Supplementary Material: Data Report: Overview of (Sub)mesoscale Ocean Dynamics for the NAAMES Field Program

1 STATISTICAL PROPERTIES OF COHERENT MESOSCALE STRUCTURES (CMS) IN THE NAAMES REGION

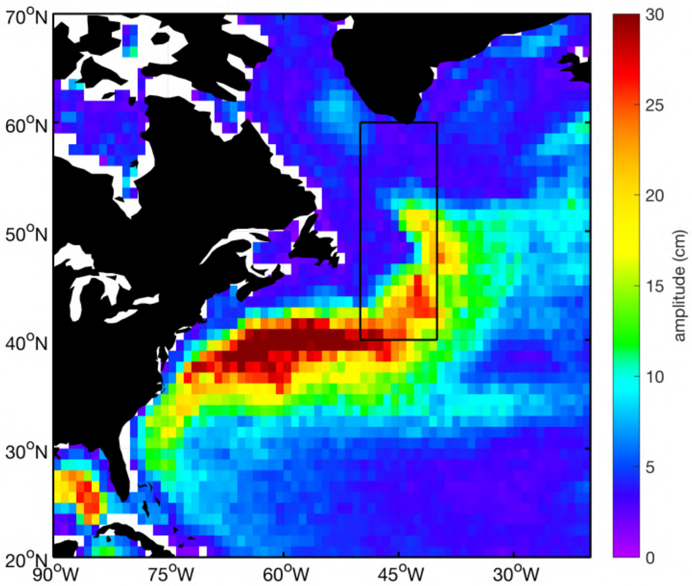

Figure S1. Mapped mean CMS amplitude per 1° square. The region over which statistics and the histograms shown in Fig. S2 are computed is indicated by the black rectangle. CMS amplitude is taken from the global Chelton eddy atlas avaialble at `http://wombat.coas.oregonstate.edu/eddies/`

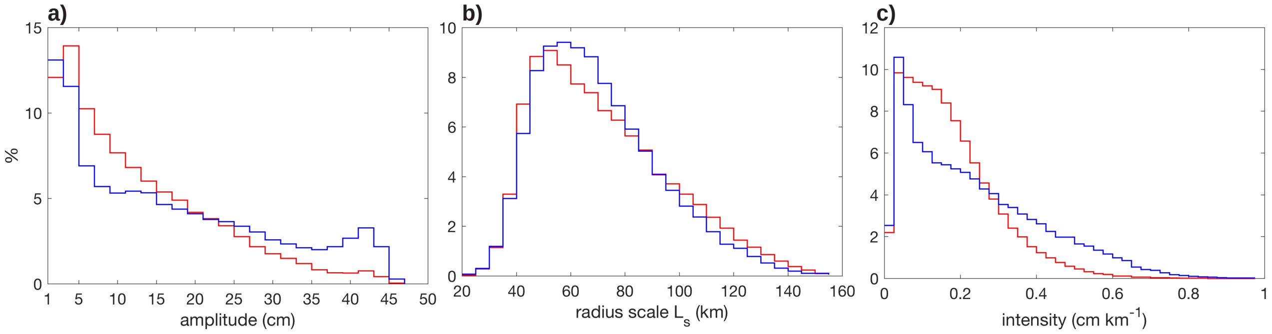

Figure S2. Histograms of (a) CMS amplitude, (b) speed-based radius scale L_s, and (c) intensity, defined as A/L_s where A is CMS amplitude. These are constructed from all eddies in the NAAMES region over the 20-year satellite altimetry era. Anticyclones are shown in red and cyclones in blue.

2 EXAMPLE OF COMPUTATION OF A MASK OF ORIGIN OF WATER PARCELS

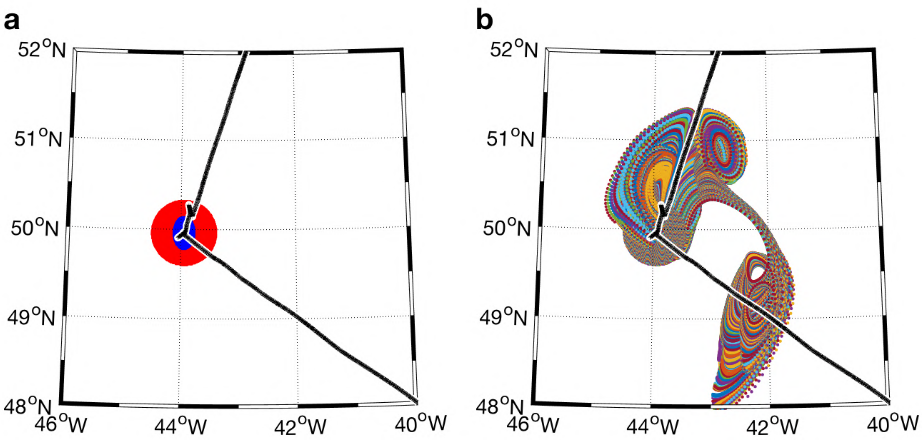

Figure S3. (a) Example of the definition of the 20-km (in blue) and 40-km (in red) disks for NAAMES2 - Station 3, and (back)trajectories for the water parcels occupying the 40-km disk. Different colors refer to the trajectories of the different water parcels contained in the 40-km disk.

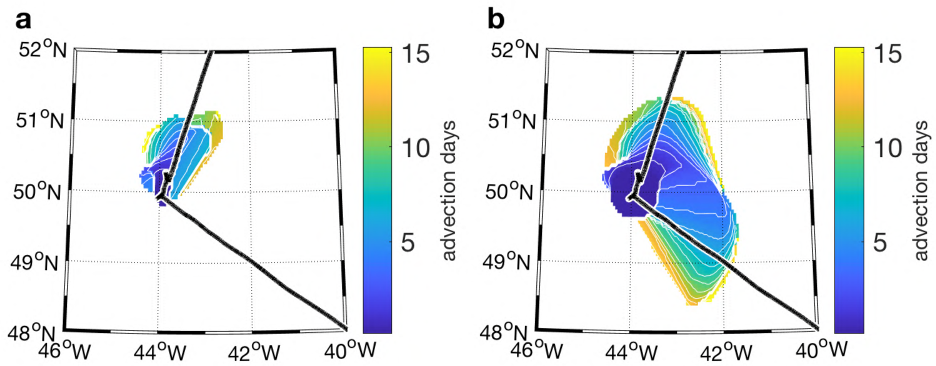

Figure S4. Example of the 20-km (a) and 40-km (b) masks for NAAMES2 - Station 3. Note how the 20-km disk mask includes mostly water parcels within the eddy core (which was coherent during the 15 days backward advection), whereas water parcels referring to the 40-km disk have a more varied origin.

3 (SUB)MESOSCALE FIELD FOR EACH NAAMES FIELD STATION

The supplemental materials presented herein provide a synopsis of the mesoscale field and water parcel history of each NAAMES field station, summarized in Figure S5. The data is presented in individual sections labeled by their campaign (NAAMES 2015, NAAMES 2016, NAAMES 2017, and NAAMES 2018) and organized in subsection by station number (S1, S2, S3, ...).

The accompanying figure for each section displays the SLA centered around the location of the respective station. Overlaid are the trajectory of the R/V Atlantis and the paths of drifters within 15 days of out arrival at the station.

Besides instantaneous images of the SLA field, this document contains images of several Lagrangian diagnostics calculated from the altimetry-derived velocity field: the Finite Size Lyapunov Exponents (FSLE) – an indicator of frontal activity, the eddy Retention Parameter (RP) – a measure of for how long water parcels are trapped within the eddy core, and the origin of water parcels – *i.e.,* the location of water parcels 15 days before the observations.

The data used to produce these plots can be accessed on SeaBASS at the URL
http://seabass.gsfc.nasa.gov/archive/UWASH/gaube/NAAMES/documents.

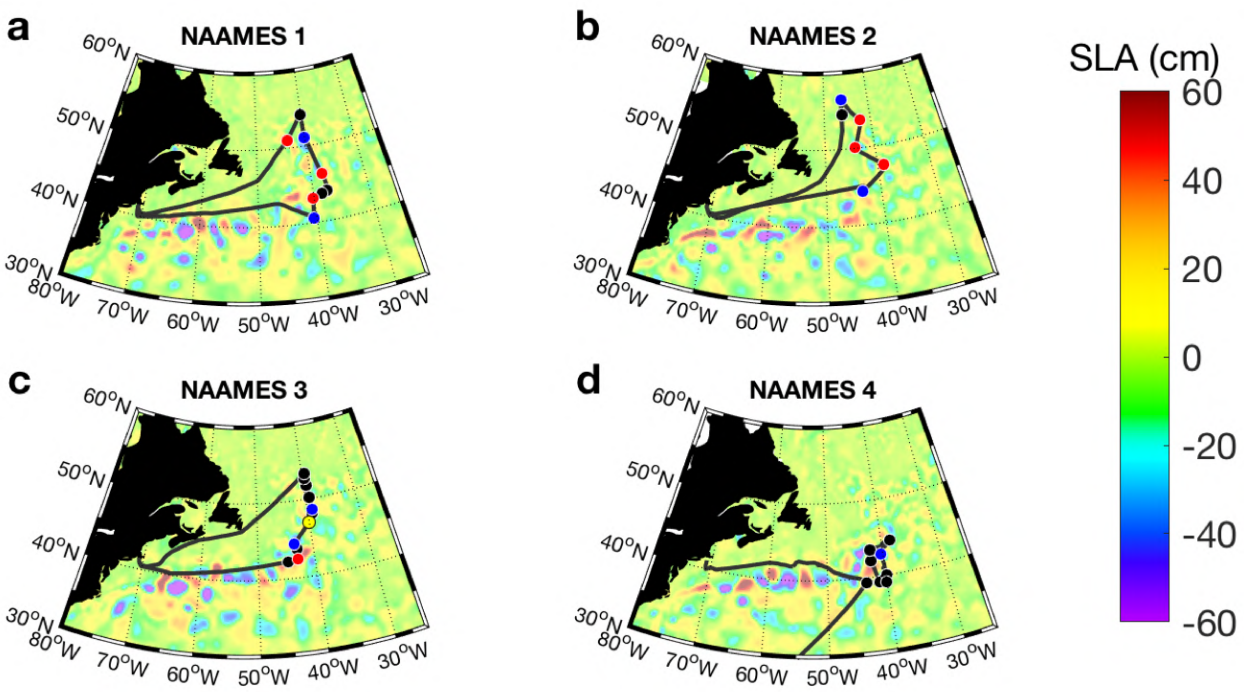

Figure S5. Eddy features sampled during the four expeditions of the NAAMES program (a-d). Cyclonic features are color coded in blue, anticyclones in red and the mode-water eddy sampled during NAAMES3 is marked in yellow. Stations that were not located within an eddy are marked in black. The background maps represent SLA referring to the respective expeditions (20/11/2015 for a), 23/05/2016 for b), 12/09/2017 for c) and 01/04/2018 for d)).

3.1 NAAMES 1 - 2015

3.1.1 S1 NAAMES-1

This station was chosen as a "dry run" and was positioned where we crossed into a non-retentive (S7 b)) anticyclonic eddy. This particular anticyclone was sampled again on NAAMES-2 at S3. The drifter deployed in this particular eddy during NAAMES-1 made a full loop around the anticyclone and returned to within 1 km of its deployment location, before moving eastward and into the Gulf Stream.

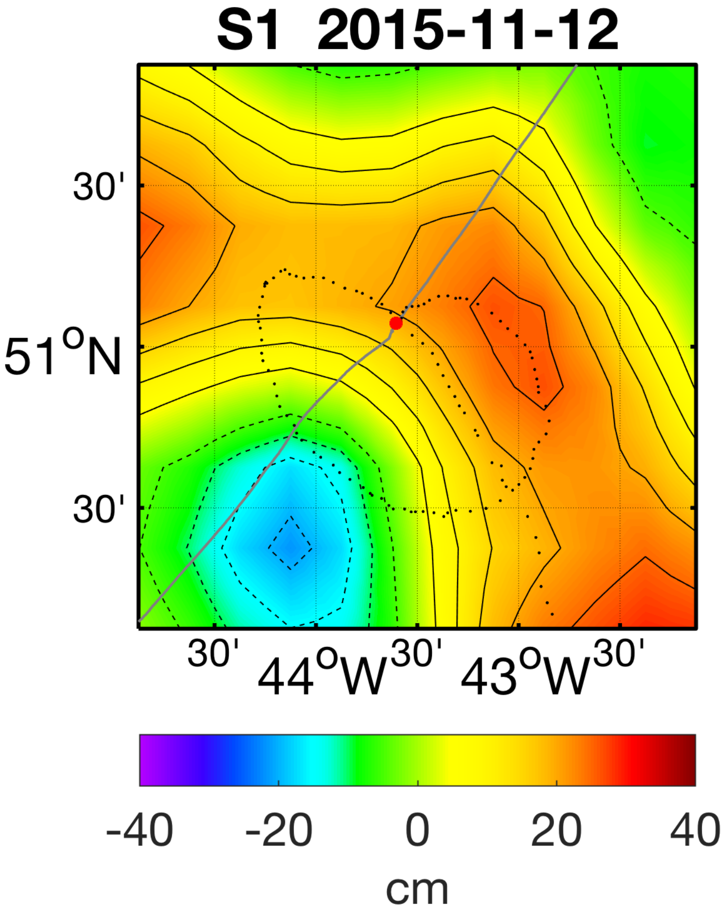

Figure S6. (a) Mapped sea level anomaly at Station 1. Solid (broken) black contours indicate SLA at an interval of 5 cm. Grey line is the track of the R/V Atlantis. Small black points indicate hourly drifter location for all drifters within the region starting on the first day of occupation of the station and continuing for 15 days.

