictive power on the low end; in other words, if an eddy had recently formed there was little indication whether it would persist for long periods or not. However, eddies that had a mean backwards retention time of >50 days were highly likely to still be retentive for well over a month into the future. Based on these results, we initiated a color-coded system based on how likely each parameter was to indicate an eddy with a long forwards retentive time (Table 3).

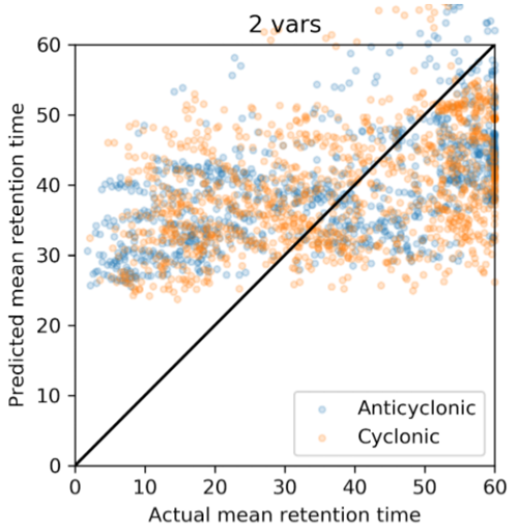

Figure 6. Comparison between calculated and predicted mean forward retention times (days). Predictions were based on two variables (backwards retention time and area).

Table 3. Color-coded system for area/size and backwards retention time.

	Area (100 km^2)	Effective radius (km)	Backwards retentive time (days)
Ideal	>60	>45	>50
Good	40-60	35-45	30-50
Not ideal	<40	<35	<30

4. Method Application

We used past years' altimetry data in a series of "Dry Runs" to test eddy selection process. These Dry Runs were conducted for 2018, 2019, and 2020, as well as within a high-resolution numerical model. We started each Dry Run on 01 April, which was the time at which we expected to deploy gliders near PAP-SO. We then made decisions based on the altimetry data, supplemented with ocean color when available, updated our decisions on 15 April, and made a final "decision" on 1 May. We then looked at altimetry data from 15 May to help determine whether or not we had made the "correct" choice. Each Dry Run is described in the sections below, except for 2020, which was our first Dry Run and several conventions on making and displaying figures had yet to be established.

A surprising result of these Dry Runs was the extent to which eddy characteristics can change on sub-monthly timescales, especially with respect to individual eddy-eddy interactions in the small region studied here. This cemented the importance of having multiple gliders surveying different eddy candidates early on, as this allowed us to have multiple options when some of the eddies dissipated. However, we did note that often our projected glider tracks were optimistic with respect to distance traveled by gliders. While conducting the Dry Runs, we often assumed

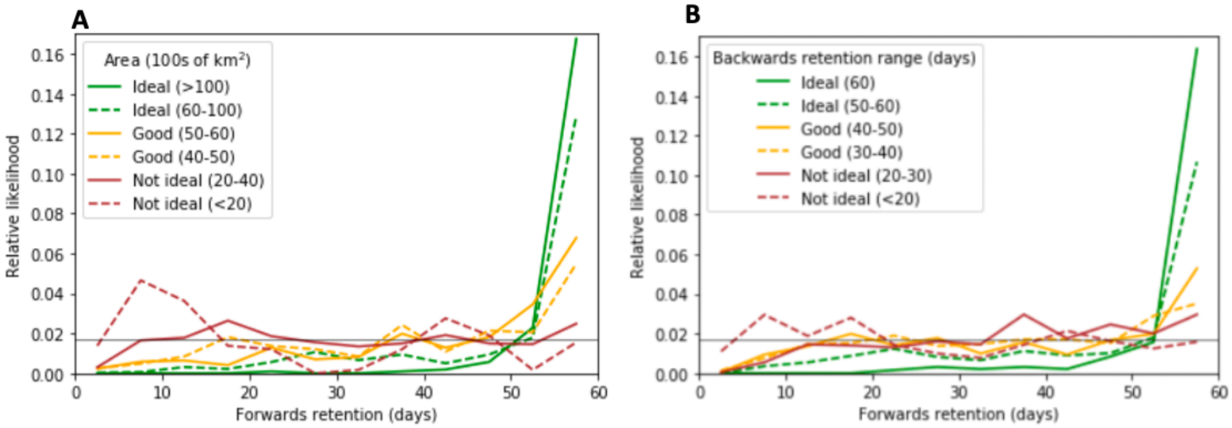

Figure 7. Normalized likelihood of a given eddy retention based on (A) area and (B) backwards retention time, color-coded according to ideal (green), good (yellow), and non ideal (red). Dashed and solid lines differentiate further within these ranges.

glider speeds of about 20 km/day, which is possible but highly dependent on how much the glider is transiting with, rather than fighting against, ocean currents.

The model results were useful in understanding the vertical structure of different eddies. The anticyclones appeared to be strongest, in terms of their interior potential vorticity (PV, defined in Section 4C), at about 400-500 m, suggesting that this is where the eddy would be most retentive. That is, assets deployed at about this depth would be much more likely to be retained in the eddy over long time scales than assets deployed nearer the surface. A modeled cyclone also had a PV anomaly at about that depth, although it was weaker than that of the anticyclone. This could indicate that anticyclones tend to be more stable, as they tend to be associated with stronger PV anomalies. The other interesting feature was that these eddies, both anticyclones and cyclones, were present down to at least 1000 m, which was the deepest depth that we extracted from the model output. These features were therefore quite deep, making it more likely that they would persist for long time periods. These numerical model-derived predictions were subsequently borne out in the *in situ* data (see Sections 5 and 6).

A. 2018 Dry Run

On 01 April 2018, there were a number of promising cyclones and anticyclones in the target region, mostly located south and west of PAP-SO (Figure 8). Using the two-variable regression model described in Section 3, the five eddies that were predicted to be most retentive were:

1. A cyclone at 45˚N, 19˚W (59 days, 100% retention at 30 days),
2. An anticyclone at 46˚N, 20.5˚W (51 days, 87%),
3. An anticyclone at 48.5˚N, 21.5˚W (49 days, 82%),
4. An anticyclone at 47.5˚N, 16˚W (46 days, 77%), and
5. A cyclone at 47.5˚N, 18.5˚W (45 days, 73%).

The first three options were each over 350 km away from PAP-SO; it would take a glider deployed at PAP-SO, traveling an optimistic 20 km/day, over two weeks to reach these eddies. We accordingly focused on eddies *4* and *5*, an anticyclone and a cyclone. However, since the retention prediction for eddy *4* was likely an overestimate, given its deformation, we also decided to look at the two next-best options:

n. A cyclone at 46.5˚N, 16.5˚W (41 days and 66%), and
m. An anticyclone at 48.5˚N, 19.5˚W (35 days and 56%).

With three gliders, we decided to sample *4*, *5*, and *n*; since eddies *4* and *n* both lay directly south of PAP-SO, we sent two gliders to eddy *4*; one would continue on to *n* and the other would next go to *5* (Figure 8).

By 15 April, altimetry in the region had changed significantly (Figure 9). Eddy *4* had decreased in strength, while *5* and *n* were still present and appeared to be good candidates. Another eddy also emerged as a possible contender; an anticyclone that had been between PAP-SO and

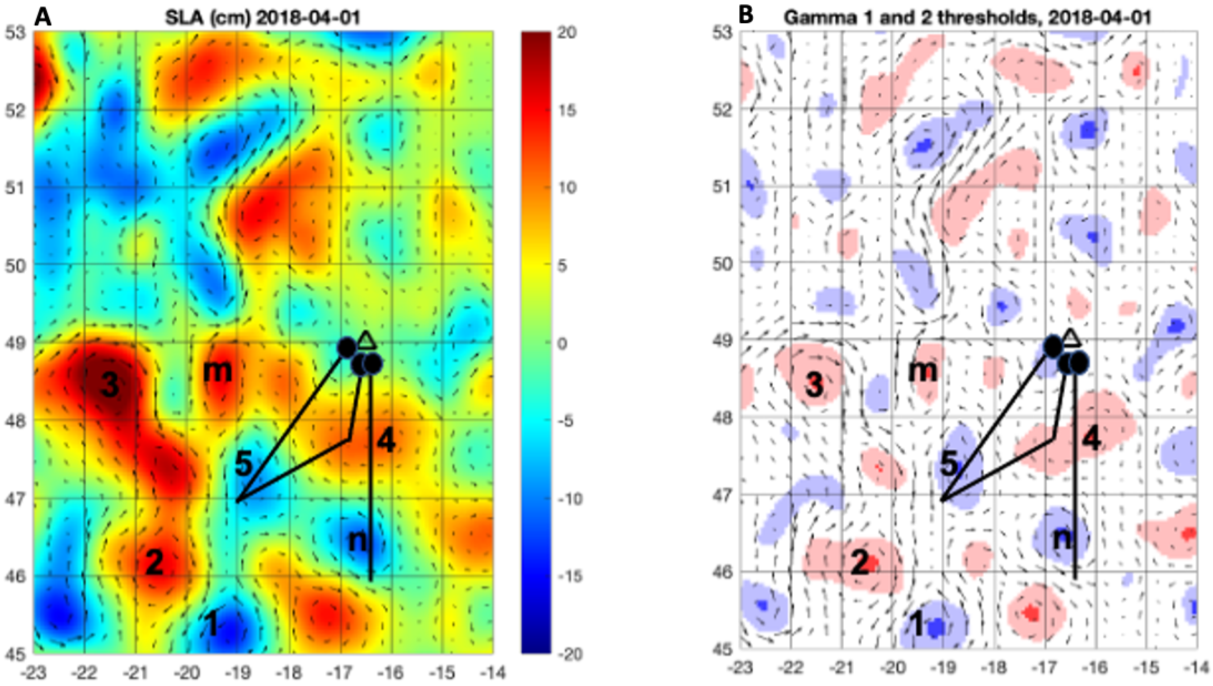

Figure 8. (A) CMEMS sea level anomaly (SLA) and (B) vorticity parameters (see Eq. 1, 2) for 01 April 2018. Areas with Γ_2 greater than $2/\pi$ (less than $-2/\pi$) are shaded in light blue (pink) and denote the extent of an eddy. Areas with Γ_1 greater than 0.9 (less than -0.9) are shaded in dark blue (pink) and denote the eddy core. The black triangle is PAP-SO, black circles denote starting glider positions, and black lines show planned glider trajectories. Numbers and letters refer to named eddies in the text.

eddy *5* had strengthened. We termed this eddy *o*, and decided to send one of the gliders in eddy *5* back through this new feature; indeed, it may have even been sampled previously by the glider transecting directly to eddy *5* from PAP-SO. The other two gliders were tasked to stay in their respective eddies (*5* and *n*) and give transects of the features.

Between 15 April and 01 May, we also had a relatively clear day, and were able to find an ocean color image of the area (Figure 10). Although patchy, this image did appear to show a high-chlorophyll anomaly within eddy *5*, and possibly also within eddies *2*, *n* and *o*.

By 01 May, we would have had gliders sampling eddies *5* and *n* for about two weeks, in which time we likely could have had at least 2 transects of each, and possibly more. In contrast, eddy *o* would only have had at most one transect from a glider. The altimetry data from 01 May also suggested that eddy *o* had significantly weakened (Figure 11), so we were left to decide between eddy *5* and *n*. We ultimately chose eddy *5* because we had stronger evidence from satellite observations that it was in the middle of a chlorophyll bloom; with glider observations this prediction would have been stronger. Eddy *5* was also near a strong anticyclone, which would have provided a useful contrast site or a back-up eddy if eddy *5* were to break up. The strong geostrophic velocities on the western edge of eddy *5*, up to 30 cm/s, would be difficult for gliders to navigate and could provide strong dispersion of the deployed assets on the deployed assets, but would also provide for a strong front that could be scientifically interesting to sample.

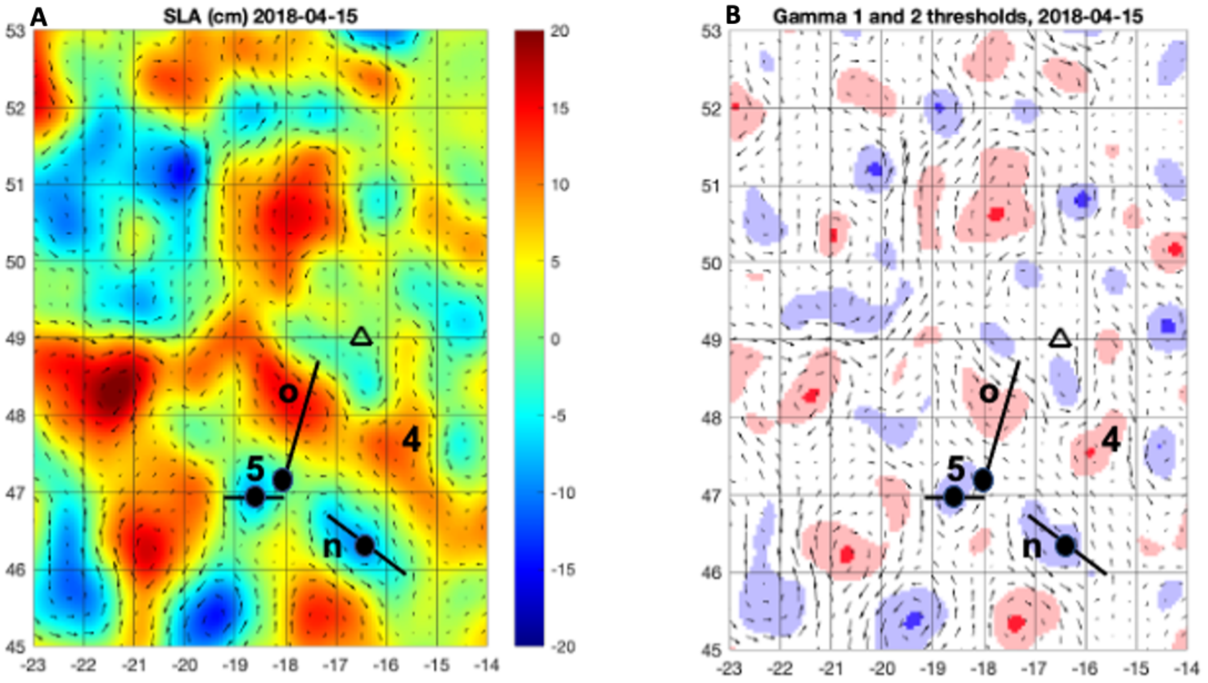

Figure 9. (A) CMEMS sea level anomaly (SLA) and (B) vorticity parameters (see Eq. 1, 2) for 15 April 2018. Areas with Γ_2 greater than $2/\pi$ (less than $-2/\pi$) are shaded in light blue (pink) and denote the extent of an eddy. Areas with Γ_1 greater than 0.9 (less than -0.9) are shaded in dark blue (pink) and denote the eddy core. The black triangle is PAP-SO, black circles denote starting glider positions, and black lines show planned glider trajectories. Numbers and letters refer to named eddies in the text.