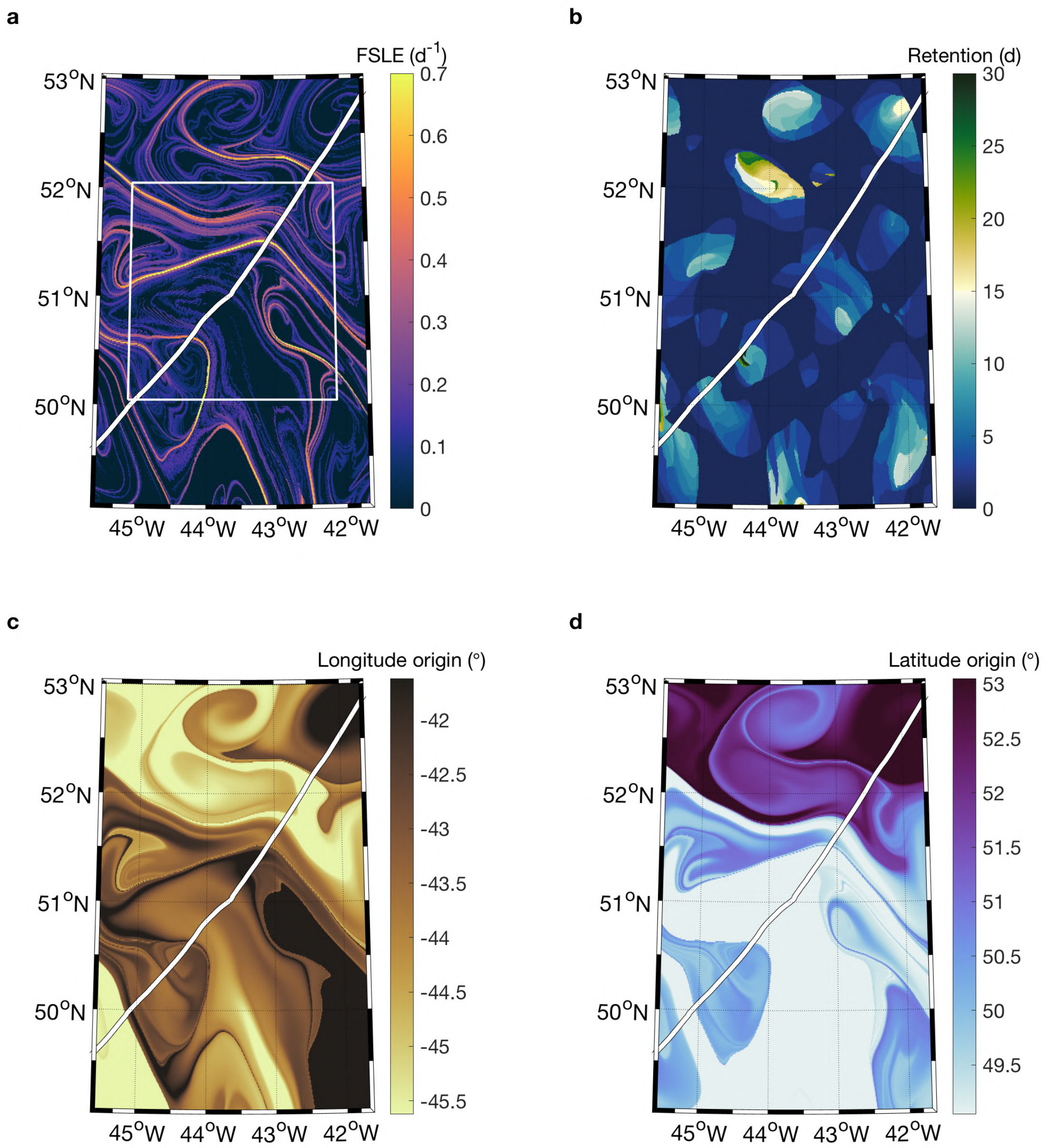

Figure S7. FSLE (a), RP (b) and water origin (c) and (d) calculated for Station 1 and surrounding waters for 12/11/2015. While the region is not particularly retentive, FSLE and water origin suggest the presence of strong gradients. White lines indicate the trajectory where the entire in-line system was on. The white rectangle corresponds to the axes of the SLA map in Figure S6.

3.1.2 S2 NAAMES-1

Station 2 was the northern-most station on NAAMES-1. This station was located in a region that could be called an “eddy desert”. The trajectories of the drifters indicate that there was very little surface current and most of the motion is limited to small inertial loops.

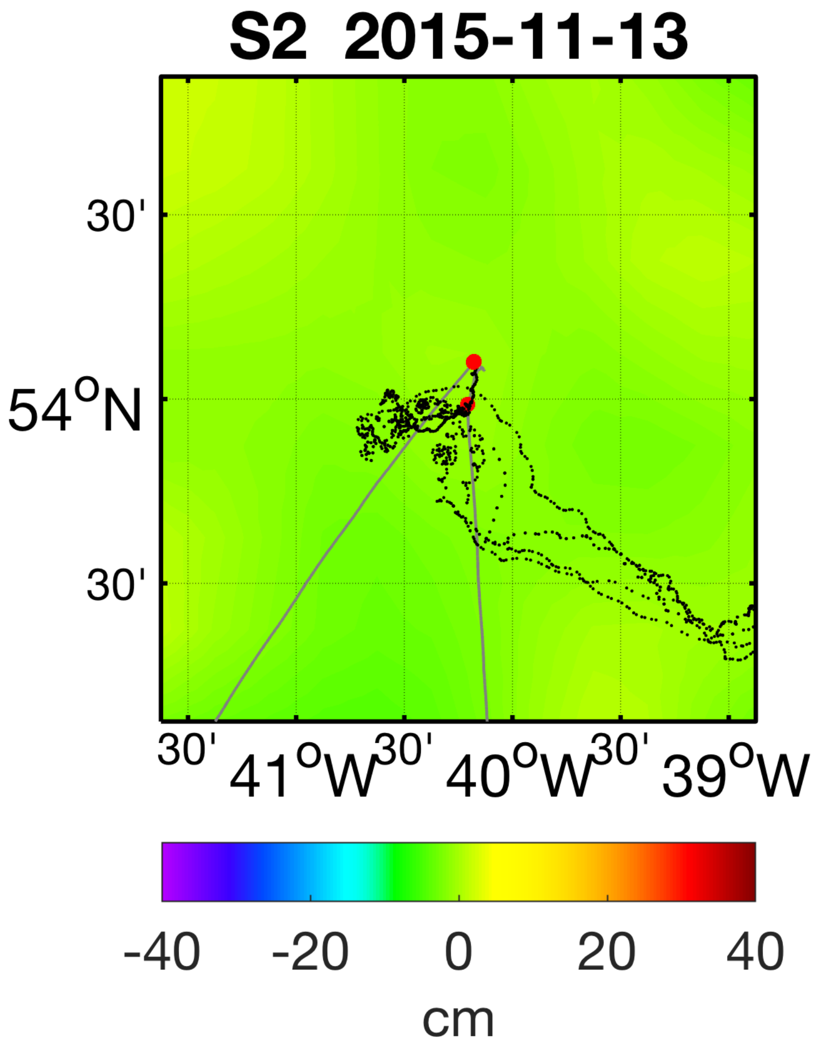

Figure S8. Same as Figure S6.

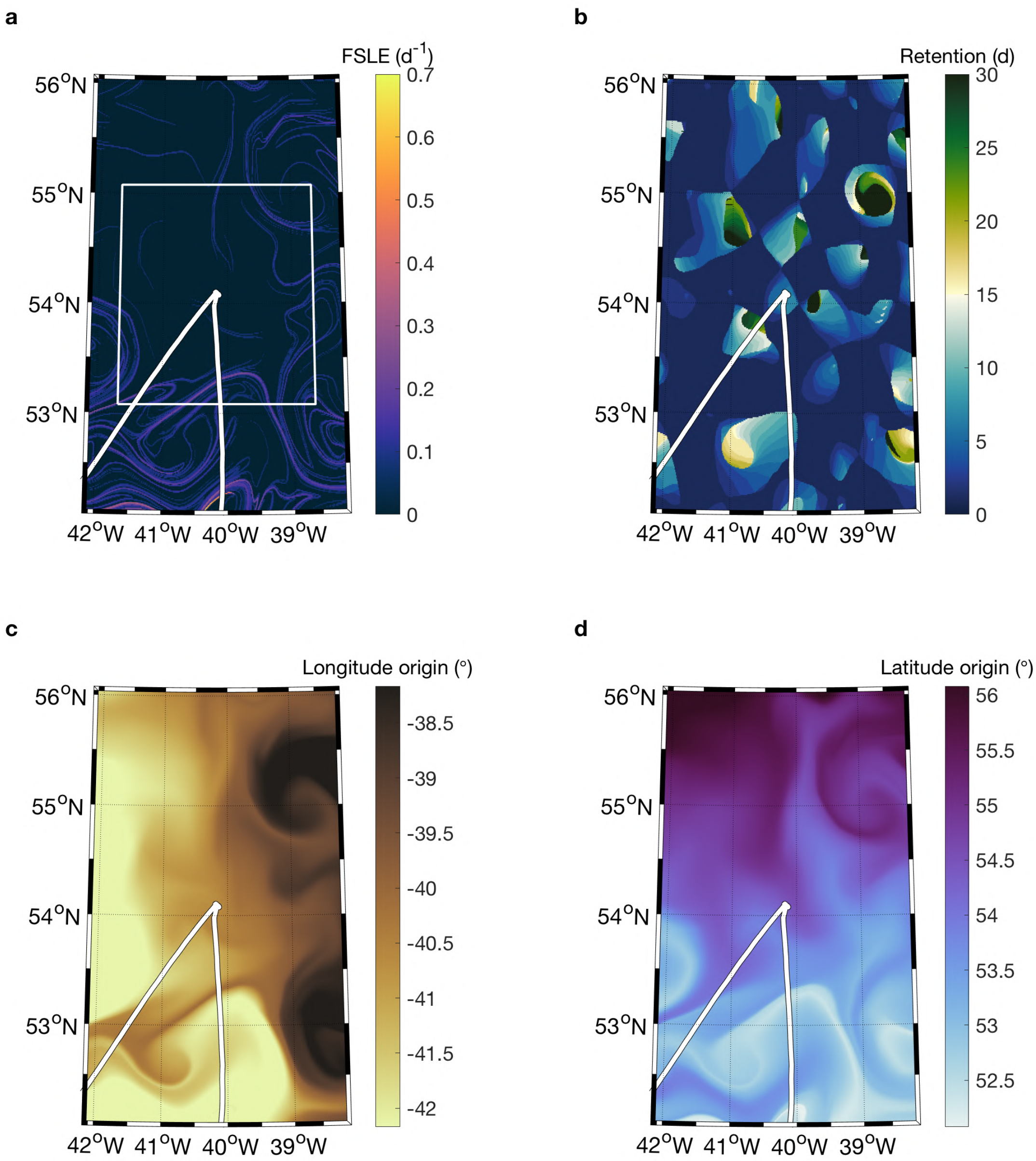

Figure S9. Same as Figure S7.

3.1.3 S3 NAAMES-1

Station 3 was located within a small and compact cyclonic eddy. The amplitude of this cyclone was very small, $\approx$ 8 cm, yet Lagrangian re-analyses suggest that it may have been retentive (Figure S11).