There was another, weaker cyclone to the northwest of eddy *5*; it was possible that these would merge and make the eddy stronger. We therefore decided to locate the 2018 "deployment" in eddy *5*. However, we recognized that an interesting-looking cyclone (marked *) was also forming directly south of PAP-SO. This cyclone had been steadily strengthening throughout April. We accordingly recommended that at least one of the ships pass through this eddy to get ADCP measurements.

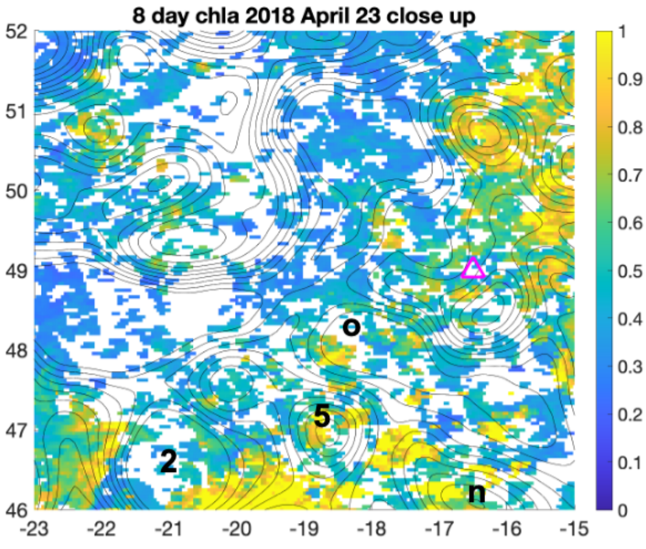

Figure 10. 8-day average chlorophyll-a (mg m^{-3}) from MODIS Aqua starting on 23 April 2018. Numbers and letters reference eddies in the text.

Following the outcome of this exercise, in 2018 the EXPORTS field deployment would have occurred within a cyclone. We looked at AVISO data from 15 May to determine whether or not we made a good choice (Figure 12). These data showed a strong, axisymmetric cyclone that appeared to have merged and strengthened as a result of

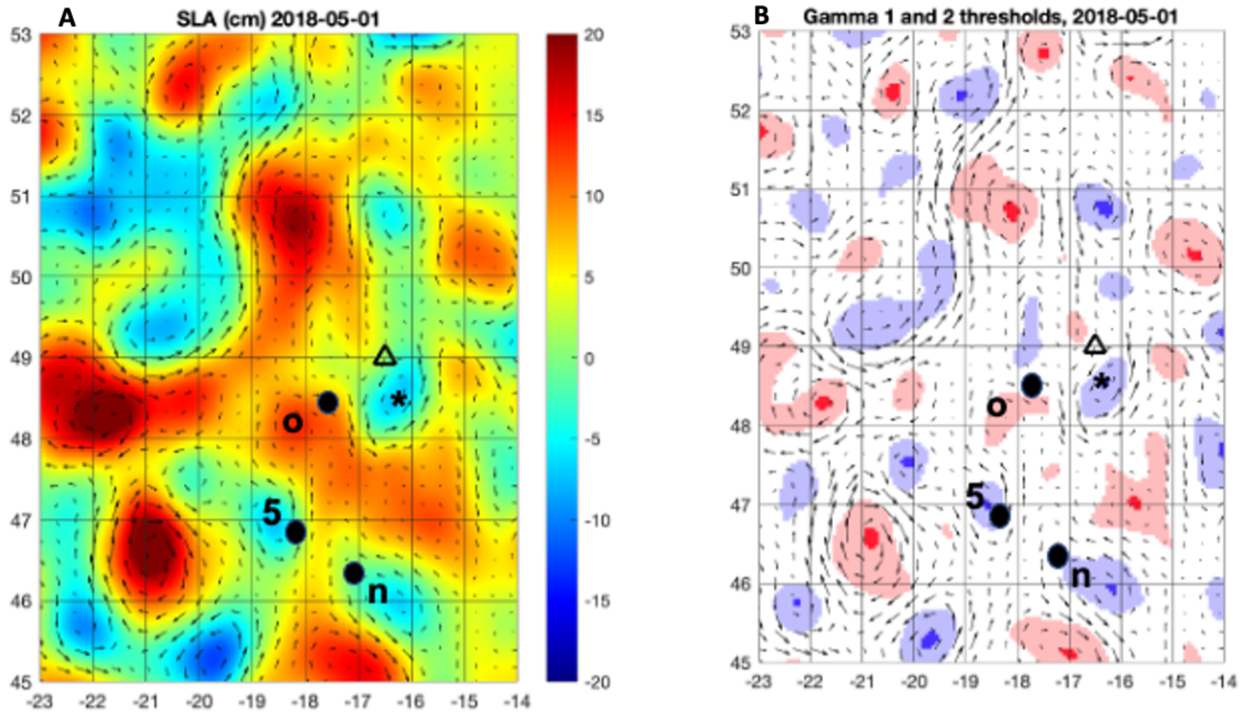

Figure 11. (A) CMEMS sea level anomaly (SLA) and (B) vorticity parameters (see Eq. 1, 2) for 01 May 2018. Areas with $\Gamma 2$ greater than $2/\pi$ (less than $-2/\pi$) are shaded in light blue (pink) and denote the extent of an eddy. Areas with $\Gamma 1$ greater than 0.9 (less than -0.9) are shaded in dark blue (pink) and denote the eddy core. The black triangle is PAP-SO, black circles denote starting glider positions, and black lines show planned glider trajectories. Numbers and letters refer to named eddies in the text.

interacting with the cyclone to its northwest. The anticyclone labeled eddy *2* had also persisted and would have made for a convenient contrasting environment. Eddy *n*, which we had opted to decline, also seemed to be a good choice, although its associated SLA was smaller in magnitude than eddy *5*. We then looked into the future to determine how retentive eddy *5* was. Eddy *5* had a mean retentive time of 60 days (the maximum, as particles were only advected for 60 days) and had 100% particle retention over a 30-day horizon, making it an ideal eddy.

In this dry run, the cyclone that had started to develop directly south of PAP-SO (*) would have made an excellent candidate. This feature was also long-lived, and was located very close to PAP-SO, which would have made the measurements from the long-term mooring very useful. However, in mid-April this feature was barely present, and at the time when we needed to decide where to locate the deployment there would have been no *in situ* glider data of this eddy. We therefore feel comfortable in our decision not to locate the deployment in this feature despite its other merits.

B. 2019 Dry Run

On 01 April 2019, there were a number of strong anticyclonic features in the study area, primarily south and west of PAP-SO (Figure 13). There were also a few cyclonic features

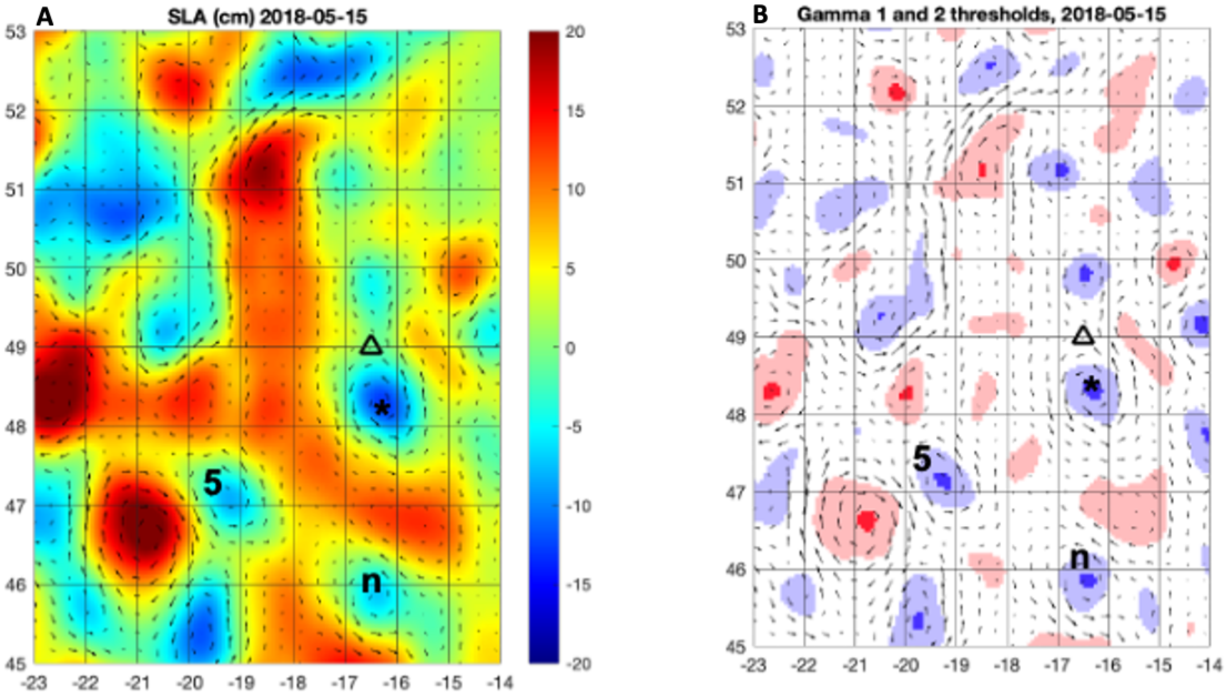

Figure 12. (A) CMEMS sea level anomaly (SLA) and (B) vorticity parameters (see Eq. 1, 2) for 15 May 2018. Areas with Γ_2 greater than $2/\pi$ (less than $-2/\pi$) are shaded in light blue (pink) and denote the extent of an eddy. Areas with Γ_1 greater than 0.9 (less than -0.9) are shaded in dark blue (pink) and denote the eddy core. The black triangle is PAP-SO. Numbers and letters refer to named eddies in the text.

predicted to be retentive, but substantially fewer than anticyclones. The best options predicted by the two-variable regression (Section 3) were:

1. An anticyclone at 47˚N, 20.5˚W (55 days, 91% retentive at 30 days),
2. An anticyclone at 40˚N, 21˚W (53 days, 89%),
3. An anticyclone at 52˚N, 17.5˚W (50 days, 83%),
4a. A cyclone at 48˚N, 19˚W (46 days, 74%),
4b. A cyclone at 46˚N, 16˚W (46 days, 74%),
5a. An anticyclone at 47˚N, 17.5˚W (45 days, 74%), and
5b. An anticyclone at 45˚N, 15˚W (45 days, 74%).

Note that the strongest feature on this map is the cyclone at about 51˚N, 19˚W (marked with an *); in our scheme this eddy wasn't even tracked because it did not have a large enough central vorticity (Γ_1>0.9). We found a number of features throughout past years in this exact area. They

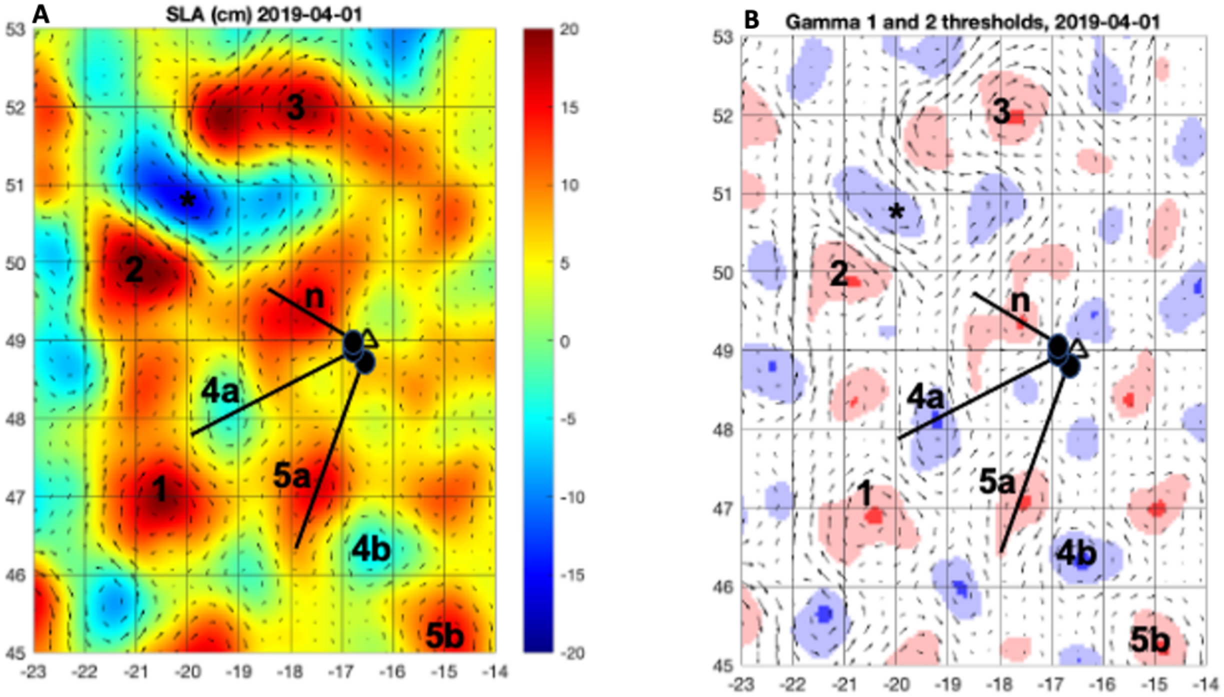

Figure 13. (A) CMEMS sea level anomaly (SLA) and (B) vorticity parameters (see Eq. 1, 2) for 01 April 2019. Areas with Γ_2 greater than $2/\pi$ (less than $-2/\pi$) are shaded in light blue (pink) and denote the extent of an eddy. Areas with Γ_1 greater than 0.9 (less than -0.9) are shaded in dark blue (pink) and denote the eddy core. The black triangle is PAP-SO, black circles denote starting glider positions, and black lines show planned glider trajectories. Numbers and letters refer to named eddies in the text.

were often very strong and moved quickly through the scene in a southeastward direction. Although they persisted for months, there was some uncertainty that they may be an artifact of the gridding used by this particular CMEMS product (Ballarotta et al., 2019).