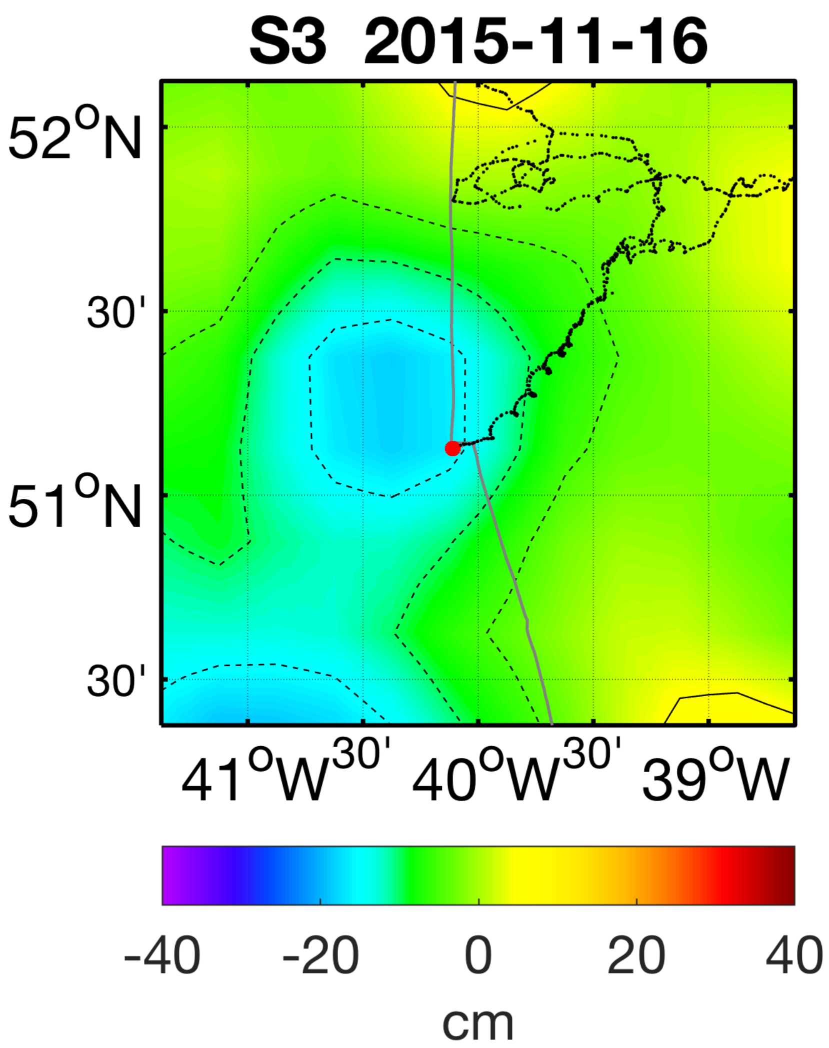

Figure S10. Same as Fig. S6

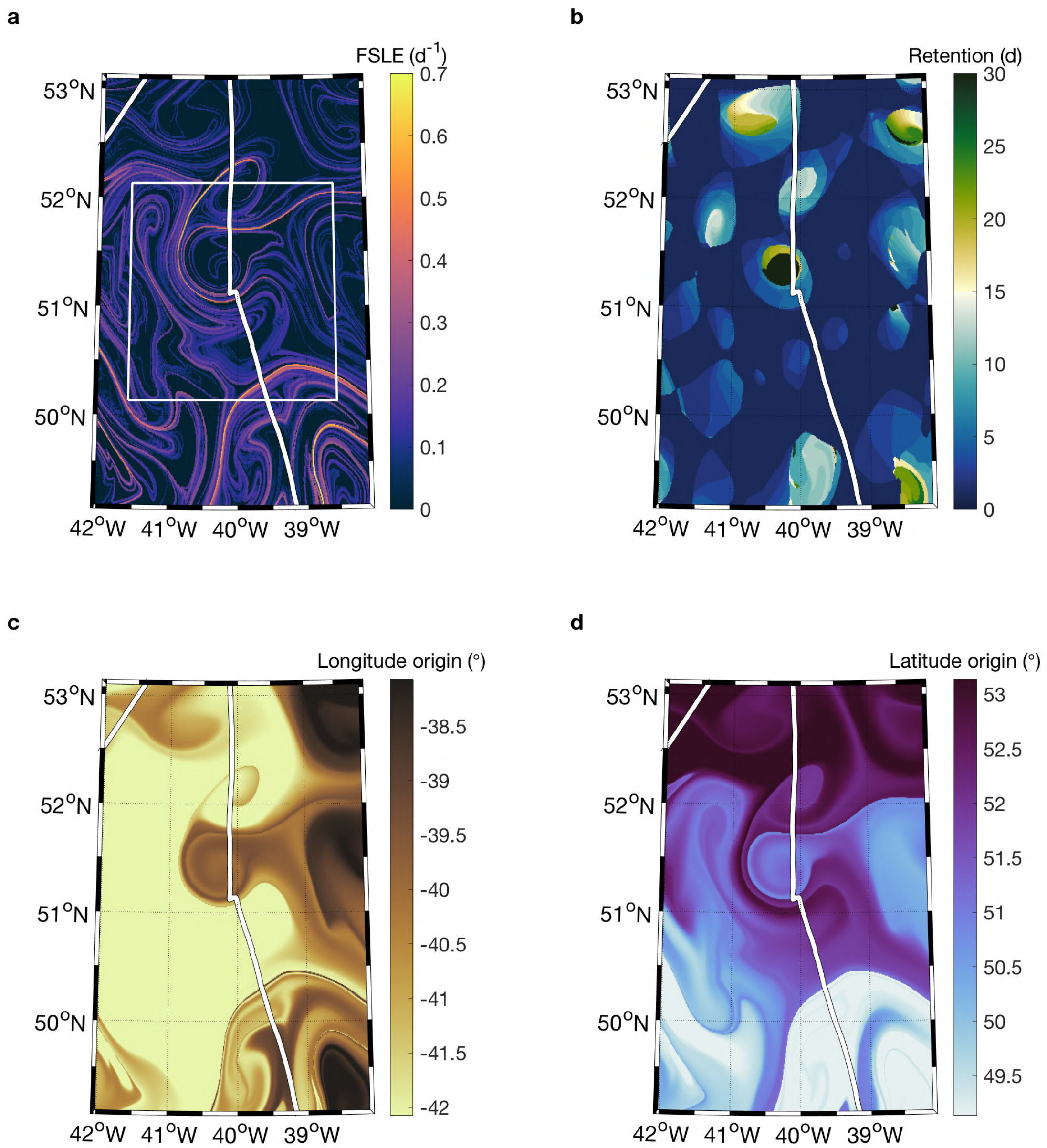

Figure S11. Same as Fig. S7

3.1.4 S4 NAAMES-1

This station was along the periphery of an anticyclonic eddy. This anticyclone was of moderate amplitude when sampled (17 cm). The drifters released at this location propagated northeastward around the anticyclone and remained within the eddy for at least 15 days following occupation. Lagrangian re-analyses indicate that this eddy was weakly retentive (Figure S13).

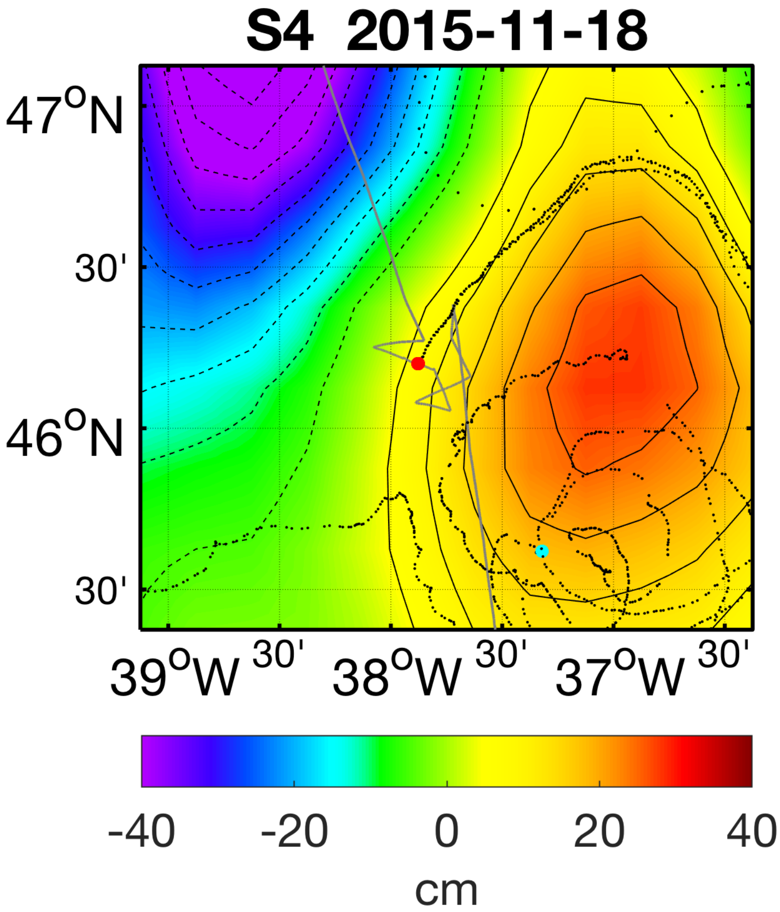

Figure S12. Same as Fig S6

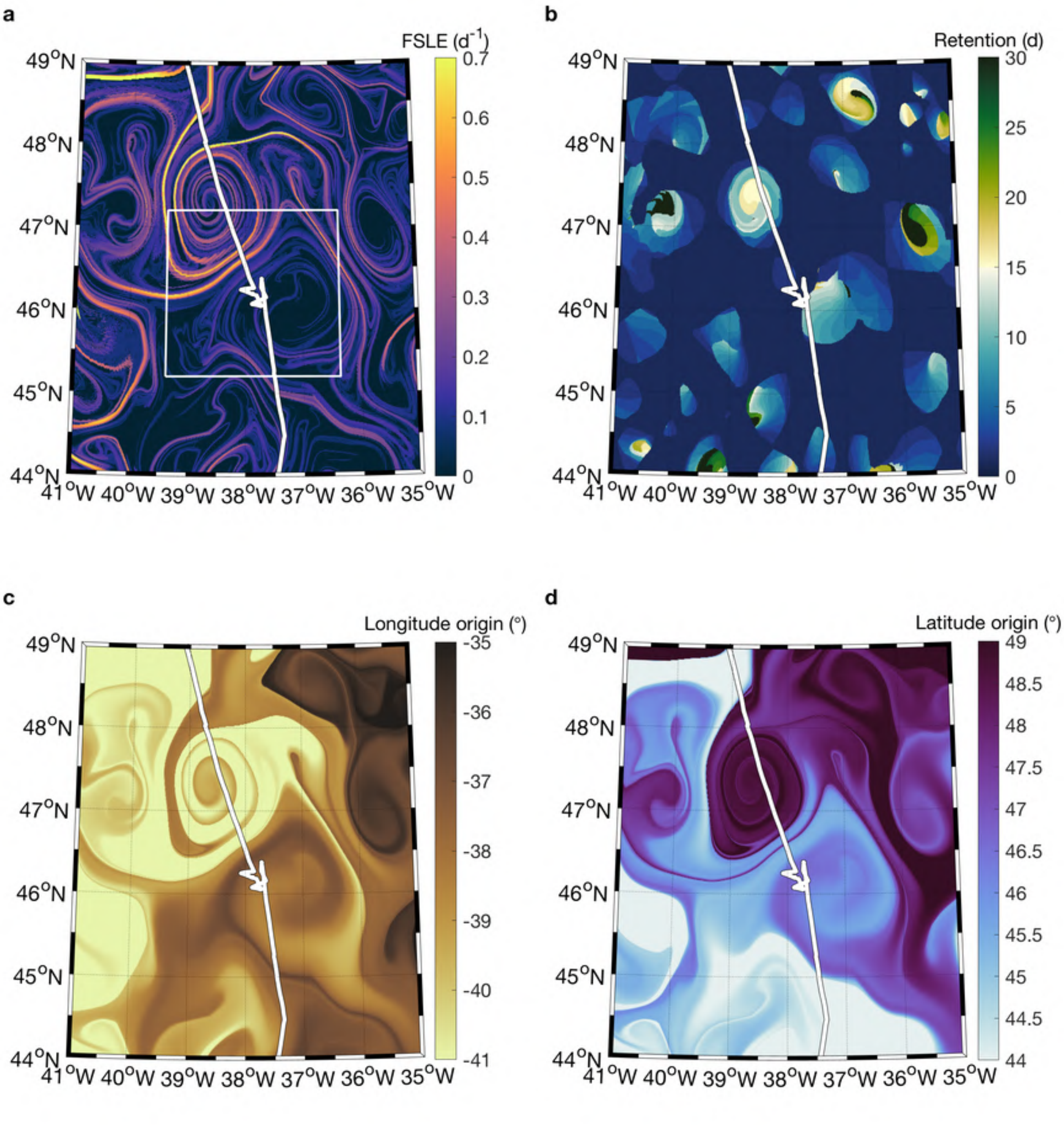

Figure S13. Same as S7.

3.1.5 S5 NAAMES-1

Station 5 was located along a front between two eddies. This is a dynamic region characterized by robust geostrophic currents. The drifter immediately moved to the north/northeast and made very pronounced inertial loops. After a few days, the drifter was entrained into the adjacent anticyclone.

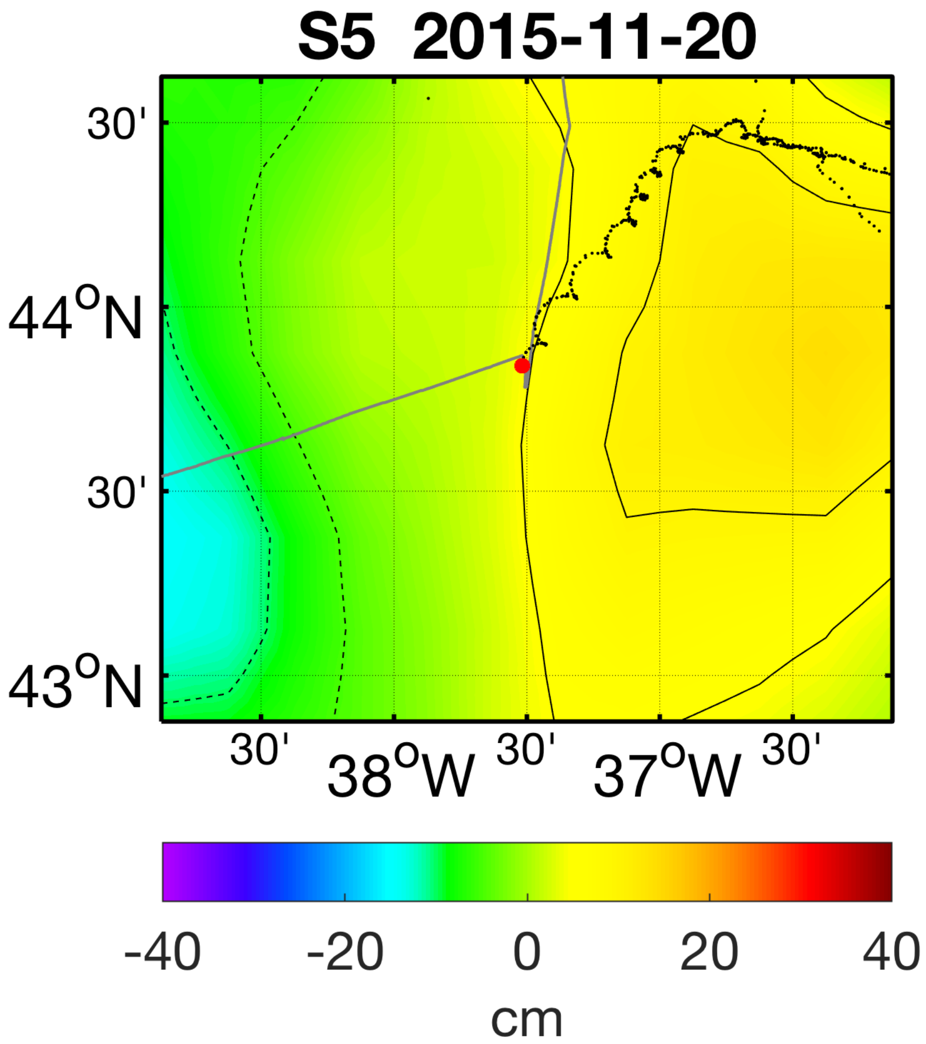

Figure S14. Same as Fig. S6

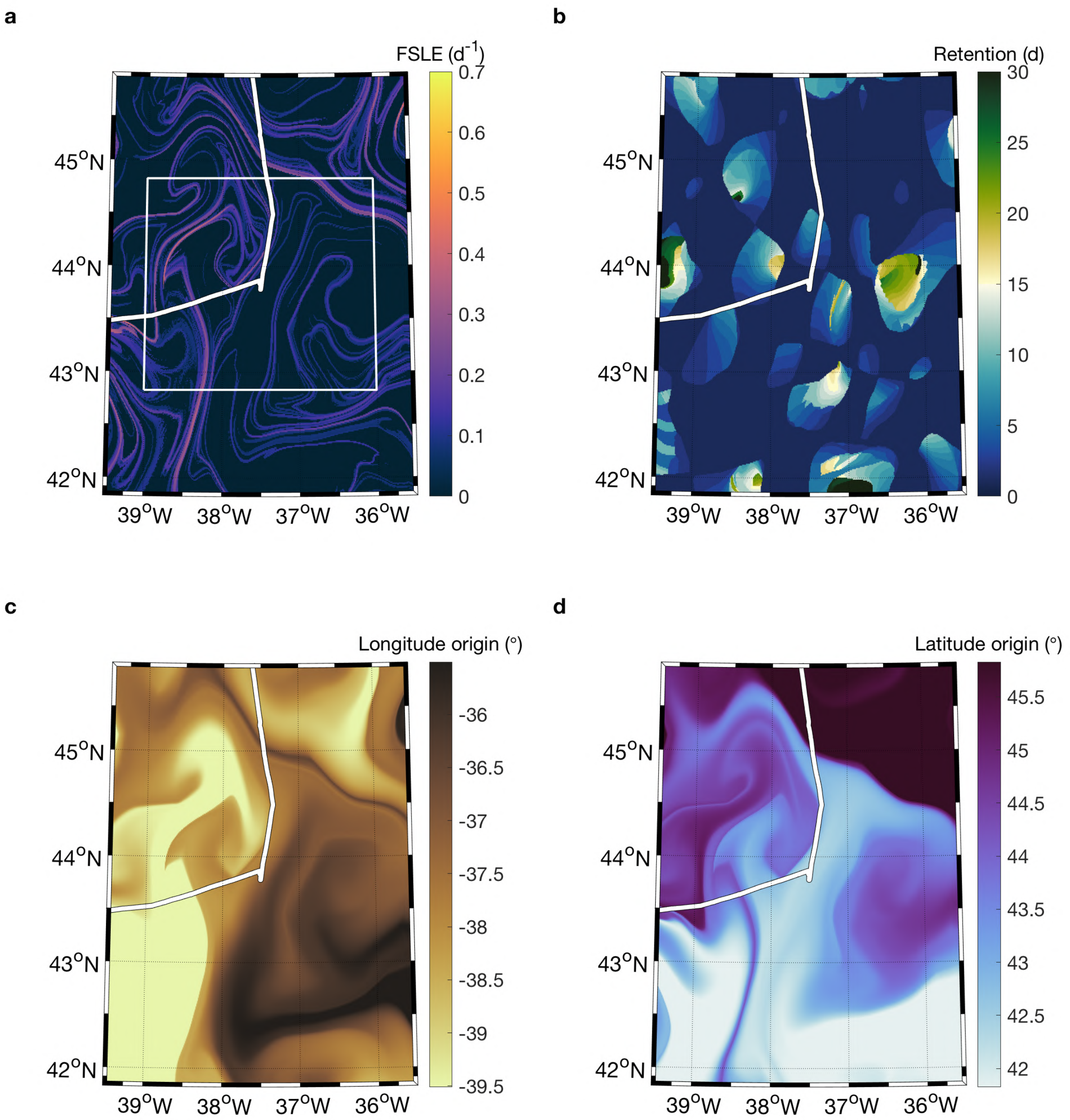

Figure S15. Same as Fig. S7.

3.1.6 S5b NAAMES-1

Station 5b was an in-between station. It was not located in an eddy.

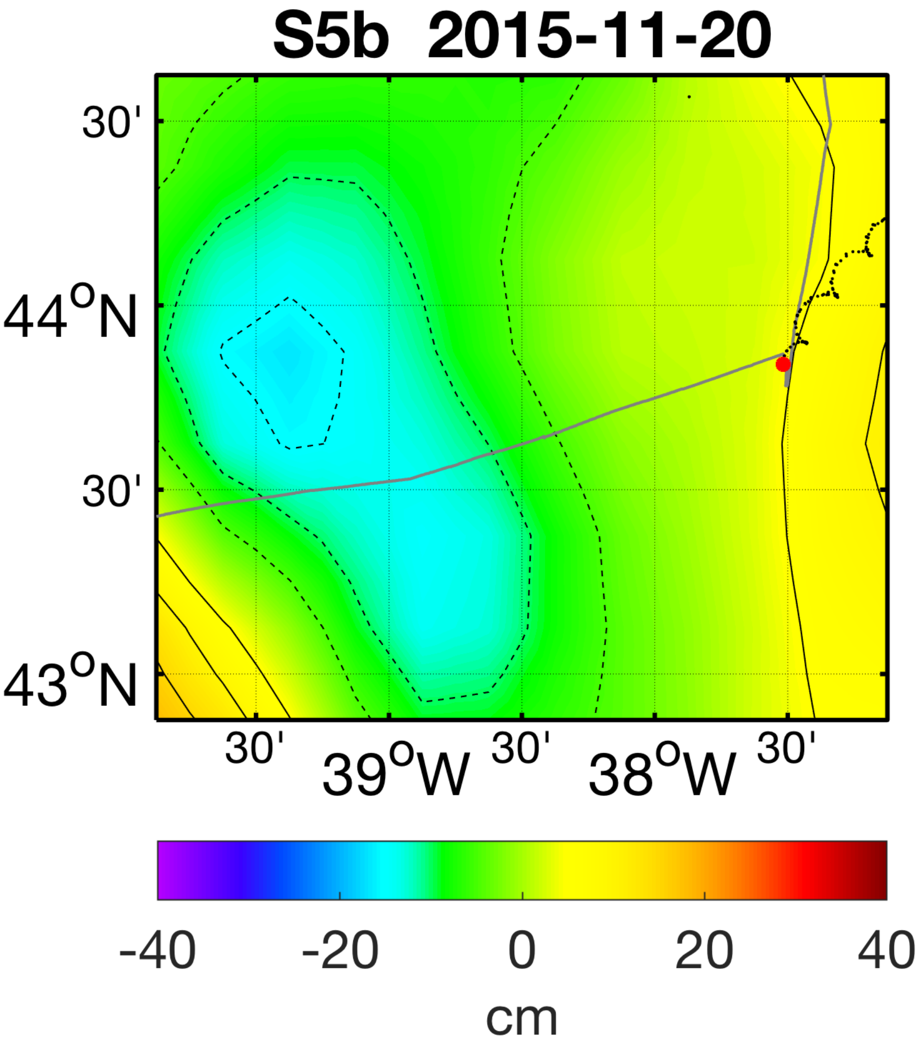

Figure S16. Same as Fig. S6

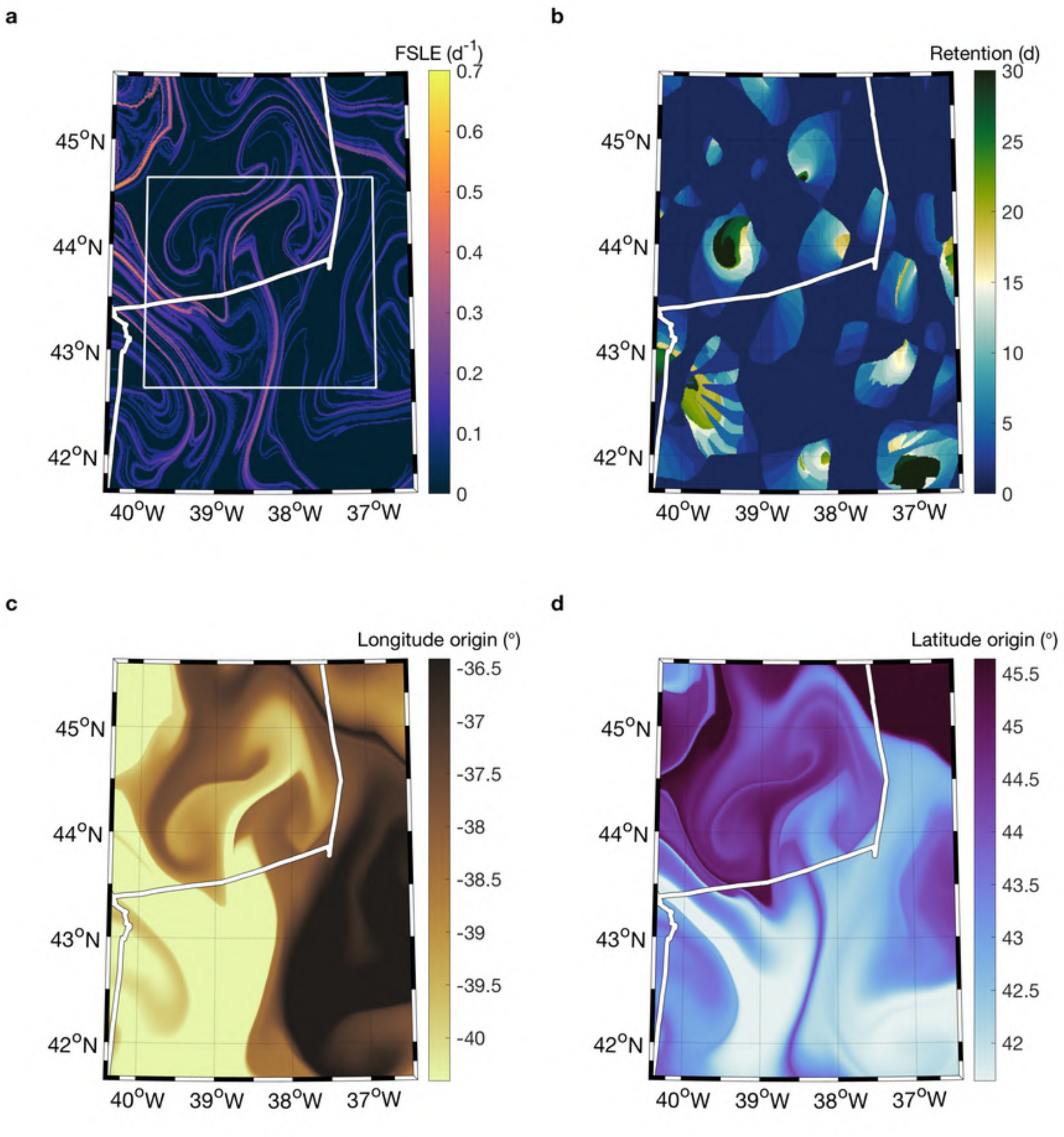

Figure S17. Same as Fig. S7.

3.1.7 S6 NAAMES-1

Another stop along the periphery of a relatively small anticyclone, Station 6 was a location of the deployment of a number of drifters. Most of the drifters were advected southward by the clockwise-rotating eddy.