As in 2018, some of these options were considerably far from PAP-SO, such that a glider transiting to them would take several weeks to reach its target. The two closest candidates were *4a* and *5a*, so we decided to send one glider each to these eddies. Each was about 220 km from PAP-SO, so even these relatively nearby eddies would take a glider transiting at an optimistic 20 km/day 11 days to reach. There was also an anticyclone very close to PAP-SO that wasn't very strong and was awkwardly (*i.e.*, decidedly non-circularly) formed, but would have logistically been ideally placed. We therefore also decided to send a glider to sample this weaker eddy, labeled *n*.

By 15 April, the *4a* eddy appeared to be weakening (Figure 14). Eddy *5a* was still well-formed, so we decided to keep the glider currently sampling that feature in the same region, and spend the next few weeks doing transects at perpendicular angles through the eddy. The glider in *4a* we chose to send to the *n* feature. There were a number of other features in that area that

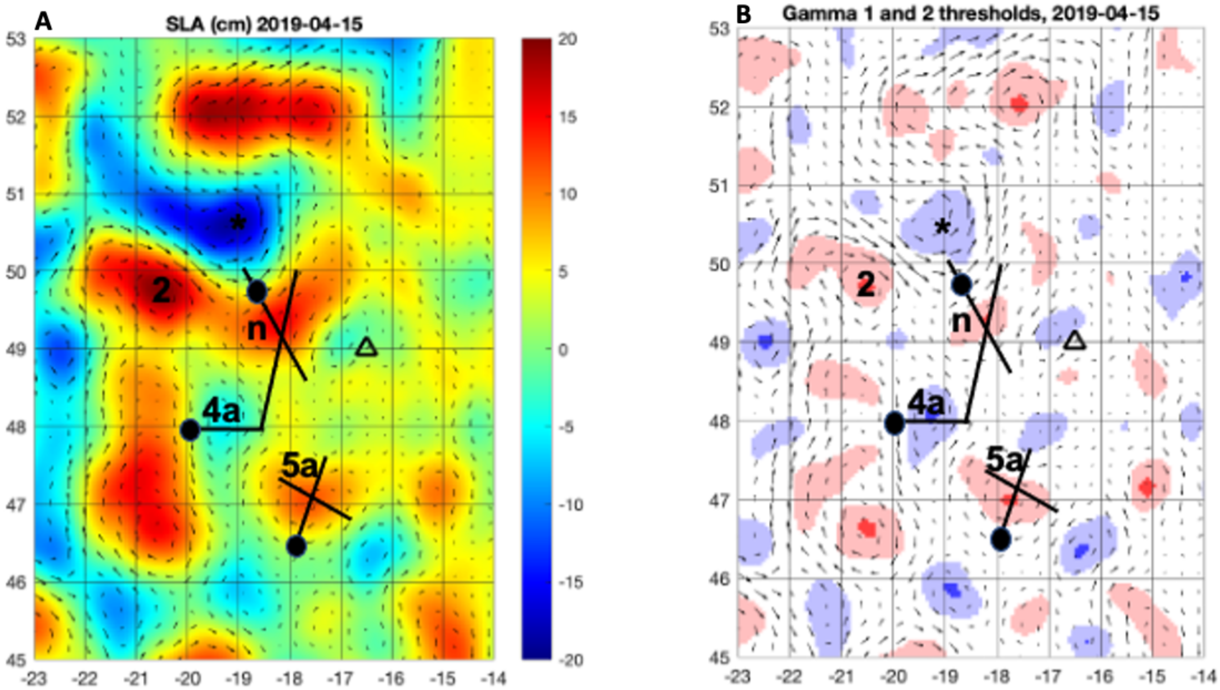

Figure 14. (A) CMEMS sea level anomaly (SLA) and (B) vorticity parameters (see Eq. 1, 2) for 15 April 2019. Areas with Γ_2 greater than $2/\pi$ (less than $-2/\pi$) are shaded in light blue (pink) and denote the extent of an eddy. Areas with Γ_1 greater than 0.9 (less than -0.9) are shaded in dark blue (pink) and denote the eddy core. The black triangle is PAP-SO, black circles denote starting glider positions, and black lines show planned glider trajectories. Numbers and letters refer to named eddies in the text.

seemed interesting, including the large cyclone (*) that had moved considerably far southeast in the previous two weeks.

As in 2018, between 15 April and 01 May we had a relatively clear ocean color image that showed a phytoplankton bloom in eddy *5a* (Figure 15). The area to the west of PAP-SO, where the other gliders were sampling around feature *n*, did not appear to have elevated chlorophyll, although there was an indication of higher chlorophyll in the unnamed cyclone (*).

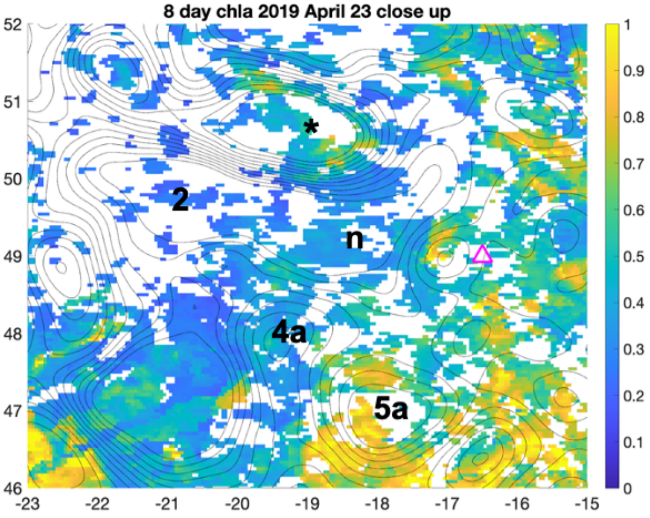

Figure 15. 8-day average chlorophyll-a ($mg\ m^{-3}$) from MODIS Aqua starting on 23 April 2019. Numbers and letters reference eddies in the text.

By 01 May anticyclone *5a* at 47˚N, 18˚W still appeared to be a coherent and retentive feature, and by this point would have been sampled for a few weeks by one of the gliders (Figure 16). The *n* feature had all but disappeared, although the anticyclone labeled as *2* had moved eastward (now at 49.5˚N, 19˚W) and was in a much better position relative to PAP-SO. We re-ran the predictive analysis for the cyclone (*) and *5a*, since these

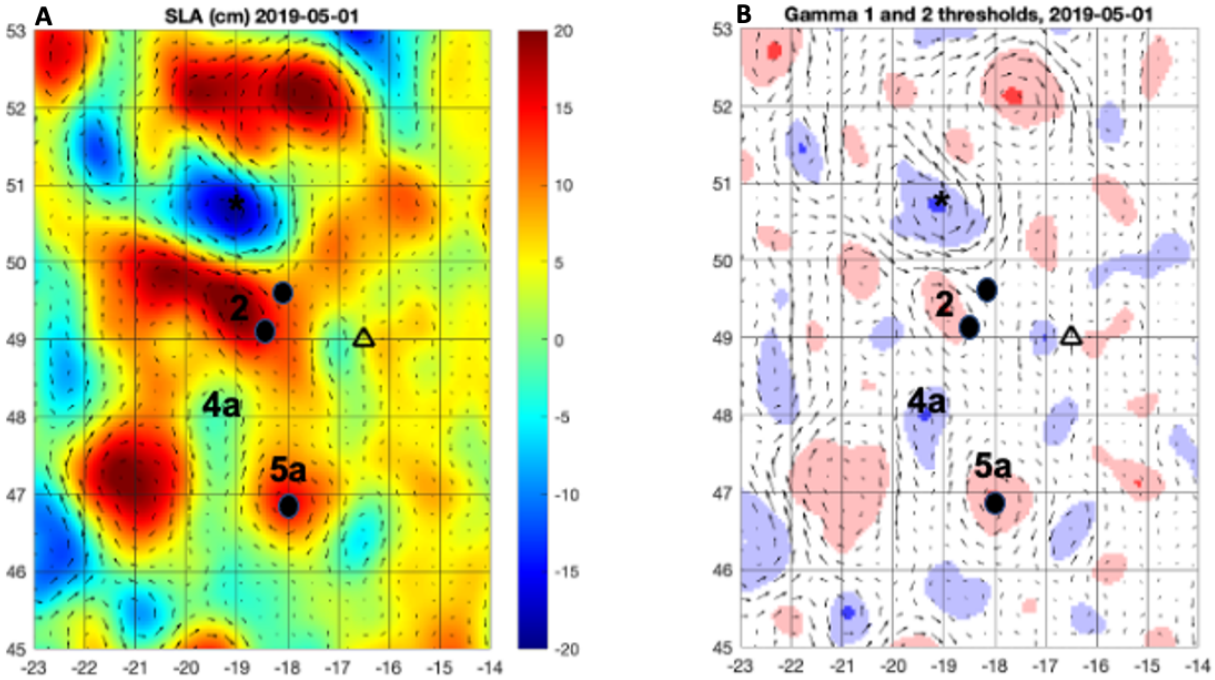

Figure 16. (A) CMEMS sea level anomaly (SLA) and (B) vorticity parameters (see Eq. 1, 2) for 01 May 2019. Areas with Γ_2 greater than $2/\pi$ (less than $-2/\pi$) are shaded in light blue (pink) and denote the extent of an eddy. Areas with Γ_1 greater than 0.9 (less than -0.9) are shaded in dark blue (pink) and denote the eddy core. The black triangle is PAP-SO, black circles denote starting glider positions, and black lines show planned glider trajectories. Numbers and letters refer to named eddies in the text.

were our main contenders. The results were almost identical, with a predicted 49 day mean retentive time (82% over 30 days) for anticyclone *5a* and a predicted 50 day mean retentive time (90% over 30 days) for the cyclone marked *. However, we were still unsure how much to trust this area's altimetry products, and were also worried that the very large velocities on the edge of the cyclone (*), if accurate, would be difficult to navigate with the gliders. Accordingly, we decided to pick the anticyclonic feature *5a* for the field deployment. As the other two gliders were near each other, we decided it would be convenient for one of the ships to pick them up on its way to *5a*.

Our decision was validated by looking at AVISO data from 15 May (Figure 17). Anticyclone *5a*, at 47˚N, 18˚W, was still stable and axisymmetric. The other features northwest of PAP-SO were highly energetic, with large velocities approaching 30 cm/s around their edge, which would have been difficult to navigate with many of the assets. Interestingly, the cyclone (*4a*) at 48˚N, 19.5˚W was still present, despite our prediction that it was fading, and likely would have also been a good area for the experiment. However, circulation around this feature was likely dominated by the surrounding anticyclones, so may still have been more susceptible to shearing forces throughout the experiment, and possible entrance or exit pathways into the area as the surrounding anticyclones moved around the region throughout the month of May (e.g., there appears to be an entrance/exit region on the northwest side of this feature in the 15 May altimetry).