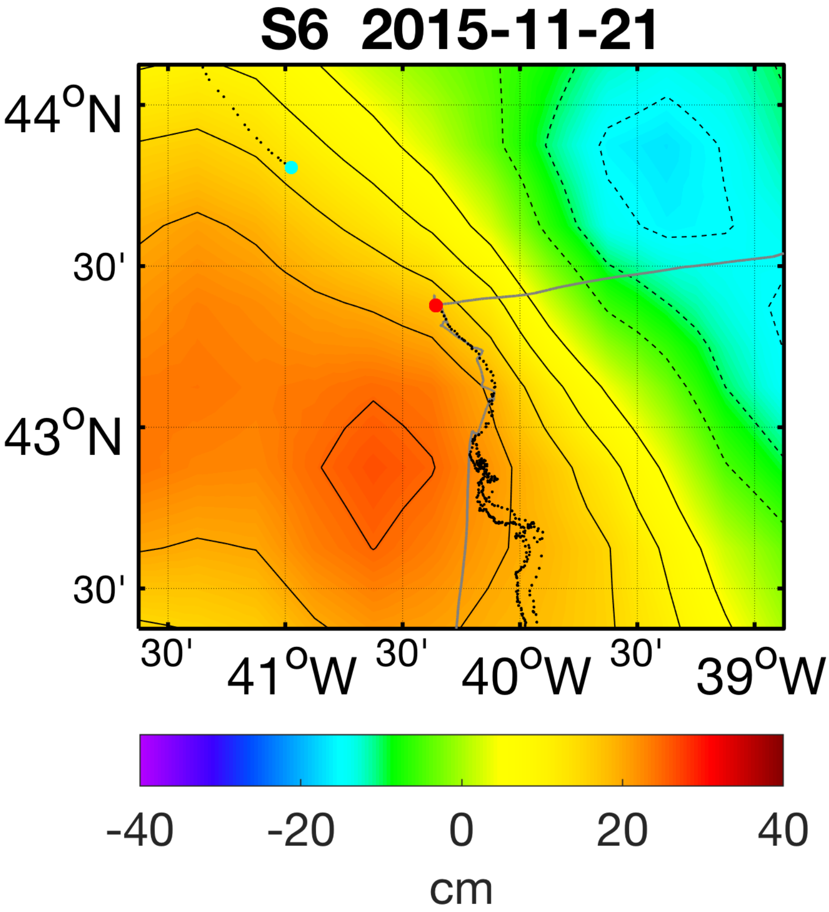

Figure S18. Same as Fig S6

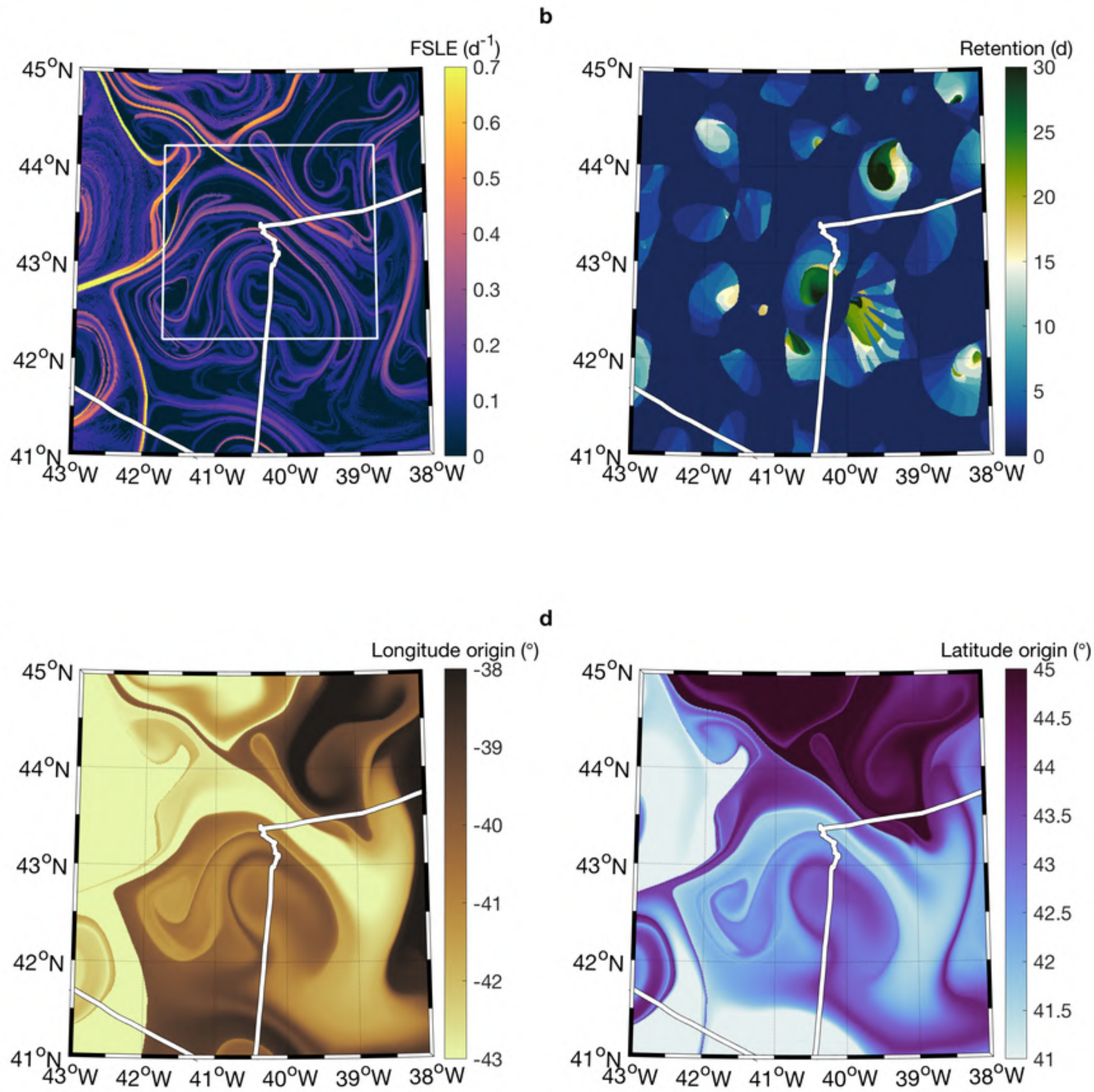

Figure S19. Same as Fig. S6.

3.1.8 S7 NAAMES-1

Station 7 was in a coherent and retentive cyclone located south of the Gulf Stream. The drifters were effectively trapped by this eddy for nearly a month following deployment. This station represents the conditions in a cyclonic eddy in the southern most reaches of the NAAMES region.

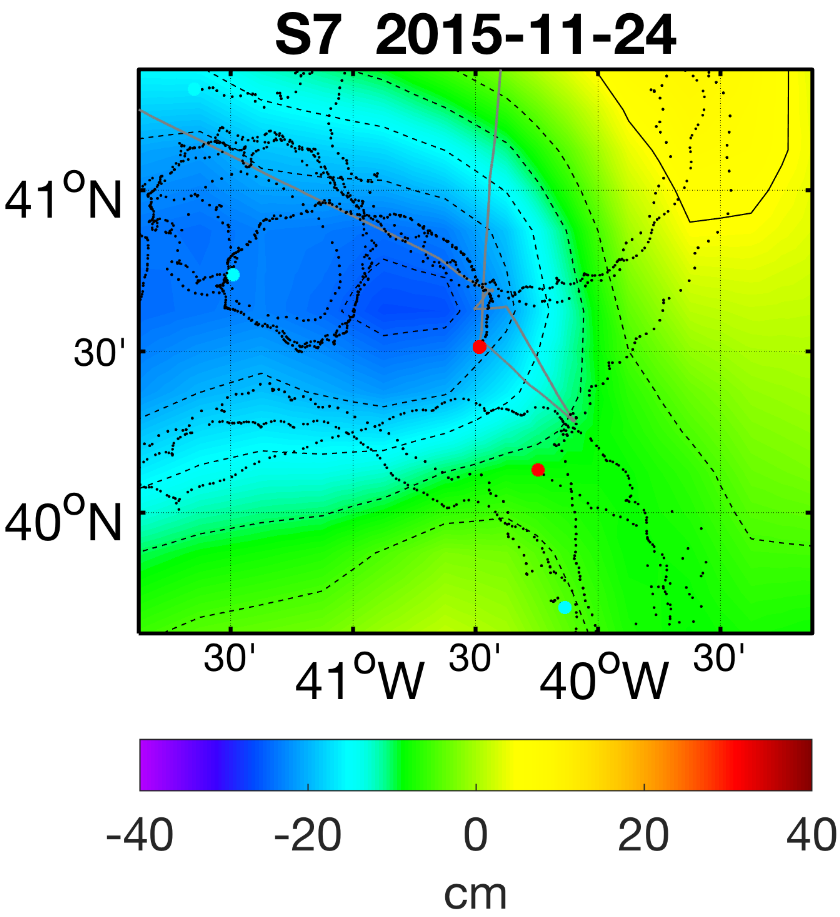

Figure S20. Same as Fig. S6.

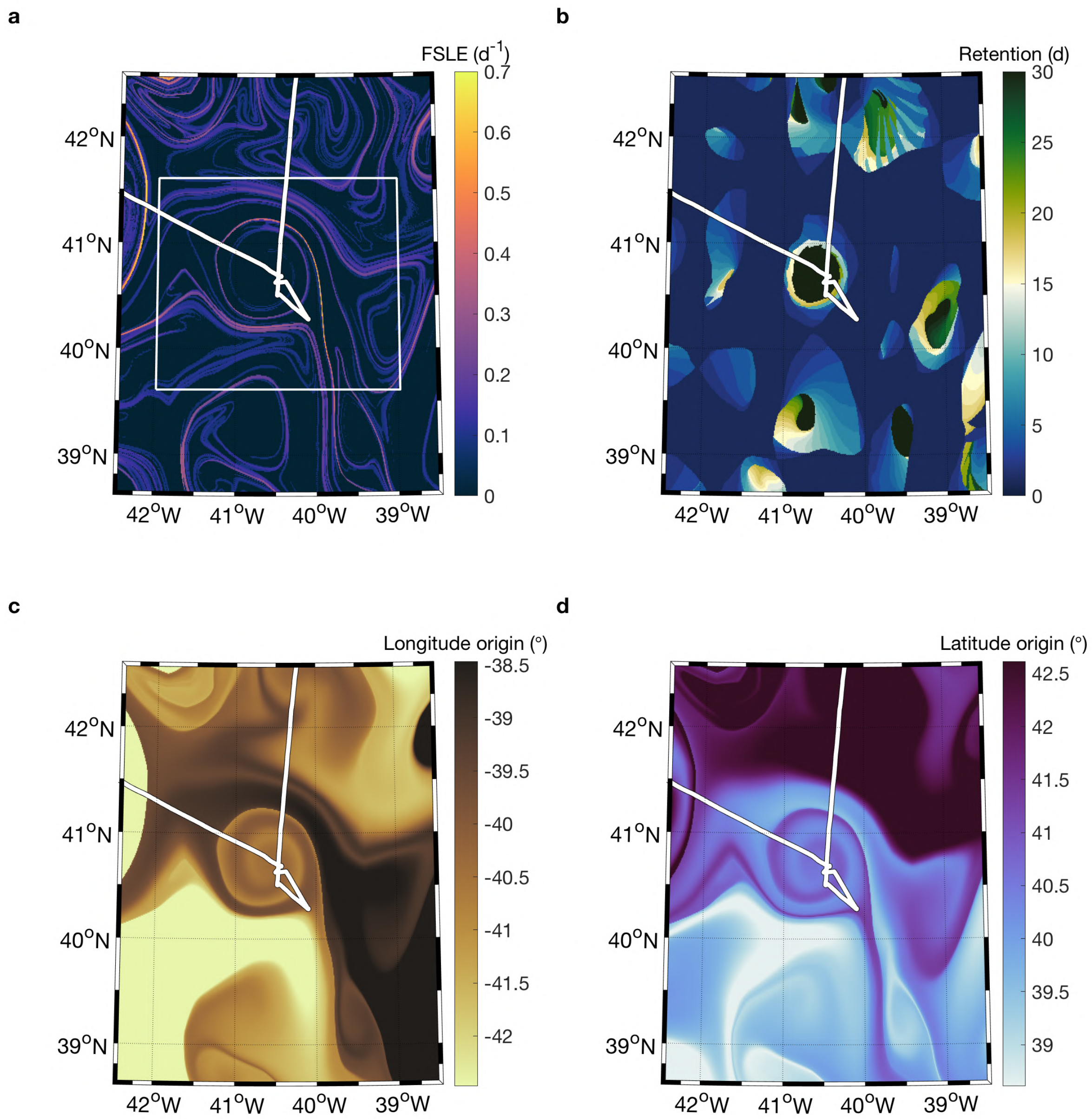

Figure S21. Same as Fig. S7.

3.2 NAAMES 2 - 2016

3.2.1 S0 NAAMES-2

Station “zero” was used as a dry run. This station was outside of any eddies.

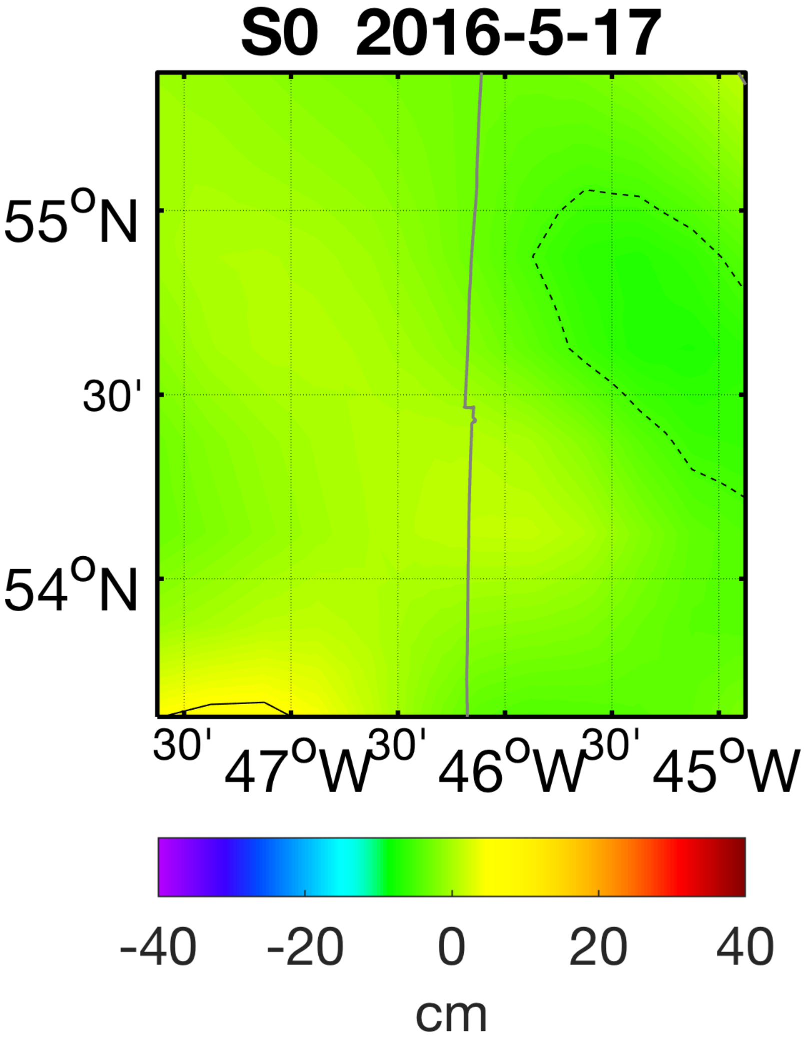

Figure S22. Same as Fig. S6.

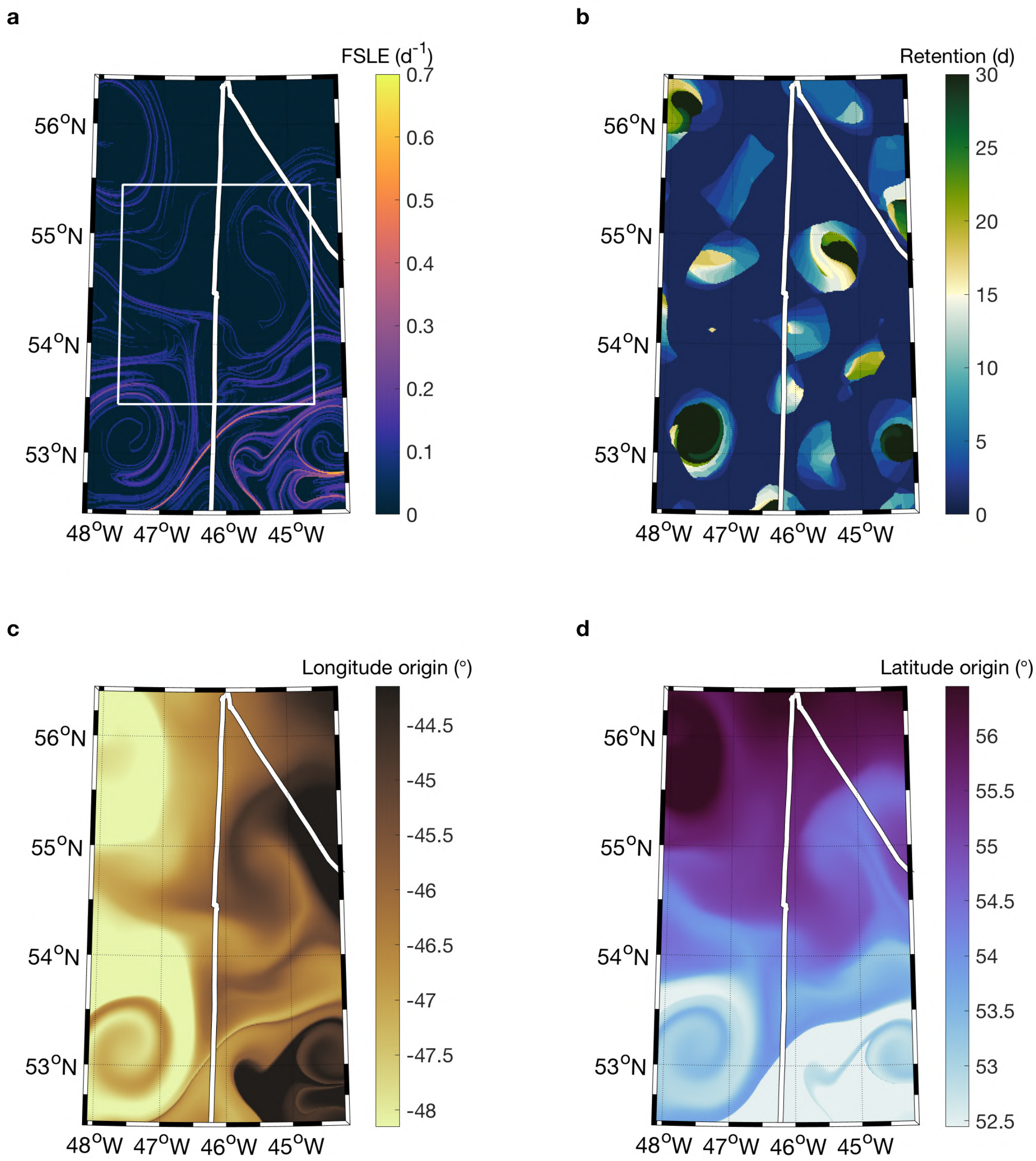

Figure S23. Same as Fig. S7.

3.2.2 S1 NAAMES-2

Station 1 was our northern-most station sampled during the entire NAAMES program. The trajectories of the drifters indicate that there was cyclonic rotation in the region, suggesting an eddy was present. Indeed, When SLA field is displayed with colorbar scaling $1/4$ that of the other images, a cyclonic eddy is very clear (Fig. S26b)

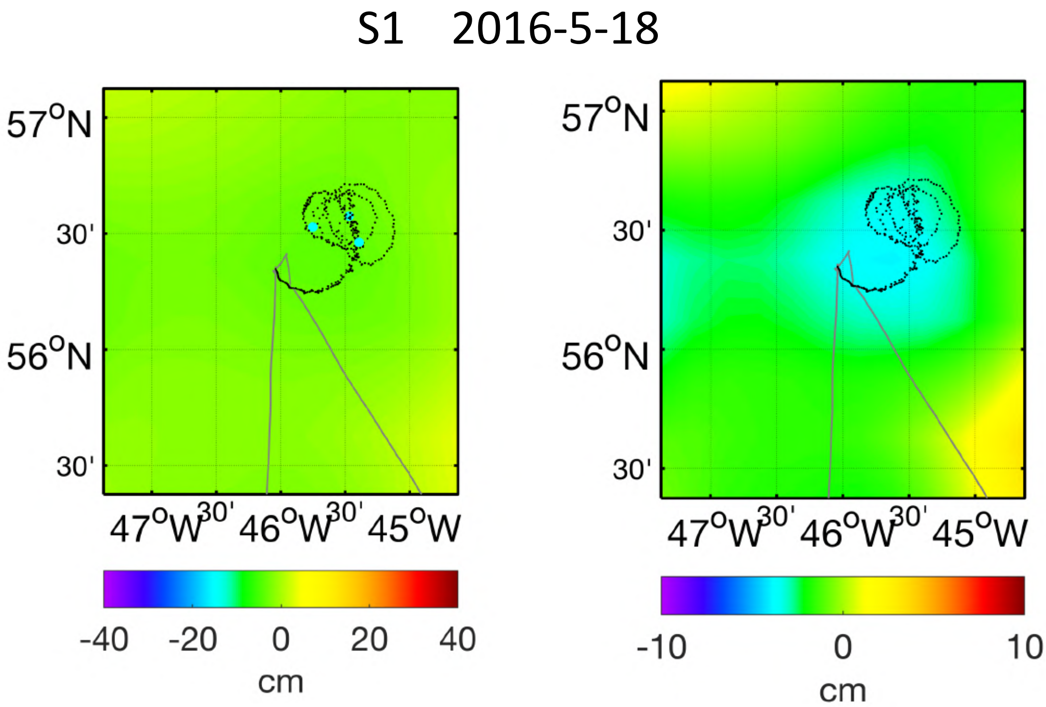

Figure S24. Same as Fig. S6 for the date of 18/05/2016.

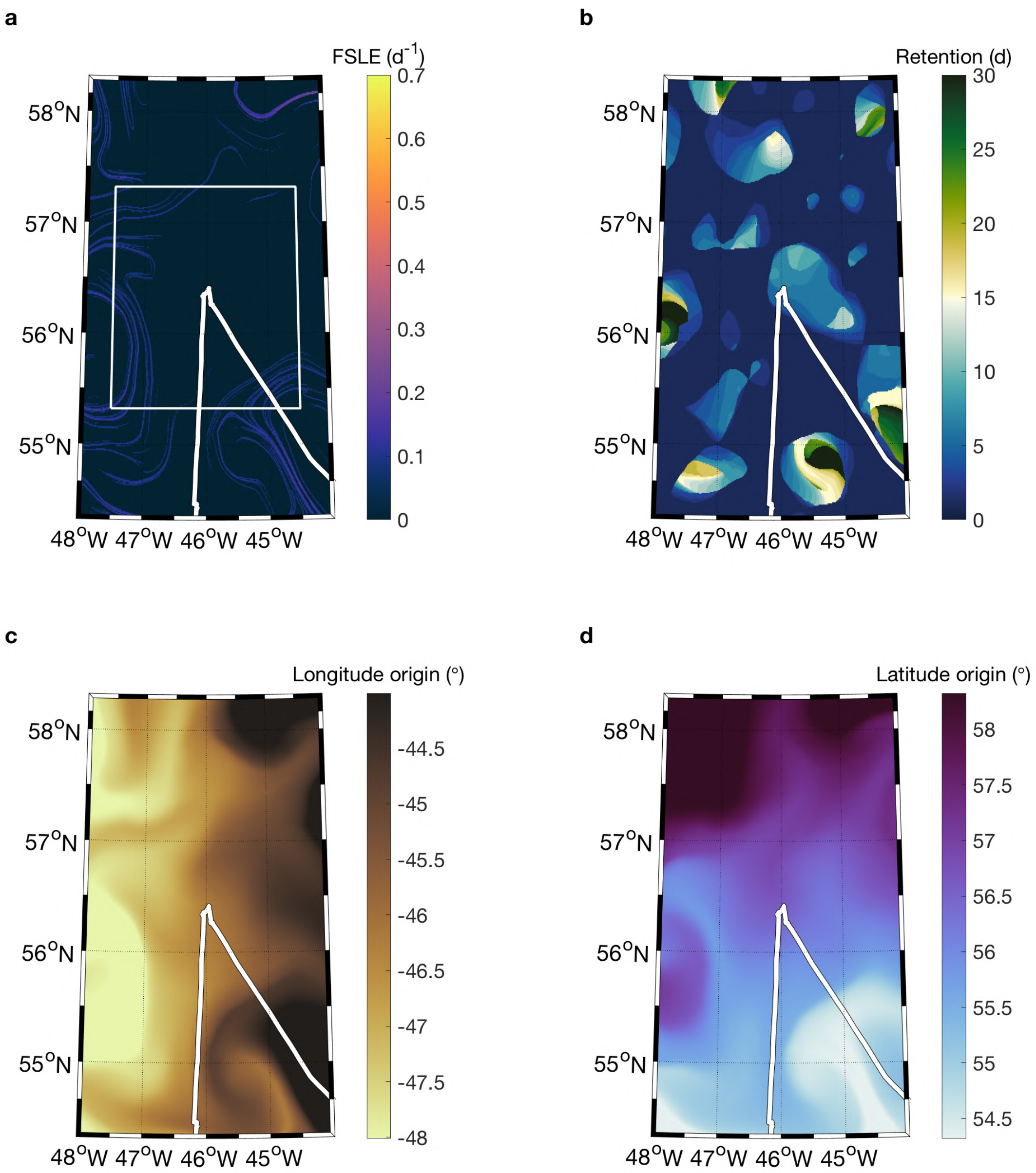

Figure S25. Same as Fig. S7.

3.2.3 S2 NAAMES-2

This stations was located at the last-known surfacing location of a Bio-Argo float. The location was near a non-retentive anticyclonic eddy and the rotational currents of this eddy are readily visible in the drifter tracks (Fig. S26).

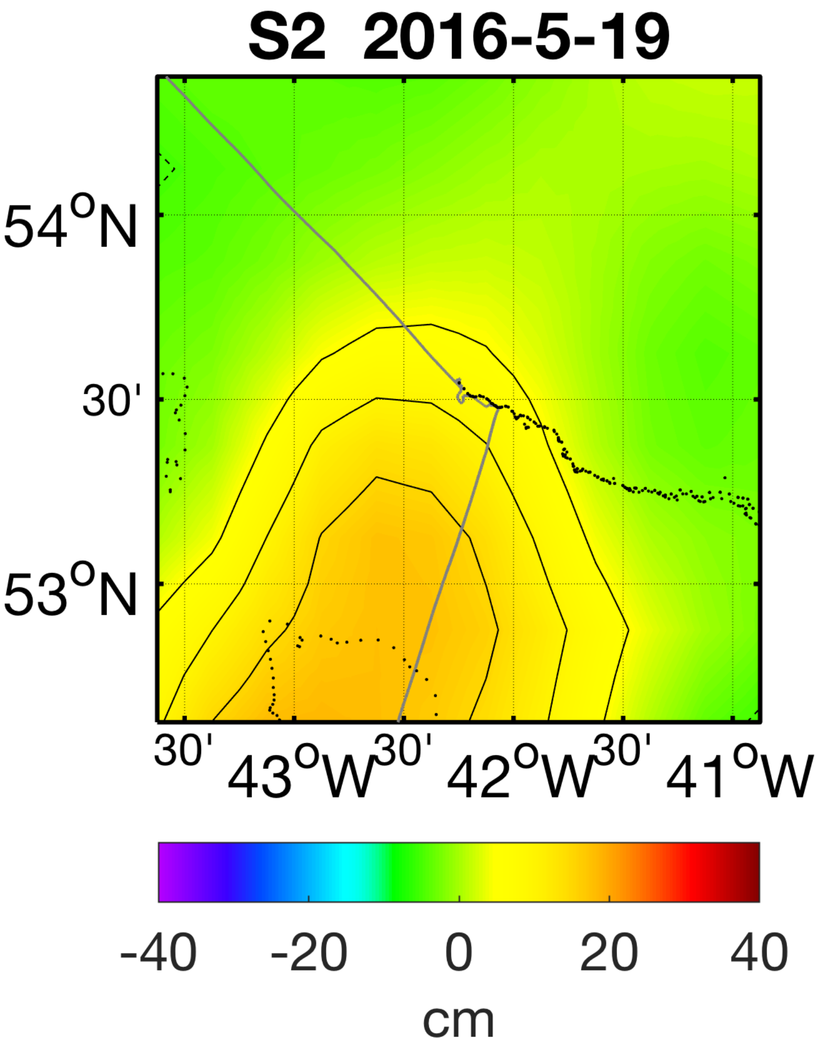

Figure S26. Same as Fig. S6.