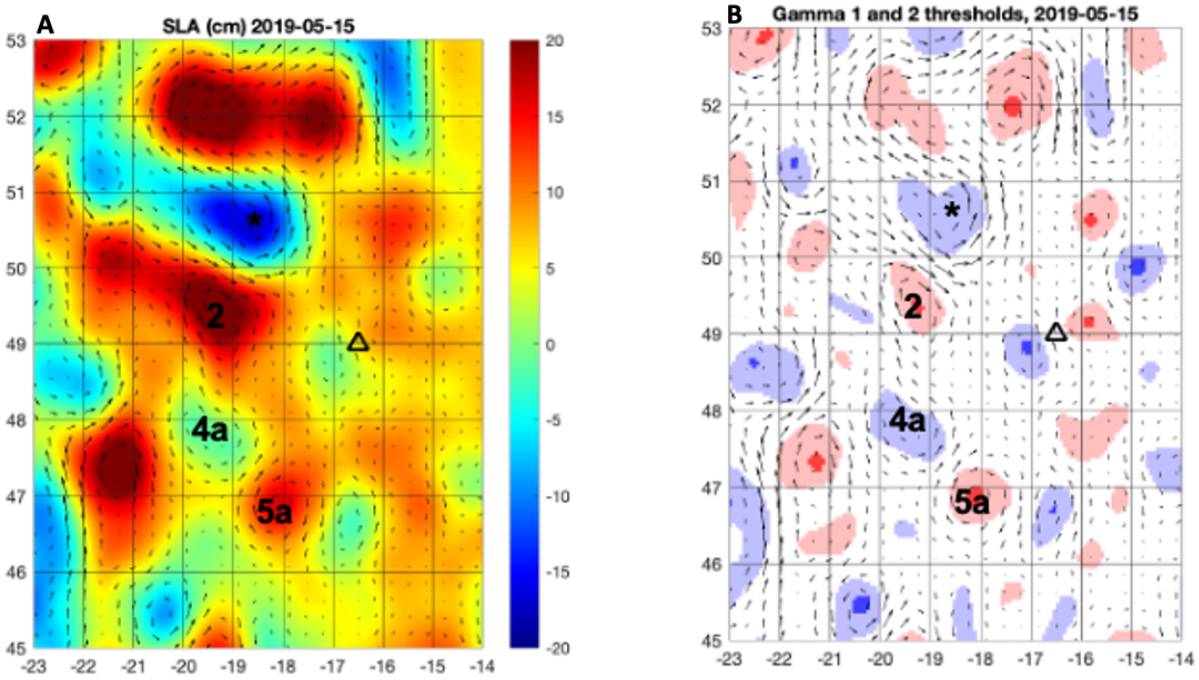

Figure 17. (A) CMEMS sea level anomaly (SLA) and (B) vorticity parameters (see Eq. 1, 2) for 15 May 2019. Areas with Γ_2 greater than $2/\pi$ (less than $-2/\pi$) are shaded in light blue (pink) and denote the extent of an eddy. Areas with Γ_1 greater than 0.9 (less than -0.9) are shaded in dark blue (pink) and denote the eddy core. The black triangle is PAP-SO. Numbers and letters refer to named eddies in the text.

C. Numerical Model

We also used the same approach with output from numerical model output in the region. For this purpose, we used a global run of a 1/48˚ MITgcm, from which we extracted a region near the PAP-SO mooring. This model was spun up from data-assimilating ECCO (Estimating the Circulation and Climate of the Ocean) models and forced using meteorological data from 2011-12, but did not assimilate data during this time period (Menemenlis et al., 2008). Therefore, it was not appropriate to use satellite ocean color or altimetry from this period for this Dry Run. However, we did have access to modeled sea surface height data and temperature, salinity, and horizontal velocities at all depths from the surface to 1000 m, allowing us access to information similar to what would be available from gliders.

An example of the sea level anomaly from this region is shown in Figure 18. The most prominent feature in the region is an anticyclone, about 40 km in diameter, centered on 49.4˚N, 17.1˚W. Interior transects of the eddy (shown in distance from southeast to northwest) show deepening isopycnals all the way to the bottom of this extracted region at 1000 m. The Brunt-Vaisälä frequency, N^2 (s^{-2}), is also shown for the transect, where $N^2=b_z$, the vertical derivative of buoyancy. N^2 is near-zero (white colors) near the surface within the mixed layer. Within the eddy core, step-like changes in density lead to intermittently large N^2, with layers at about 200, 400, and 900 m. The eddy itself is mostly defined by the increase in N^2 associated with the isopycnal

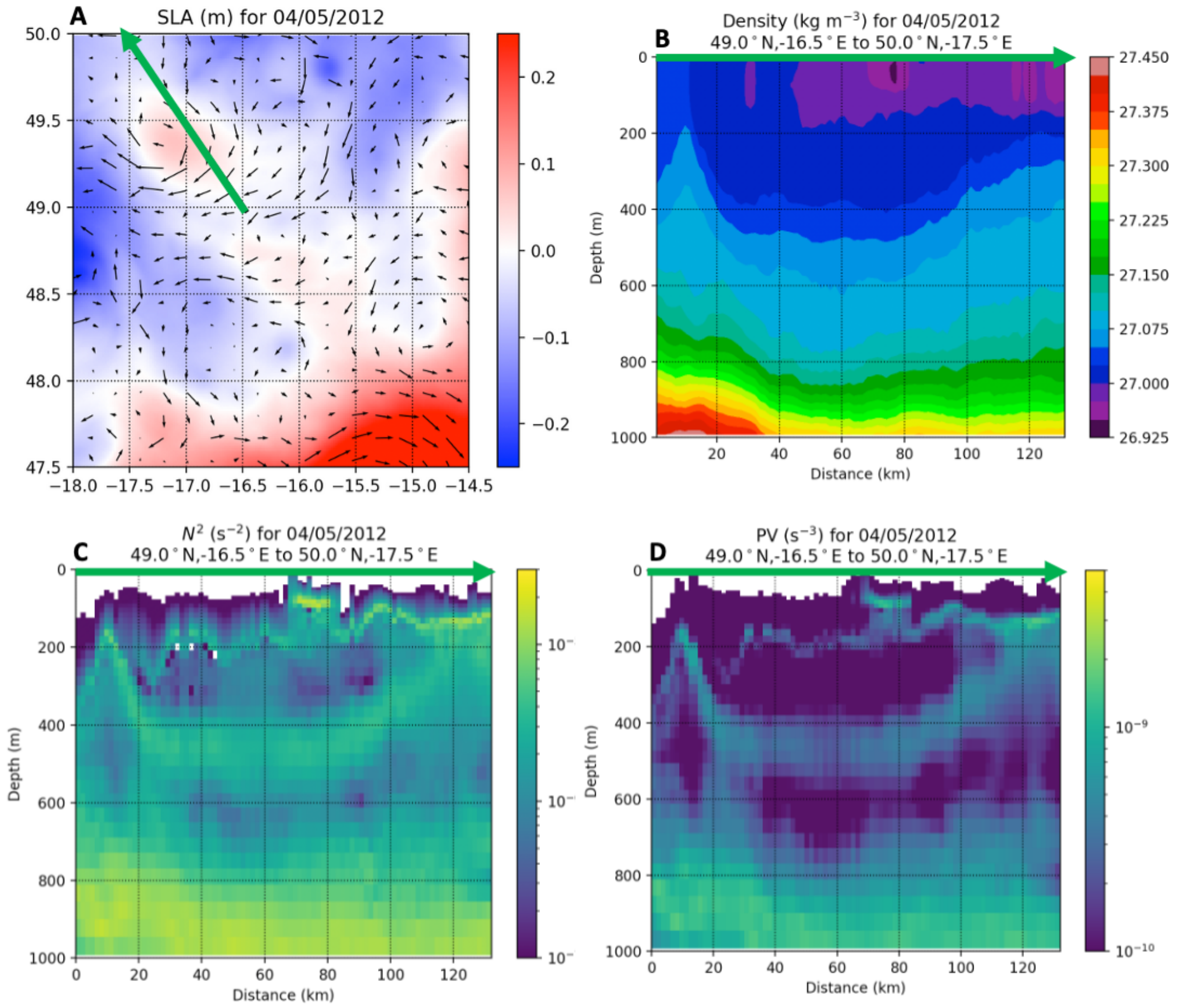

Figure 18. (A) Sea level anomaly (SLA) and depth-averaged velocities from 05 April 2012 in the 1/48˚ MITgcm. Green line gives a sample transect through an anticyclone, with (B) density, (C) N^2, and (D) potential vorticity (PV) shown.

at about 27.05 kg m^{-3}, which deepens from about 200 m at the eddy periphery to about 450 m at the eddy center. We also calculate Ertel potential vorticity (PV):

$$PV = (f + v_x - u_y)b_z + u_z b_y + v_z b_x \qquad \text{(Eq. 3)}$$

where f (s^{-1}) is the planetary vorticity, u and v are the zonal and meridional velocities, b is buoyancy, and subscripts denote partial derivatives (in this equation we have neglected terms associated with gradients in vertical velocity). Variation in PV is dominated by the fb_z term, indicating that if we can measure vertical changes in buoyancy we will have a relatively complete description of the system.

After 10 days, this anticyclone had translated about 50 km northeast and strengthened (Figure 19). A cyclone that was just off the map to the west had also translated eastward into the extracted model region. These two eddies both have sea surface temperature signatures, where

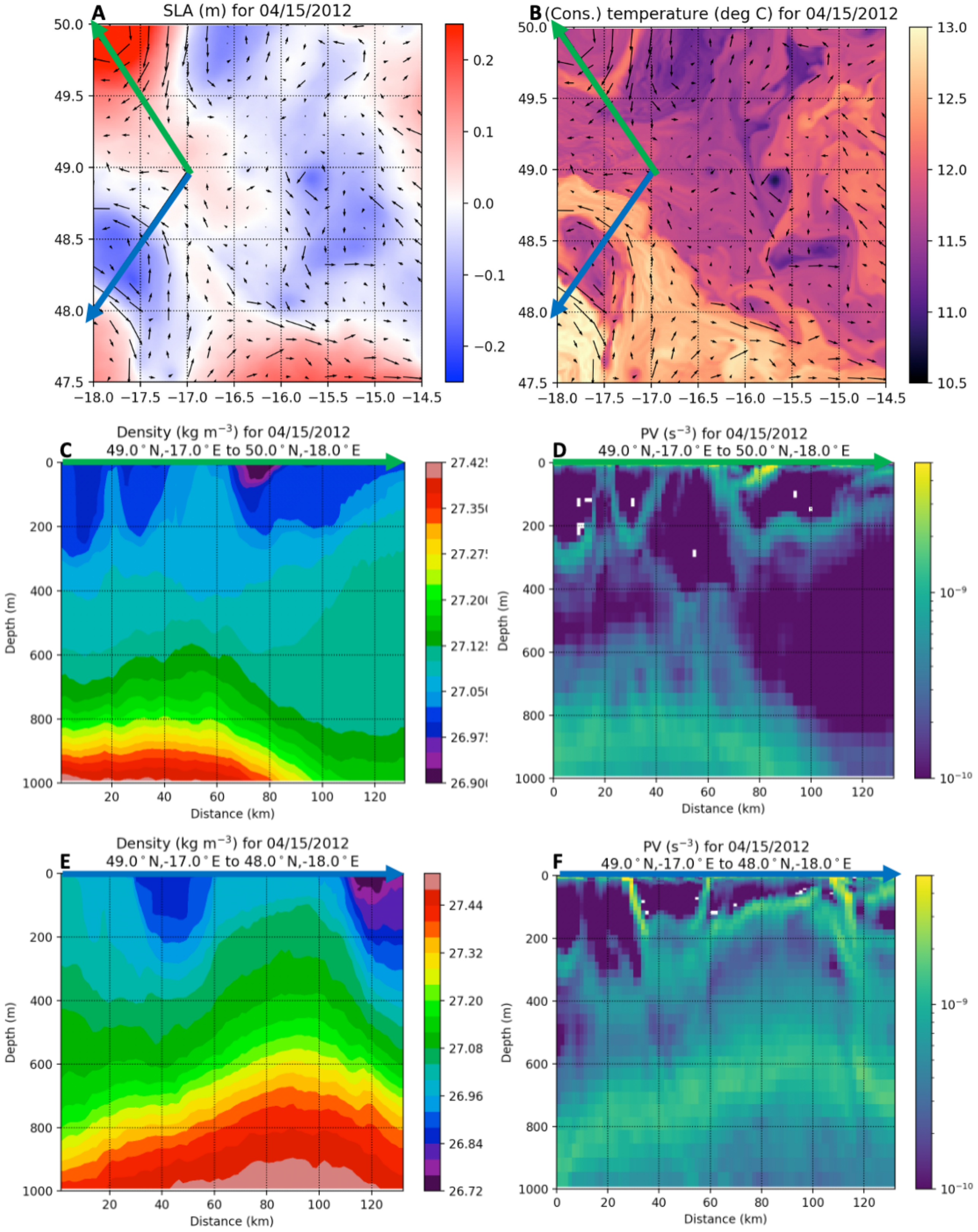

Figure 19. Sea level anomaly (SLA) and (B) sea surface temperature (SST) from 15 April 2012 with depth-averaged velocities in the 1/48˚ MITgcm. Green line gives a sample transect through an anticyclone with (C) density and (D) potential vorticity (PV) shown. Blue line gives a sample transect through a cyclone, with (E) density and (F) PV shown.