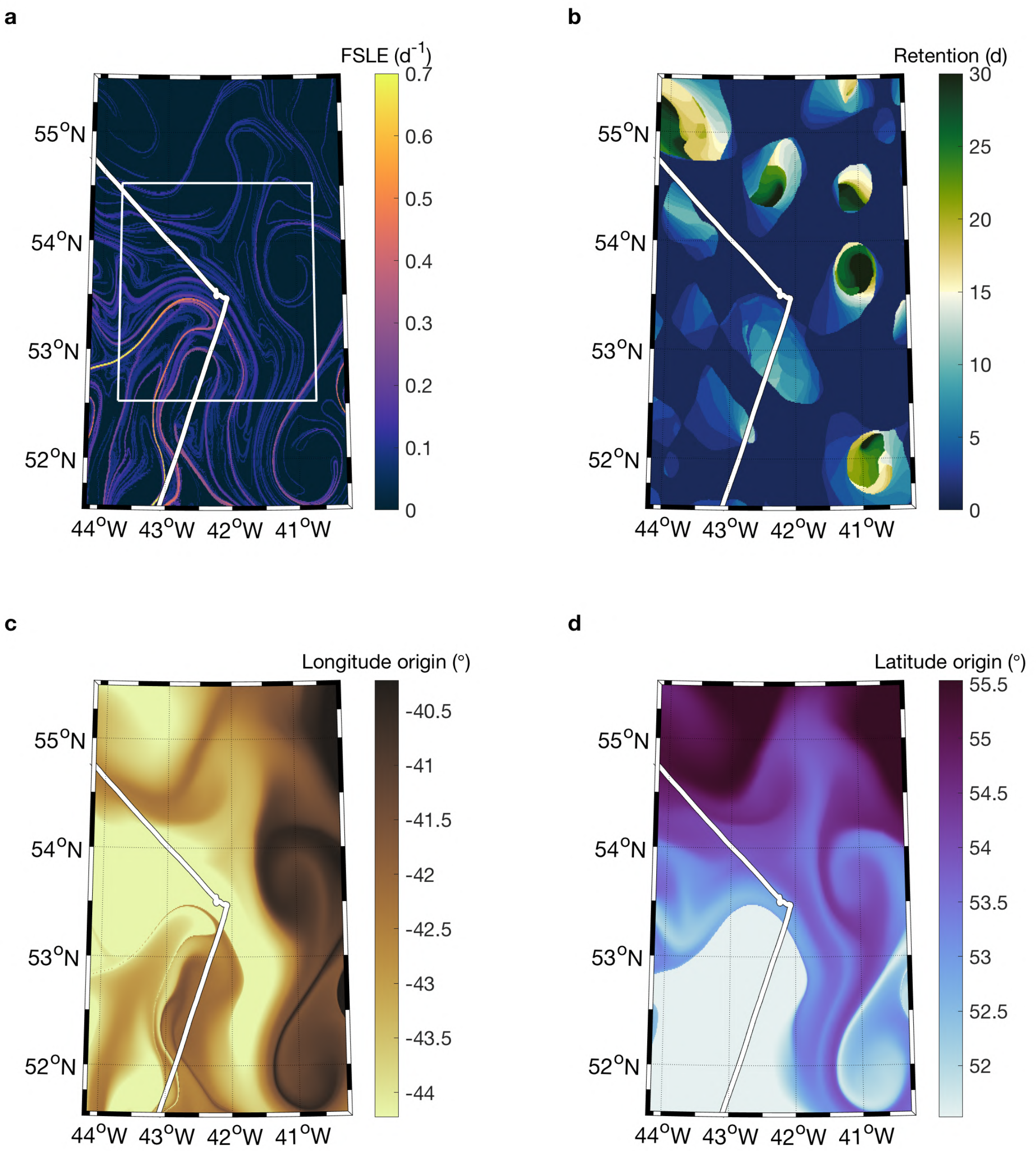

Figure S27. Same as Fig. S7.

3.2.4 S3 NAAMES-2

This location was chosen to be at the center of an anticyclonic eddy. This is the same anticyclone that was sampled at S1 on NAAMES-1 (See Fig. S6). This is a perfect example of the danger inherent in using optimally interpolated SLA products to guide field work. Although the station appeared to be in the core of the eddy according to the SLA signature (Fig. S26), the station was actually just outside of the eddy core and along the periphery, which is indicated by the trajectories of the drifters.

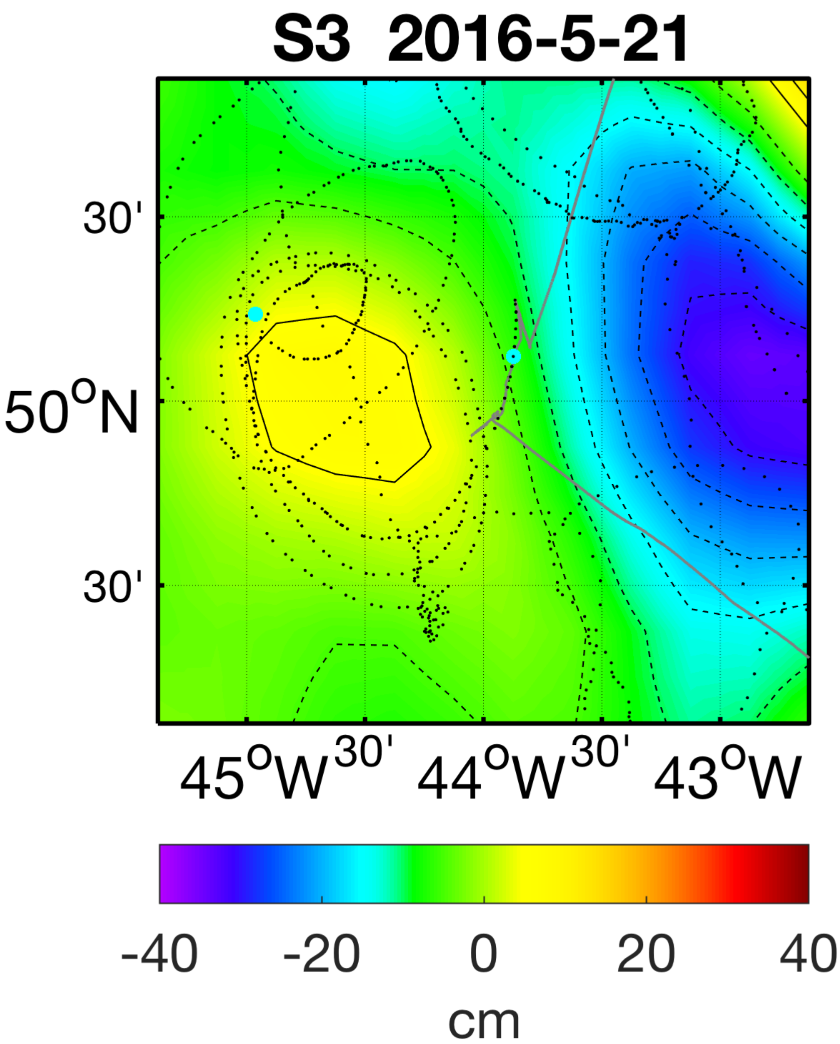

Figure S28. a)Same as Fig. S6.

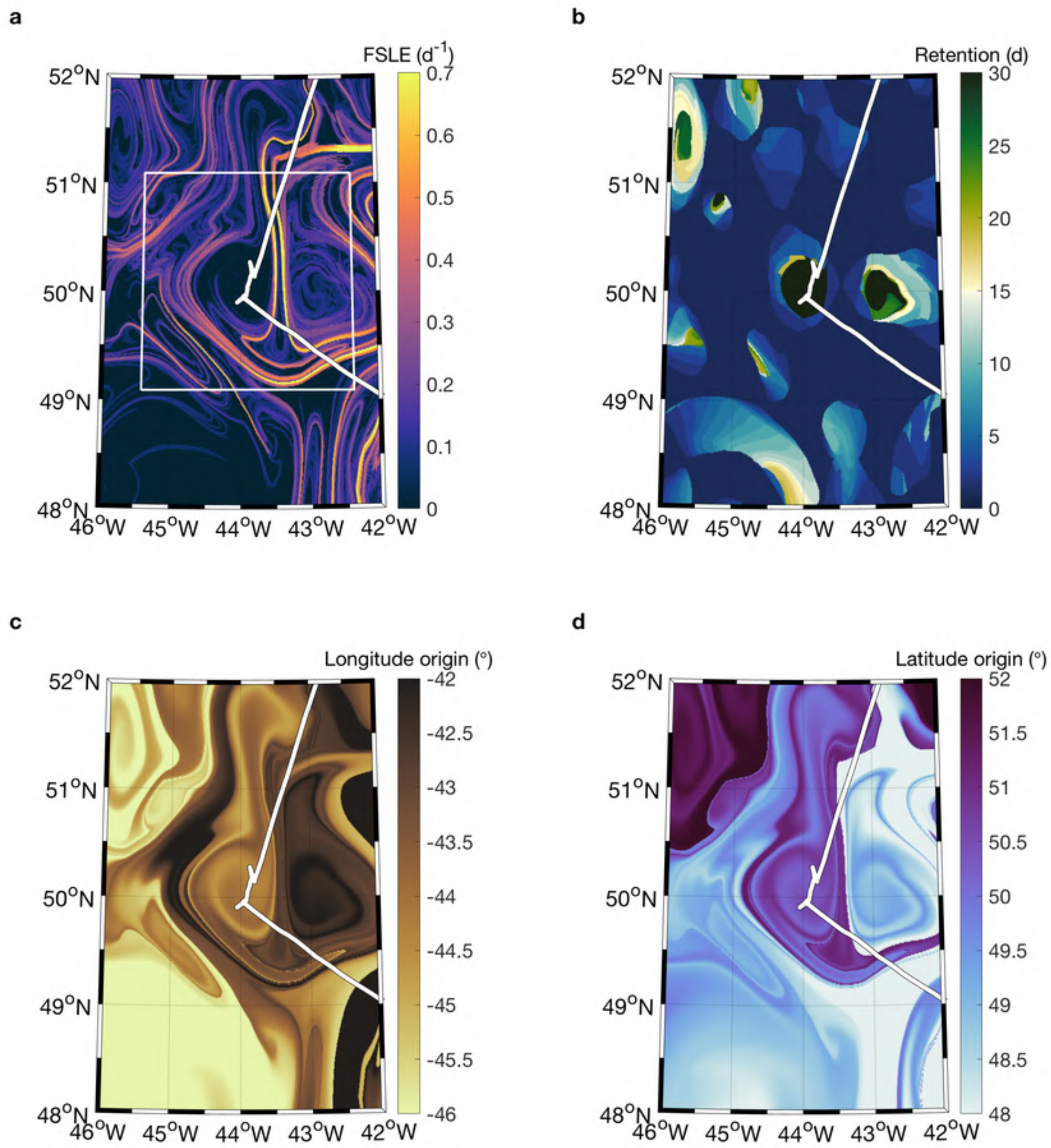

Figure S29. Same as Fig. S7.

3.2.5 S4 NAAMES-2

Station 4 was located within an anticyclone. Upon arrival surface Chlorophyll values were close to zero. The first few CTD casts indicated that the surface was well mixed to a depth of $\approx 230\ m$ (Fig. 3 a) in Mojica and Gaube (2018)). Within the first 24 hours, the water column began to stratify and the surface mixing layer was constrained to upper $\approx 20\ m$ (Mojica and Gaube, 2018).

The trajectory of the drifter was due southeast, likely as a result of the rotational currents of the anticyclone and the wind. We continued to follow the drifter and the float for 4 days. The trajectory of the R/V Atlantis allowed for the sampling of the radial gradient of the physical and biological properties of the eddy from the center to the periphery.

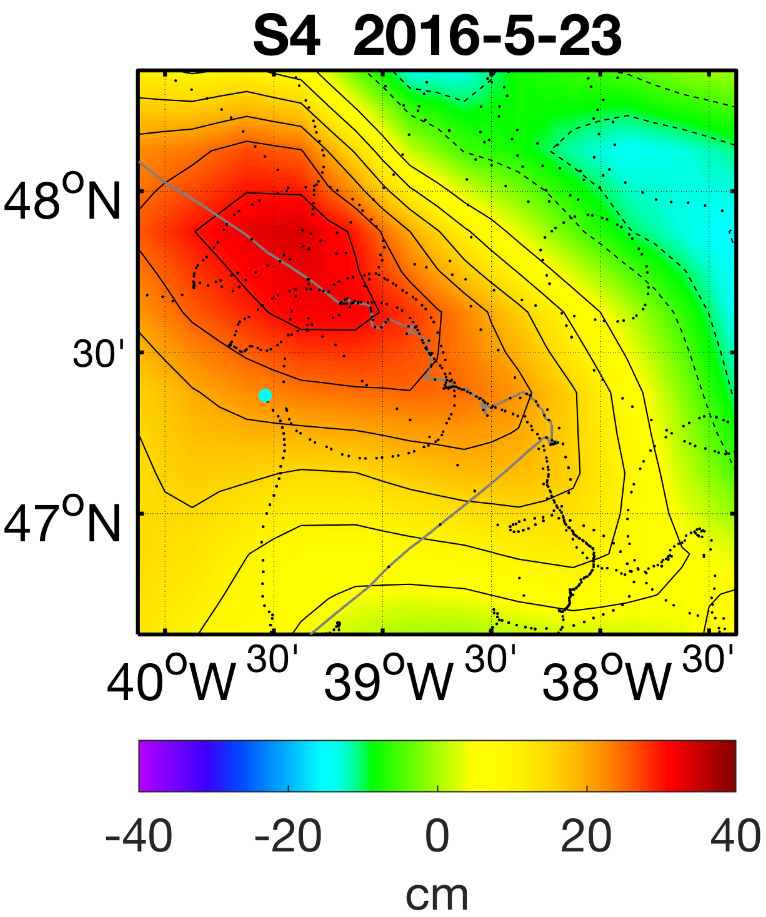

Figure S30. Same as Fig. S6.