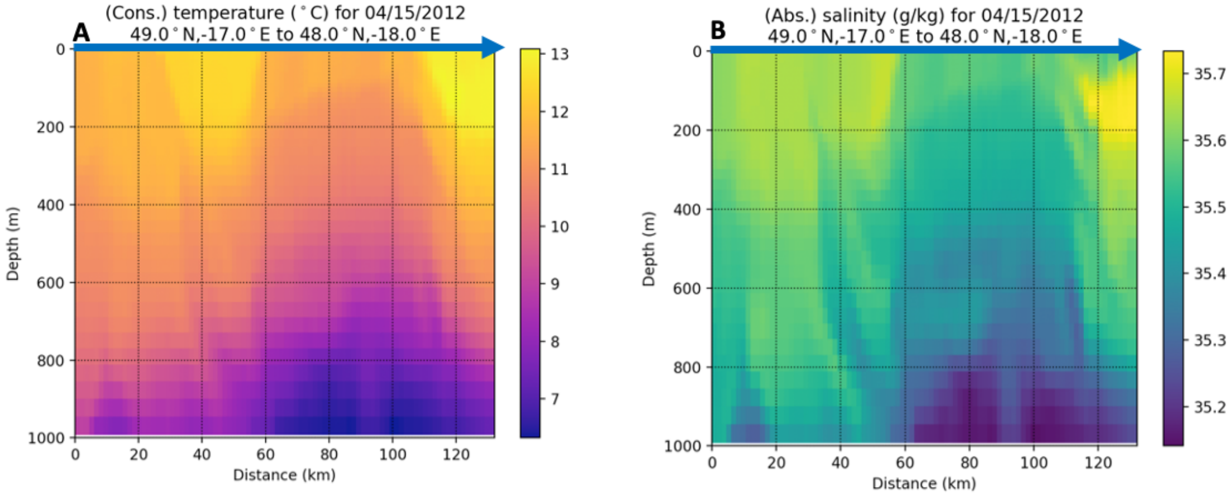

Figure 20. (A) Temperature and (B) salinity from the transect across the cyclone in Figure 19 (blue line).

they are ringed by relatively warmer water, at about 12.5˚C, and have cores with a temperature signature about 1˚C cooler. The cool signature in the anticyclone is initially surprising, as these features typically have warm cores. The interior structure of this anticyclone, however, reveals it to be a mode water eddy, characterized by deepening isopycnals in the interior but shoaling isopycnals near the surface, leading to an eddy core of low N^2 at the sub-surface, here about 500 m. This transect also shows a number of smaller features outside of the eddy, with deepening isopycnals. These smaller features only extend to about 300 m, however, and do not appear to be associated with an eddy-like feature.

In contrast to the mode water anticyclone, the cyclone centered at 48.3˚N, 17.7˚W has consistently upward-sloping interior isopycnals. The deep high-PV layer at about 900 m shoals to 600 m in the interior of this cyclone, and a low-PV region, although not as low as in the anticyclone, is present and centered at about 400 m.

For this cyclone we also looked at the interior temperature and salinity distributions (Figure 20). As expected from the isopycnals and from the sea surface temperature map, the interior of the cyclone was relatively cold, and party density-compensated by higher salinity. On the eddy periphery we also saw intrusions of different water masses, suggesting a possible subduction feature.

5. EXPORTS-NA Eddy selection

A. Eddy tracking, March 2021

On March 19, 2021, approximately two weeks before the launch of the gliders, we began tracking eddies in the general Northeastern Atlantic study region from CMEMS altimetry for the purpose of finding the optimal EXPORTS-NA field deployment site (Figure 21). We mainly looked at three altimetry-based maps in the area: sea level anomaly (SLA; cm), vorticity

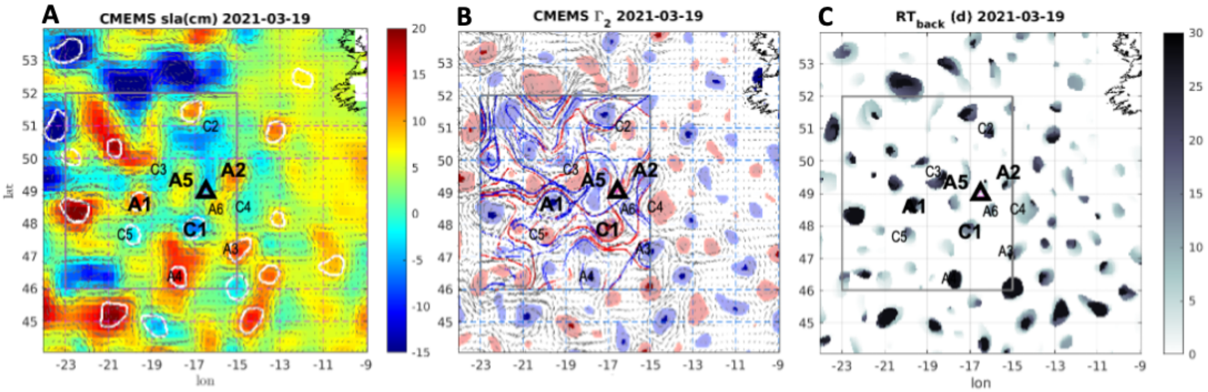

Figure 21. (A) CMEMS sea level anomaly (SLA), (B) vorticity parameters (see Eq. 1, 2) and area of high FTLE, and (C) backwards retention time (RTback) for 19 March 2021. The black box gives the study area. Numbers and letters refer to named eddies in the text. In panel A, contours denote eddies tracked as described in the text. In panel B, areas with Γ_2 greater than $2/\pi$ (less than $-2/\pi$) are shaded in light pink (blue) and denote the extent of an eddy. Areas with Γ_1 greater than 0.9 (less than -0.9) are shaded in dark pink (blue) and denote the eddy core. Darker red and blue colors denote regions of high FTLE (over 0.13 day^{-1}) forwards and backwards in time, respectively. Note the change in color convention in panel B from the 2018 and 2019 Dry Runs.

thresholds (Γ_1 and Γ_2), and backwards particle retention (RTback, days). Our primary data product was from CMEMS, but we also considered a model result from Mercator (http://www.mercator-ocean.fr) and the NOAA CoastWatch/OceanWatch gridded sea level anomaly product (https://coastwatch.noaa.gov/). We were mainly interested in the area from 46–52˚N, 15–23˚W, as this region was easily accessible by ships, near the PAP-SO mooring at 49˚N, 16.5˚W, and off of the continental shelf. On March 19th, we identified three promising eddies:

- *A1*, an anticyclone at 48.8˚N, 19.5˚W;
- *A2*, an anticyclone at 49.5˚N, 15.0˚W; and
- *C1*, a cyclone at 47.9˚N, 17.0˚W.

Of the three, *A1* was the feature with the largest backwards retention; however, *C1* and *A2* were much closer to PAP-SO. A number of other features were also present; we held meetings twice a week through March and many of these eddies were named in subsequent meetings. In all, we tracked 6 anticyclones (*A1–A6*) and 5 cyclones (*C1–C5*). Our last update before starting to deploy gliders was on 29 March 2021 (Figure 22). For each of the named eddies, we tracked multiple properties: longitude, latitude, area, distance from PAP-SO, backwards retention time, whether or not they had an eddy core (as determined by the Γ_2 threshold), predicted retentiveness (using the two-variable method described in Section 3), and whether or not they were surrounded by regions of high strain, calculated using finite-time Lyapunov exponents (FTLEs; Waugh et al., 2012) integrated over four weeks. FTLEs (day^{-1}) are an estimate of the dispersion of particles, and calculations in both the forward (repelling; blue colors on Figures 21 and 22) and backwards (attracting; red colors on Figures 21 and 22) time direction help to identify coherent eddy features (Beron-Vera et al., 2008). For each of these metrics, we color-coded ideal (green), good (yellow), and non-ideal (red) conditions. The results for *A1*, *A2*, *A5* (another eddy in serious contention, partly because of its proximity to PAP-SO) and *C1* are reproduced in Table 4 below for the entire pre-deployment period.

Table 4. Tracking of four of the eddies considered for the EXPORTS-NA Field Deployment during March and April. Green, yellow, and red colors denote ideal, good, and non-ideal conditions (see also Table 3). Sometimes only qualitative observations are given, for these Y/M/N: Yes/Maybe/No, L/M/S: Large/Medium/Small, H/M/L: High/Medium/Low.

A1													
Date	3/19	3/23	3/26[a]	3/29	4/2	4/5	4/9	4/13	4/16	4/20	4/23	4/26	4/30
Lon	19.5	19.5	19.5	19.4	19.2	19.3	19.3	19.3	19.3	19.3	19.3	19.1	19.1
Lat	48.8	48.7	48.7	48.8	48.8	48.8	48.9	48.8	48.8	48.8	48.8	48.7	48.7
predRT (days)			36	32		38	38	37	37	33	34	40	42
dist (km)	220	220	220	210	200	210	200	200	210	200	210	190	200
FTLE	Y	Y	M	M	M	Y	Y	Y	Y	Y	M	Y	Y
area (100 km^2)	S	S	31	34	S	49	50	37	32	22	21	46	57
backRT (days)	M	M	39	25	M	33	33	38	40	36	39	40	40
Eddy center	Y	Y	M	M	Y	Y	Y	Y	Y	Y	M	Y	Y
Notes				Shearing	Weak SLA						Long meander?	Long meander?	
A2													
Date	3/19	3/23	3/26[a]	3/29	4/2	4/5	4/9	4/13	4/16	4/20	4/23	4/26	4/30
Lon	15	15.1	15.1	14.8	14.7	14.7	14.6	14.5	14.6	14.7	14.7	14.7	14.9
Lat	49.5	49.5	49.5	49.6	49.5	49.4	49.3	49.3	49.3	49.2	49.2	49.2	49.2
predRT (days)			29	28	30	34	33	32	34	34	34	38	38
dist (km)	120	120	120	140	140	140	140	150	140	130	130	130	120
FTLE							Y	M	Y	Y	Y	Y	Y
area (100 km^2)	S	S	30	28	30	33	37	29	28	28	31	39	49
backRT (days)	L	M	20	16	22	32	27	28	35	33	33	38	34
Eddy center	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Notes	E of box	E of box	E of box	E of box	E of box	E of box	symmetrical	symmetrical	symmetrical	symmetrical	symmetrical	symmetrical	symmetrical
A5													
Date	3/19	3/23	3/26[a]	3/29	4/2	4/5	4/9	4/13	4/16	4/20	4/23	4/26	4/30
Lon	17.3	17.3	17.3	17.3	16.9	16.8	17.0	17.2	16.9	17.0	16.9	17.0	17.1
Lat	49.2	49.2	49.2	49.2	49.3	49.2	49.1	49.0	49.1	49.0	49.1	49.0	48.9
predRT (days)					33	33	36	36	34	39	37	35	32
dist (km)	60	60	60	60	50	30	40	50	30	40	30	40	50
FTLE	M	M	M	M	M	M	M	M	Y	M	M	M	M
area (100 km^2)	M	M	M	M	46	43	51	40	56	56	37	35	26
backRT (days)	L	L	L	L	21	22	27	31	18	32	38	34	31
Eddy center	N	N	N	N	Y	Y	M	N	N	Y	Y	Y	N
notes	Sheared	Sheared	Eccentric	Eccentric			Has a meander?	Weak SLA, weak OW	Asymmetrical, weak SLA	Weak SLA			Weak SLA
C1													
Date	3/19	31/23	3/26[a]	3/29	4/2	4/5	4/9	4/13	4/16	4/20	4/23	4/26	4/30
Lon	17.0	17.0	17.0	17.1	17.1	17.0	17.0	16.5	16.5	16.4	16.2	15.9	15.9
Lat	47.9	48.0	48.0	47.9	48.0	48.0	48.0	48.1	48.1	48.1	48.1	48.4	48.4
predRT (days)			38	40	39	42		30	38	36	33	28	34
dist (km)	130	120	120	130	120	120	120	110	100	100	100	80	70
FTLE	Y	M	M	M	M	M	M	M	M	M	M	M	M
area (100 km^2)	M	B	62	65	56	74	B	35	39	30	21	41	36
backRT (days)	L	L	20	26	27	26	M	13	34	33	29	4	24
Eddy center	Y	Y	Y	Y	Y	Y	N	M	Y	Y	N	N	N
Notes							Weak SLA	Elongated			Weak SLA	Weak SLA, western C1 is better	Weak SLA

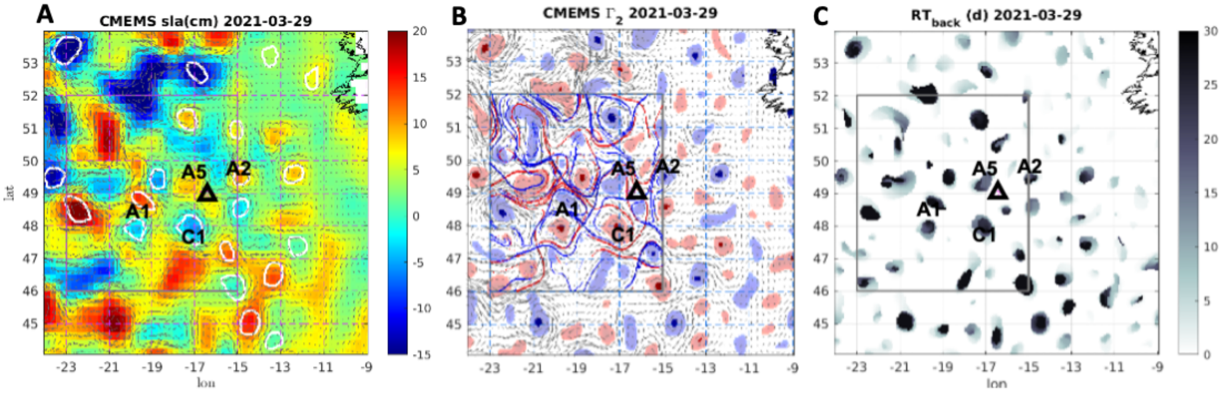

Figure 22. (A) CMEMS sea level anomaly (SLA), (B) vorticity parameters (see Eq. 1, 2) and area of high FTLE, and (C) backwards retention time (RTback) for 29 March 2021. The black box gives the study area. Numbers and letters refer to named eddies in the text. In panel A, contours denote eddies tracked as described in the text. In panel B, areas with Γ_2 greater than $2/\pi$ (less than $-2/\pi$) are shaded in light pink (blue) and denote the extent of an eddy. Areas with Γ_1 greater than 0.9 (less than -0.9) are shaded in dark pink (blue) and denote the eddy core. Darker red and blue colors denote regions of high FTLE (over 0.13 day^{-1}) forwards and backwards in time, respectively. Note the change in color convention in panel B from the 2018 and 2019 Dry Runs.

The first instruments deployed during the EXPORTS-NA field deployment were the three gliders, which were deployed from a cruise preceding the NA EXPORTS cruise aboard the *RRS Discovery* (DY130) on a mission to service the PAP-SO mooring (see also Table 1). The gliders were deployed at the location of the mooring, 49˚N, 16.5˚W, and piloted to different eddies: *C1*, *A2*, and *A5*.

B. Eddy summaries as of 01 April

The following summaries were generated by the entire eddy tracking team when deciding where to deploy the gliders, and have been lightly edited.

C1: At the beginning of April, *C1* was a dominant feature near PAP-SO. However, it showed up strongly in CEMEMS altimetry but much less strongly in Mercator modeling or in the NOAA altimetry product. Part of the reason to send a glider to sample *C1* was to resolve this discrepancy in the different products. *C1* was also located in the southern part of the region we were considering, and the glider that was sent to *C1* would therefore be in a good position to potentially target *A4*, a dominant feature in Mercator data, in the southwest or *A3*, a potentially strong eddy candidate in the southeast.

A2: At the beginning of April, *A2* was a contender mainly because it had been steadily growing stronger over the past few weeks. Even though our metrics put it at a “not ideal” eddy (red colors) in March, we could see it strengthening and its relative isolation from other features made it less likely that this eddy would be interacting with other eddies that could shear it out or cause it to merge with another eddy. Despite its relatively short predicted retention time, we considered this our strongest possibility and therefore chose to pilot a glider in this direction.

A5: At the beginning of April, *A5* was a contender mainly because it was very close to PAP-SO. This feature was not particularly strong, but we decided that we could relatively quickly get a transect of this eddy and then, if it was not promising, move the glider to another target.

C. April narrative

During April, the eddy tracking team continued to meet biweekly to consider new satellite imagery and glider data and to decide where to pilot the gliders to maximally sample each prospective eddy (e.g., Figure 23). During April we managed to get initial transects of each of these features. Initial subsurface data from *C1* (SG219) failed to show clear signs of an eddy-like feature where expected from the altimetry (Figure 24); however, it then appeared from updated altimetry that this eddy had broken up into two features to the east and west, and the glider transect had bisected through this split. We therefore determined to try another, west-to-east transect through the eastern part of the eddy, which would also bring this glider near *A2*. This data also did not show a significant eddy-like structure in *C1*.

The glider tasked with sampling *A5*, SG237, developed issues early on with its salinometer. Although this appeared to resolve itself after a few days, we remained wary of this instrument until it was able to be calibrated with respect to other platforms; preliminary analysis against biogeochemical (BGC) floats in the area suggested an offset in practical salinity of about 0.4. Altimetry suggested that *A5* was starting to merge with another feature and was quite weak. Remembering lessons learned from our Dry Runs (Section 4), we piloted SG237 west towards another candidate: *A1*, the first anticyclone identified in altimetry in March. This feature had become less promising because it was far away from PAP-SO and the other candidates; however, we decided it could be a strong candidate for a backup eddy during the deployment if necessary (Figure 25).

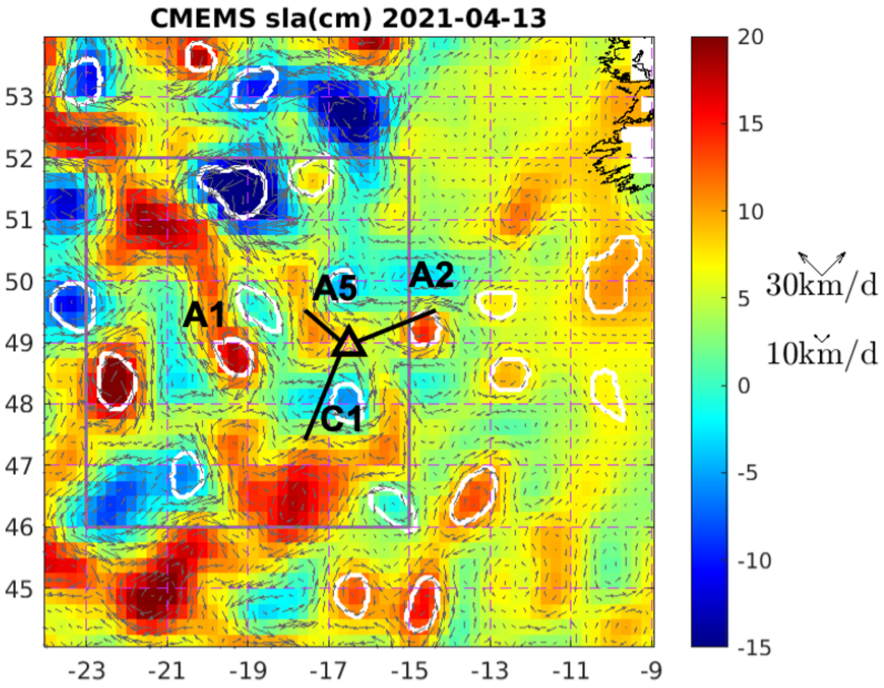

Figure 23. CMEMS sea level anomaly (cm) for 13 April 2021 with geostrophic velocities (arrows). The black triangle denotes PAP-SO, and the three lines are the planned glider trajectories following deployment in early April of gliders at PAP-SO. White contours denote tracked eddies. Black text indicates the eddies described in the text.

Data from the initial transect of *A2* indicated a subsurface potential vorticity minimum that suggested a long-lived eddy core that would be difficult to erode (Figure 26, see also analysis from Section 4C). The eddy center according to CMEMS altimetry also appeared consistent with the *in situ* data from the glider, which indicated sloping isopycnals associated with an eddy edge out to about 50 km from the altimetry-determined center, which was also where CMEMS altimetry-based tangential velocities were largest (Figures 26, 27). Glider-based chlorophyll fluorescence estimates suggested that this eddy was in the middle of a bloom, with values of about 3 µg/L measured, although the maximum chlorophyll values were near the edge of the eddy rather than the center.

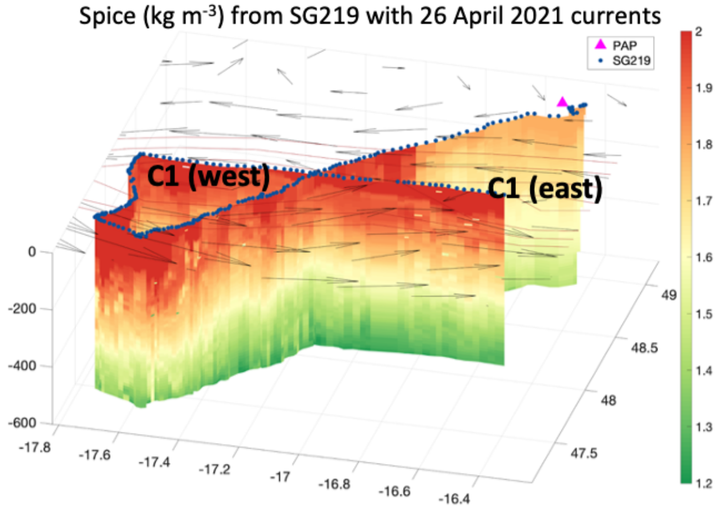

Figure 24. Spice over the upper 600 m of the water column from SG219 during its initial transect of C1. This eddy was later determined to have split into an east and west component. Each blue dot is a profile and spice is interpolated. CMEMS geostrophic currents are shown at the surface (arrows).

As we neared the end of April, we needed to make a decision on where to go for the field deployment. Our main choices were cyclone *C1*, anticyclone *A1*, and anticyclone *A2*. Summaries for each eddy were produced, and are copied below. Based on the data provided, we recommended and ultimately chose eddy *A2* as our location for the EXPORTS-NA field deployment. At the time of the start of the main part of the deployment, two gliders were at *A2*, and the third was still sampling *A1* (Figure 28).

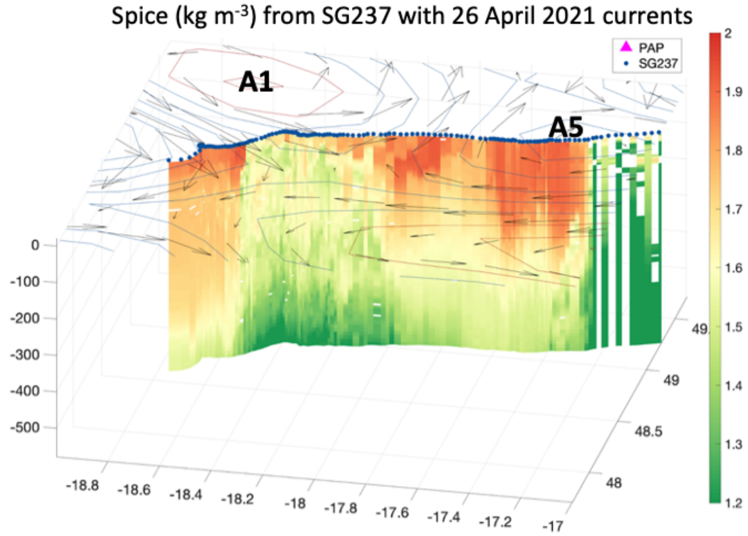

Figure 25. Spice over the upper 600 m of the water column from SG237 during its initial transects of A5 and A1. Each blue dot is a profile and spice is interpolated. CMEMS geostrophic currents are shown at the surface (arrows).

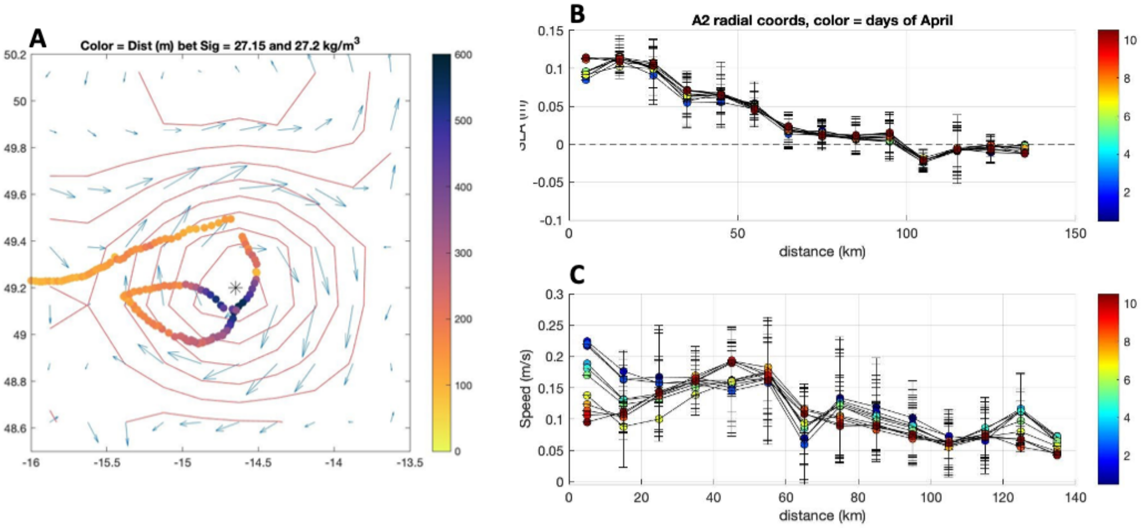

Figure 26. (A) Glider transects of eddy A2 over 01-10 April 2021. Colors show the width of the isopycnal layer between 27.15 and 27.2 kg m^{-3}. Black contours (arrows) give CMEMS altimetry (geostrophic velocities), and the asterisk marks the location of the eddy center. (B) CMEMS sea level anomaly (SLA) and (C) tangential speed for the first 10 days of April (colors) referenced to the eddy center.

D. Eddy Selection Proposal

The following recommendation was prepared by Eddy Tracking Team and shared with the broader EXPORTS group on a "Situational Awareness" WhatsApp channel for discussion. It has been lightly edited here. This submission opened a 24-hour discussion and comment window for the entire community. Following that period, with no dissenting voices, we chose A2 *as the eddy to study in the EXPORTS-NA field deployment.*

Proposal for selecting feature to study: We propose to conduct the North Atlantic EXPORTS campaign in an anticyclonic eddy, labeled *A2*, located at approximately 49.1˚N, 14.9˚W. *A2* is a small, axisymmetric feature that has been stable for the past month. *A2* has also been transected multiple times with a Slocum glider, SL305, meaning we have considerable prior information about this eddy going into the main experiment. Our rationale and methodology follow.

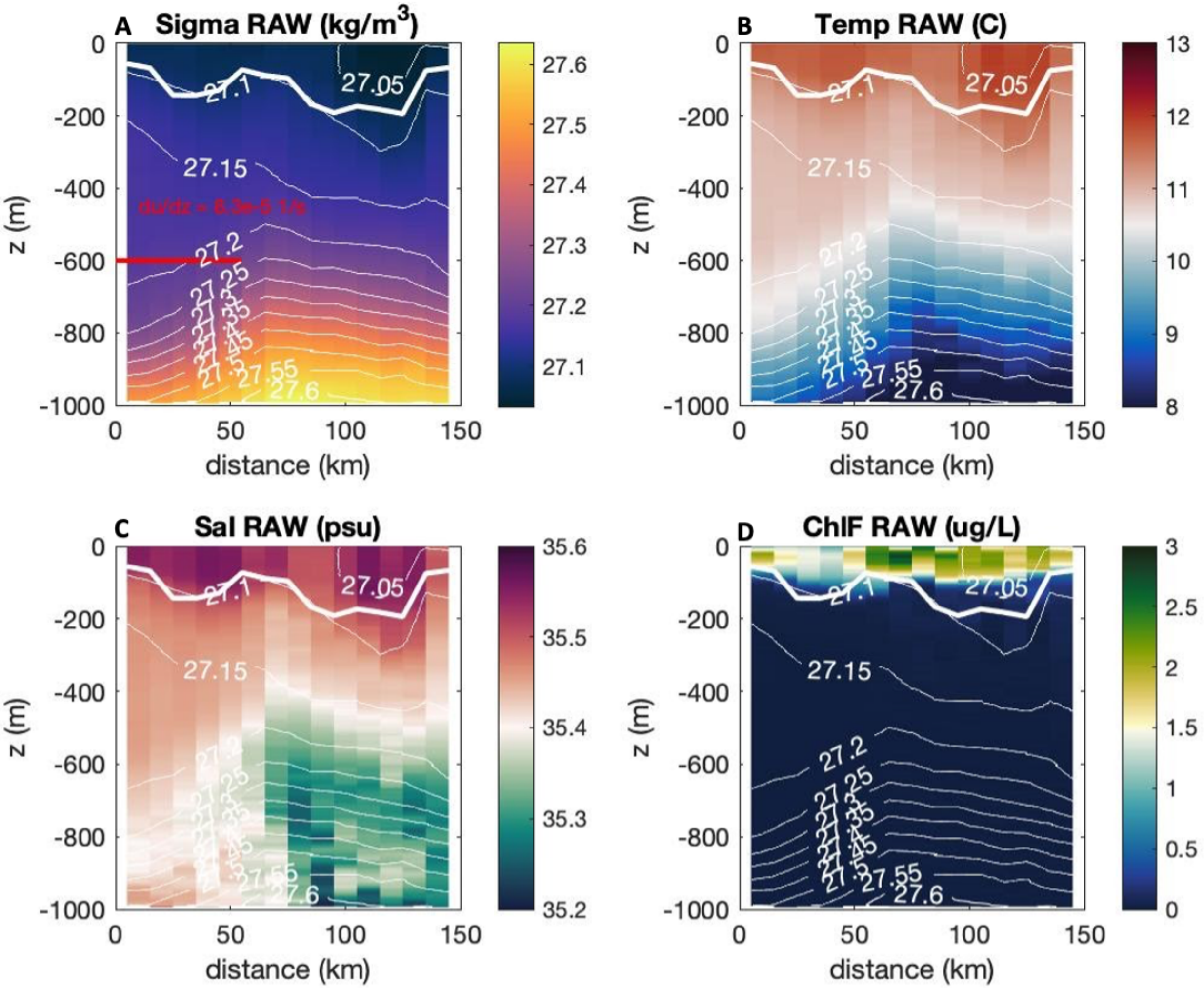

Figure 27. Averaged and interpolated in situ glider (A) potential density (Sigma), (B) temperature (Temp), (C) salinity (Sal), and (D) chlorophyll fluorescence (ChlF) referenced to the A2 eddy center (see also Figure 26). Bold white lines give the mixed layer depth, and thin white lines are contours of potential density.

Methodology: At the beginning of April, the eddy tracking team decided to send three gliders to three different eddies: two anticyclones (*A1* and *A2*) and one cyclone (*C1*). These eddies were chosen based on an analysis over the previous weeks using altimetry data and numerical models of the region. This analysis included all sizable features seen in altimetry in the area around the PAP-SO mooring. Metrics considered included 1) ability to retain particles & drifting assets throughout the experiment, 2) ecological / biogeochemical state, and 3) logistic constraints. These are listed below. Throughout April we have continued to look at altimetry data, satellite-based ocean color, and *in situ* glider data. We compared these metrics for the three features we have sampled using the gliders (*A1*, *A2* and *C1*). Feature *A2* is discussed here in more detail as we have the most measurements from this feature.

Retentiveness: Feature *A2* has been a long-lived anticyclone, emerging in early March and growing with intensity through early April. It has been stable since. It is a rather small (radius of ~50 km), axially symmetric feature that has a well-defined and stable center (defined using an altimetry-based analysis of how rotational the flow around the center is). The core is in approximate solid body rotation (according to CMEMS altimetry) with maximum velocity of about 0.2 m/s (according to glider depth-averaged currents and altimetry) at ~40 km from the center. It has strong sea level anomaly gradients and relatively high Chl values (see below) at the edges, making it an exciting feature to address physical pump export pathways that were not seen in the 2018 North Pacific experiment. The center of *A2* is moving at about 1 km/day to the south, according to altimetry data, which is consistent with glider depth-averaged currents. According to glider (SL305) data, *A2* is a mode water eddy, where isopycnals dome upwards above 400 m, with a deep core where isopycnals are still doming downward at 1000 m. Around 19 April, MLDs shoaled to <30 m within and outside of the eddy, after being nearly 200 m deep earlier this month.

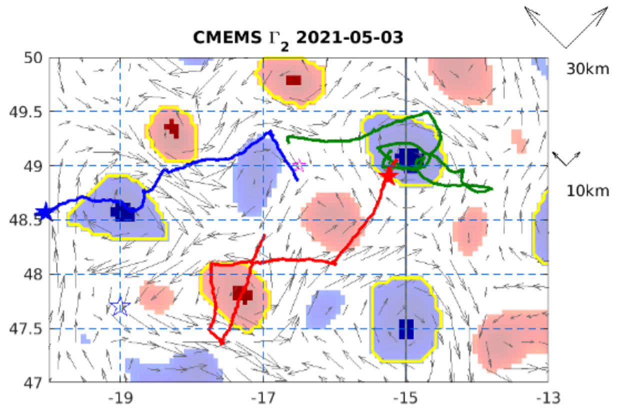

Figure 28. Glider tracks during April (lines) and positions at the start of the EXPORTS-NA field deployment (stars). The eddy chosen for the deployment is at 49˚N, 15˚W. Arrows give CMEMS-based geostrophic velocities, and colors show the vorticity parameters as in Figures 21 and 22,

In comparison with *A2*, *A1* is similarly long-lived and similarly retentive, from a CMEMS altimetry-based analysis. *A1* has not been transected as many times as *A2*, but a recent glider transect from the edge to the center revealed broadly similar features. *A1* is larger than *A2* and probably has somewhat stronger velocities at its periphery (glider depth-averaged currents were up to 0.4 m/s). The “core” of *A1* is less well-defined by altimetry, but this feature appears to be fairly stationary.

Since we first sent a glider to *C1* in early April, this eddy has divided into two cyclonic features, to the east and west. The one we chose to sample with the glider weakened according to CMEMS altimetry, although different altimetry-based products in this region give qualitatively different features, making CMEMS altimetry less reliable for this eddy. We have not seen substantial evidence from glider sampling that a strongly retentive eddy feature exists here.

Ecological / biogeochemical state: It is difficult to make definitive statements based upon raw, uncalibrated glider data or from incredibly sparse satellite ocean color imagery. We do know that *A2* shows elevated Chl and backscatter around its periphery (maybe following the high velocity core) and a center with slightly reduced Chl levels. This pattern has been seen in both satellite and glider observations. The few good ocean color observations suggest that *A2*’s surface Chl in the periphery are likely 1-2 mg/m^3. Contrasting this, recent satellite ocean color observations from *A1* are somewhat elevated and more uniform from the core past the edge of the feature. The nearby PAP mooring has shown periods of elevated surface Chl concentrations in early April followed by a reduction and now an increasing trend (now ~1 mg/m^3). The PAP-SO mooring also shows a reduction in NO_3 levels throughout the month but still elevated (although there is likely an offset issue, since values [15 uM] seem too high to be correct). Glider-determined 1% PAR [photosynthetically active radiation] depths are a calibration-independent measure of upper ocean bio-optical quantities. Depths of the 1% PAR isolumes are 40-50 m in all three eddies sampled. In summary, there is scant data currently available to distinguish between the three different eddy candidates. Given expectations of high nutrient levels from the PAP-SO mooring, substantial evolution in the ecological /biogeochemical state of all eddies is likely. To date, we have observed strong patchiness in the glider bio-optics and ocean color data, with small blooms forming above regions of shallow mixed layers. The biomass metrics integrated over depth have remained fairly constant, suggesting that the spring bloom may ramp up over the coming weeks. And in fact, yesterday's SL305 transect across *A2*'s core shows a significant increase in ChlFl, oxygen, and backscatter in the core. This transect is ongoing, but there is evidence of a very recent increase in biomass in *A2*.

A2 is somewhat close to the continental shelf, although is still at least 100 km west. It does not appear to be moving eastward, and the eddy tracking group does not believe that we are at significant risk of *A2* running up onto the shelf during EXPORTS. We have not observed clear optical signals of high backscatter at depth in the glider data, so we are likely not close enough in this feature to see sediments from the continental shelf.

Logistics: *A2* (49.1˚N, 14.9˚W) is the closest feature to port. *A1* (48.7˚N, 19.1˚W) is about 300 km west of *A2*. The position of *C1* is difficult to define, given that it recently split in two, but is at least 80 km southwest of *A2*. *A2* is the smallest of the three candidate eddies, making it easier and quicker to sample spatially with ships and gliders. However, this also means that we have a smaller area to deploy traps and other assets to make sure they stay within the eddy. One glider is currently transecting *A2*, and another is en route, and will reach *A2* by the start of EXPORTS. The third glider is currently transecting *A1* and will take several weeks to reach *A2*. If we choose *A2*, we propose to not pick up this third glider. If we choose another eddy, we may need to pick up one or more of the gliders near *A2* to get them to the other eddy. There is a cyclone developing within <100km of *A2* that could be sampled as part of the scouting expeditions conducted by the Survey Ship (DY131).

6. Eddy tracking during deployment

During the main part of the EXPORTS-NA field deployment, the main job of the shore-based EXPORTS eddy tracking team was to provide updates on the location and strength of the EXPORTS eddy, and also to monitor nearby eddies in case the assets needed to be re-deployed in a different location. Throughout the deployment, ADCP (Acoustic Doppler Current Profiler) and CTD (Conductivity-Temperature-Depth) data were shared from the ships to the shore team using an FTP server, and figures and analyses were shared between scientists on the shore and on the ships primarily using WhatsApp communication channels.

This team initially used daily CMEMS gridded altimetry to estimate the mean position of the eddy as the minimum Γ_1 (see Eq. 1). However, the spatial resolution of satellite altimetry is rather low, and the final result was found to not be precise enough for the scientists on the ships. Therefore, mid-way through the first week of the deployment the EXPORTS eddy tracking team began providing near-daily updates to the eddy center product (Figure 29) through looking at the trajectories of drifting assets, as well as ADCP measurements from the two ships (primarily the survey ship), as well as glider-based depth-averaged currents (DACs). These *in situ*-based estimates were the primary ones used by the ships to decide on sampling strategies during the deployment. They often differed by over 10 km from the CMEMS-based measurements during most of the deployment, and towards the end of the month the eddy started to become less visible in the satellite altimetry (although it still appeared stable from the *in situ* measurements) and the two estimates diverged quite significantly (Table 5).

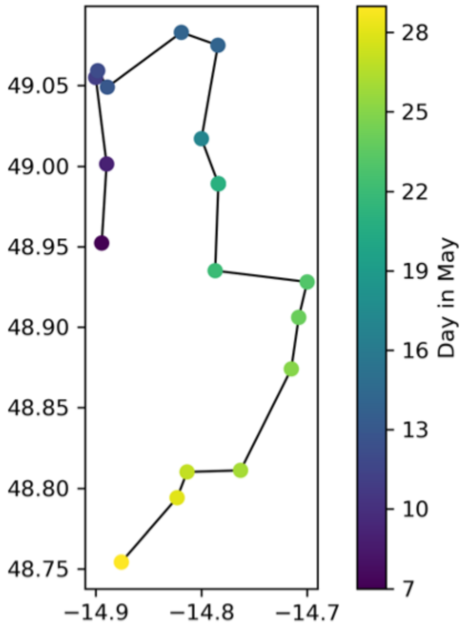

Figure 29. Track of eddy center determined by the eddy tracking group during May 2021.

Estimates of the eddy center location were based on depth-averaged ADCP velocities from the two EXPORTS ships and glider DACs. For each set of variables, the vorticity property Γ_1 (see Eq. 1) was calculated and the minimum value determined (see example in Figure 30). Drifter tracks (a few are shown in Figure 30) were also used to help verify the eddy center.

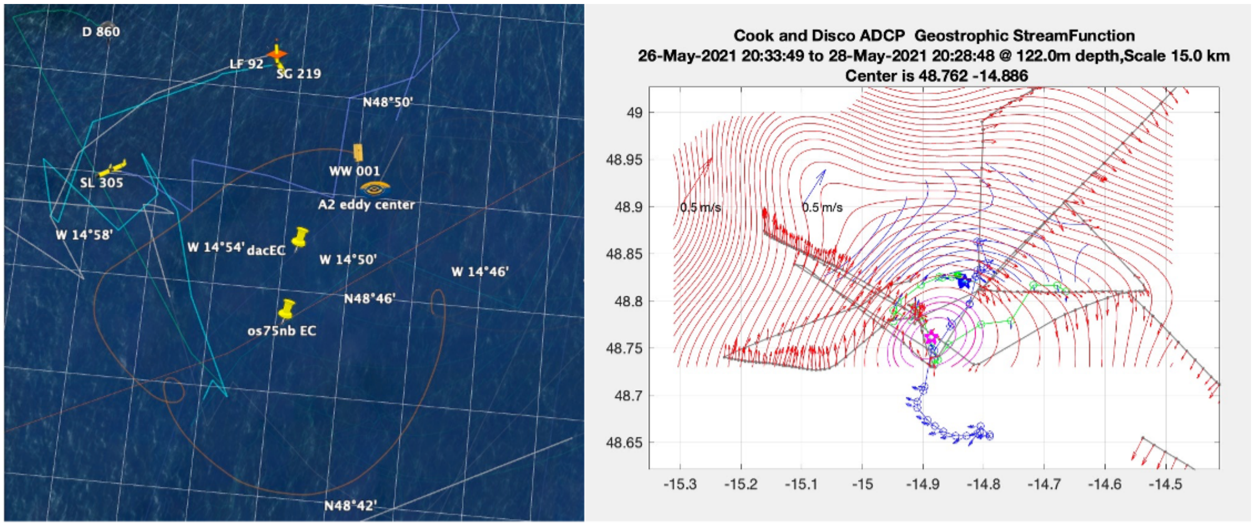

Figure 30. Example of the eddy center tracking process from 28 May 2021. (A) Location of several of the assets as well as the previous eddy center ("A2 eddy center") and the two updated locations from (B) an analysis of glider-based depth-averaged-currents ("dacE") and 75 kHz ADCP results ("os75nbEC").

SG219 was tasked with following a Lagrangian float that had been deployed to track the water mass at the center of eddy *A2*. This glider, which was continuously diving to 1000 m depth, appeared to stay within a consistent water mass, as evidenced by the lack of change in temperature with time, except for some transient surface variability (Figure 31). The eddy core could be characterized by the thickness of the isopycnal ranging from 27.15–27.20 kg m^{-3}; this thickness was very steady in the SG219 time series, at about 450 m.

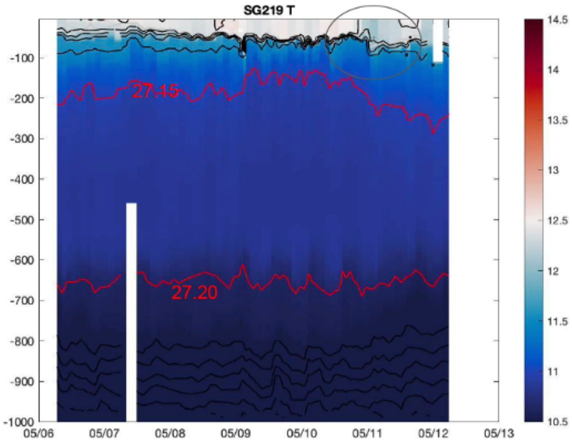

Figure 31. Temperature (T) from SG219 over the first week of the field deployment, taken from when SG219 was within the eddy A2. Density contours of 27.15 and 27.20 kg m^{-3} are marked in red. Circled area shows a deepening of the mixed layer following passage of a storm.

We also found that the eddy center was precessing in a clockwise direction (Figure 32). This was apparent from both estimates of the eddy center and the trajectory of the Lagrangian float. The eddy itself. however, did not appear to significantly move, as evidenced from its position staying relatively similar with respect to the core isopycnal thickness.

Table 5. Comparison between eddy center estimates from satellite altimetry and in situ assets, as described in the text. Days are in May of 2021.

Day	01	02	03	04	05	06	07	08	09	10
satellite	49.05, -14.92	49.05, -15.00	-9.05, -14.94	49.05, -14.96	49.07, -14.97	49.12, -14.94	49.12, -14.91	49.13, -14.93	49.14, -14.88	49.14, -14.88
in situ							48.95, -14.89		49.00, -14.89	
distance (km)							18		16	
Day	11	12	13	14	15	16	17	18	19	20
satellite	49.15, -14.86	49.16, -14.87	49.16, -14.88	49.17, -14.88	49.18, -14.90	49.14, -14.86	49.04, -14.88	49.03, 14.89	48.97, -14.94	48.94, -14.97
in situ	49.06, -14.90	49.06, -14.90	49.05, -14.89	49.08, -14.82			49.02, -14.80	48.99, -14.78	48.99, -14.78	48.99, -14.78
distance (km)	11	11	12	11			6	9	12	14
Day	21	22	23	24	25	26	27	28	29	30
satellite	48.91, -14.99	48.69, -15.26	48.74, -15.22	48.49,- 15.52	48.47, -15.60	48.54, -15.63			48.62, -15.78	48.82, -16.04
in situ	48.99, -14.78	48.94, -14.79	48.93, -14.70	48.91, -14.71	48.87, -14.72	48.81, -14.76	48.81, -14.81	48.79, -14.82	48.75, -14.88	
distance (km)	17	44	44	75	79	70			68	

7. Retrospective and Lessons Learned

In late June of 2021, the eddy tracking team held a group retrospective meeting to focus on what went well, what could be improved, and what lessons were learned through this process. A summary of the results of this meeting is provided in Table 6 below. A few of the more important discussion topics and lessons are explained in more detail here.

One thing that came up multiple times was the amount of time and effort that several members of the EXPORTS eddy tracking team were able to commit to this project, both in the preparatory phases and during the cruise. In addition to the analyses presented in Section 3 and the discussions involving the Dry Runs presented in Section 4, members of the eddy tracking team met twice per week from mid-March to the end of May to discuss eddy tracking efforts and early analyses to be shared with the ship (Sections 5 and 6), and communicated daily during the cruise to collaboratively determine and update the location and strength of the eddy core (e.g., Figures 29-32). Several members of the shore-based eddy tracking team were working at or near full time on this project during the deployment and for months beforehand. In some sense, we believe this was aided by the Covid-19 pandemic; several members felt like they had fewer other responsibilities (e.g., classes, other meetings, other cruises) and therefore had more time to spend on this, freeing them up to spend more time doing analyses on shore during the cruise. In non-pandemic years, it may have been much more difficult for all of this preparatory work to happen, and for as much discussion to happen during the field deployment by participants who were not themselves on the ships.

We believe that this work, and in particular the time and commitment put in by all of the members, was essential to the success of this field deployment. It is important to note that very little of this work was explicitly funded. Large deployments such as EXPORTS require significant advance planning and, especially when ships have limited internet access, a dedicated shore team providing real-time analysis and synthesis. Resources to do this work should be provided as part of the normal funding process. In addition, funded members of the scientific shore team should treat this time as if they were on a cruise to the extent possible, and be prepared to dedicate significant time and resources during the deployment.

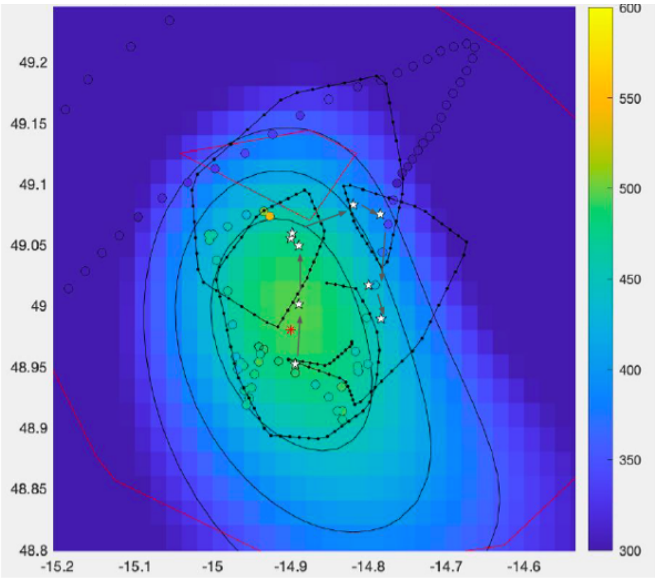

Figure 32. Thickness of the density range 27.15-27.20 kg m^{-3} (see Figure 26), interpolated using values from Seaglider and ship-based CTD casts. Black line is the track of the Lagrangian float, and colored stars are estimates of the eddy center over time, showing a clockwise precession.

Part of the preparation for the North Atlantic EXPORTS field deployment was to set up a system to transfer data between the ships and the shore team and set up a system to easily view the positions of assets and other tracked data products (such as the eddy center). This included, for example, a way to sync text-based asset position data to the ships and a file system set up to show positions in a Google Earth format (*i.e.*, with .kmz files), along with satellite altimetry and any available satellite ocean color data. This sharing of data was invaluable to help with discussion and key decision points that needed to be made by the ships. These asset position files were also critical for helping the bridge crews in their operations of the ship and for the chief scientists for planning day to day activities.

However, there were still some challenges relating to communication between the ships and the shore team. It was often unclear to people on shore when different decisions on the ships needed to be made (and therefore when people on the shore should meet to help with these decisions), and it was often similarly unclear to people on the ship when people on the shore would be having discussions and how to best contribute to those discussions. This difficulty was exacerbated by the large difference in time zones. The shore team primarily was in time zones GMT-7, GMT-4, and GMT+1, whereas the ships were on GMT+0. During the field deployment, the shore team met twice weekly to talk through EXPORTS eddy tracking issues; while these meetings were planned around the team members' schedules, discussion also happened on WhatsApp text channels. This was more difficult to plan for and often meant that large amounts of discussion and, sometimes, key decisions were made while not everyone was engaged. Future deployments utilizing text-based communication channels should explicitly determine a common discussion time before key decision points to ensure that members across all time zones are maximally able to contribute.

Table 6. Post-deployment retrospective meeting summary.

Pre-planning		
What went well?	What could be improved?	What lessons were learned?
- Started early and set up a system with many people in the loop, helping us to identify more possibilities - Dry runs helped us focus on key decision points and also acted as a team-building exercise - Development and testing of quantitative metrics was useful for knowing how to use them in the "real-world" application. - Early access to "semi-automated" remote sensing data was very helpful.	- Could have started a diary of daily eddy updates earlier to get a longer time-series of the region - We were optimistic in glider distances traveled and our ability to pick up and re-deploy gliders - Better assessment of error and uncertainty in satellite altimetry data (look at along-track altimetry and not just gridded products) - Could have done more initial research using models on the stability of eddy cores or a full observing system simulation experiment (OSSE)	- The preparatory work that went into EXPORTS-NA eddy tracking was critical to mission success and future missions should make sure to fund this work - Similarly, the time spent by PIs and other funded and non-funded individuals was essential to this success - Axisymmetric eddy features with strong sea level anomalies tend to be fairly stable over periods of several weeks - Useful to have multiple data products to compare and contrast

Eddy Selection

What went well?	What could be improved?	What lessons were learned?
- Everyone spent a lot of time and effort in plotting results and thinking about options - Good communication and rapid decision-making - Followed a “rubric” laid out in Dry Runs, with (mostly useful) quantitative metrics - End result was an eddy that was well-represented by altimetry data and persisted throughout the deployment	- Uncertainty about feasibility of back-up eddies - Could have prioritized return of some biological metrics sooner (such as backscatter spikes)	- Talking through procedure several times was helpful for future decision-making - Initial glider surveys streamlined first days of ship-based work - One month of glider data beforehand was sufficient. If had more resources, better to put into more gliders rather than earlier glider deployments - Glider measurements were crucial and it was helpful to have gliders in multiple eddies

Eddy Tracking I: Data products

What went well?	What could be improved?	What lessons were learned?
- Good end result: assets deployed near eddy center stayed in center, meaning we defined the center well at the beginning - Provided simple, useful data to ships to guide decision-making	- Be clearer in assignments, decision points, and when people are available - More informative, automatic mapping tools	- Useful to have a distinct shore team to have conversations that didn’t need to always include people on the ships - Important to have people not on the cruise who have time to work on this - Satellite altimetry is limited in its ability to detect and locate eddies on small (1-10 kilometer) scales - Important to make sure to understand how different platforms measure similar metrics (e.g., backscatter spikes between Slocum gliders and Seagliders) - Was useful to put the Lagrangian Float in right away, as this platform was a very useful metric for the eddy center.

Eddy Tracking II: Communications

What went well?	What could be improved?	What lessons were learned?
- Good communication among shore team - Useful shore team recommendations on appropriate time scales - Good communication of a simple data product (location	- Better delineate expectations, responsibilities, and when information is needed/provided by the shore team (e.g., set up a “command center” when people on shore will be available) - Hard for the shore team to know what was happening on the ship,	- Good internet on the ships is vital - or, at least, important to know beforehand how good the internet will be to make expectations of communication and data flow are reasonable - Time zones cause problems - important to think about this beforehand and make sure people are around and working at

of eddy) from the shore team to the ships - Lots of time and effort put in by everyone	and vice versa - Situational awareness reports could have been more useful - they seemed to be doing double duty between providing information for real-time decision making and acting as a source of information for people in the future looking back. - Could have used a more explicit data plan (this is where all of the data and analysis for eddy tracking goes, etc.) - Hard to keep up with all of the various WhatsApp conversations (or to know when important conversations would be happening) - Better internet on the ships would have helped for more communication between ship and shore	times that make sense, while managing between people on different sides of the world - Important to think through when data will be needed to support critical decision points - Important to delineate roles of ship and shore team and which discussion will happen where and when

8. Conclusions

The success of the EXPORTS-NA Field deployment was dependent upon choosing an eddy that was retentive, long-lived, biologically interesting, and geographically feasible. Predicting how an eddy will evolve on monthly timescales is challenging, and we were prepared to re-deploy assets in the middle of the deployment period if the eddy had dissipated or otherwise appeared unsuitable. However, through careful work before any assets were ever put into the water, we were able to maximize our chances of successfully choosing an eddy that would be suitable throughout the deployment. Dry Runs using past years' data honed our abilities to make decisions on where to send scouting gliders before the EXPORTS-NA field deployment commenced, and we used the lessons learned from these simulated deployments to aid in successfully deploying and using the gliders a month before the official start of the field deployment. Finally, during the EXPORTS-NA Field Deployment a dedicated "shore team" met daily to track the progress of the eddy, calculate its center position, and make recommendations to the sea-going scientists, through open lines of communication that were set out beforehand. Each of these steps was important and contributed significantly to the success of the EXPORTS-NA field deployment.

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