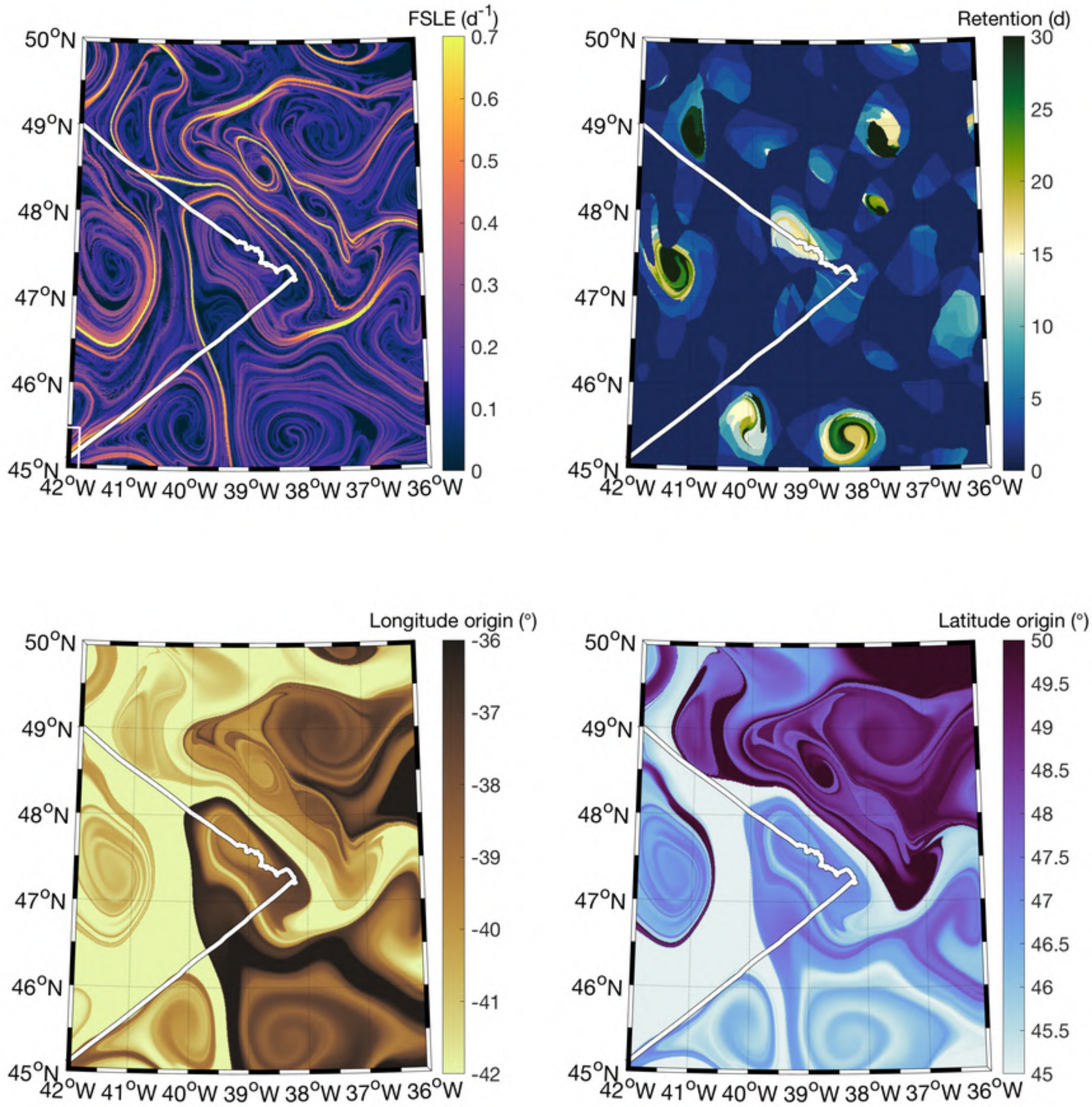

Figure S31. Same as Fig. S7.

3.2.6 S5 NAAMES-2

Station 5 was the final station for NAAMES-2. We chose the station based on the location of a Bio-Argo float. This station was also on the edge of a weakly retentive cyclonic eddy (Fig. S32). We were able to conduct standard science operation throughout the first day and then the following 40 hours were spent riding out a storm. This is why the ship track and drifters head northeast following our arrival on station.

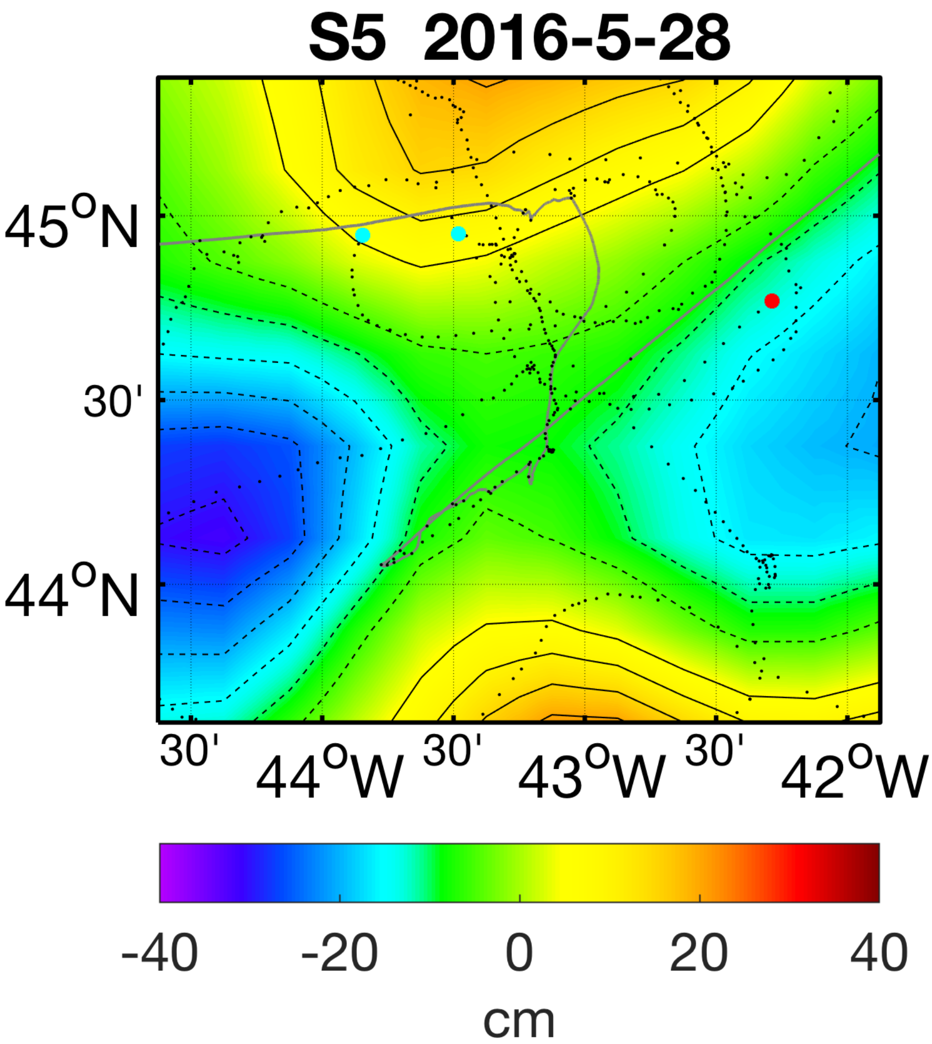

Figure S32. Same as Fig. S6.

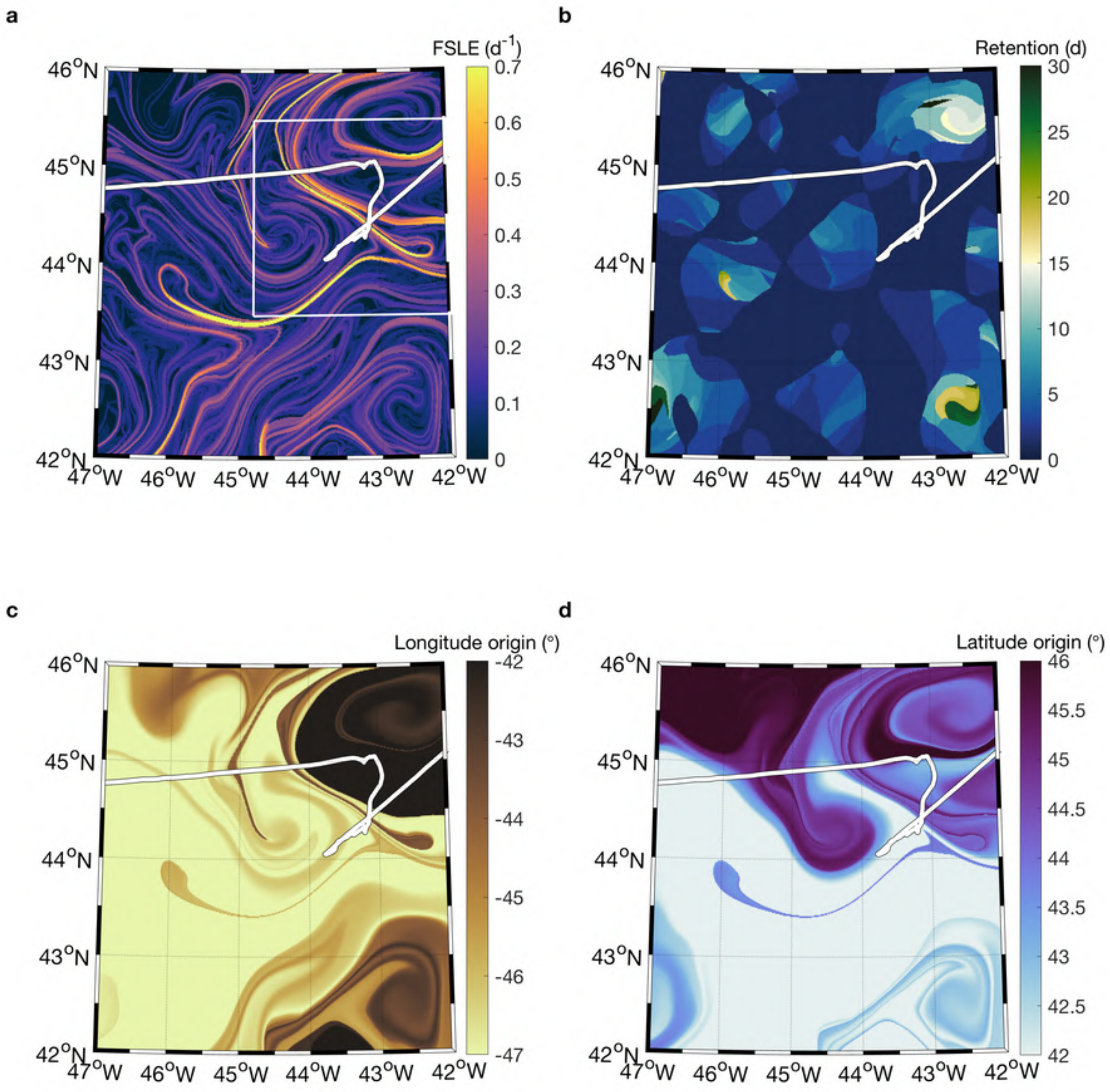

Figure S33. Same as Fig. S7.

3.3 NAAMES 3 - 2017

3.3.1 S1a NAAMES-3

Station 1a was not located within an eddy. The waters sampled at this station have a very different origin compared to Station 1 as they are separated by a strong gradient in water origin (Figure S35).

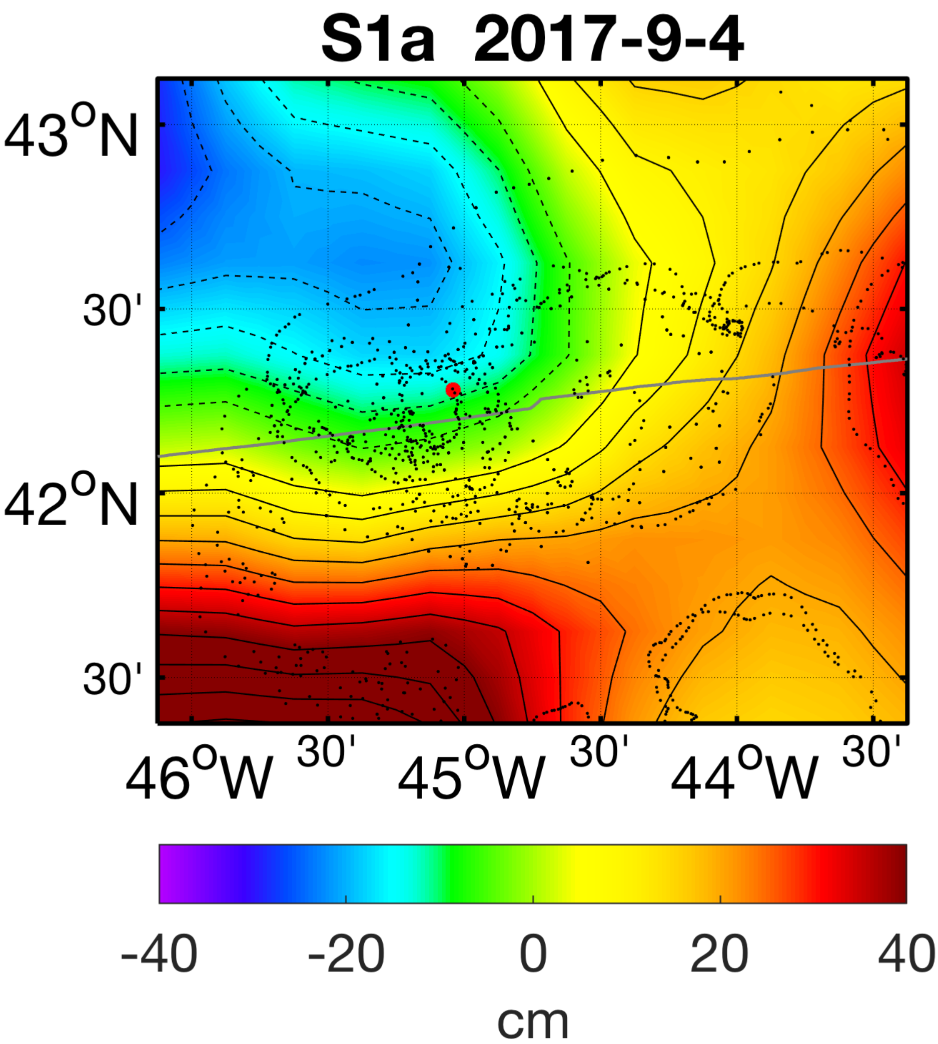

Figure S34. Same as Fig. S6.

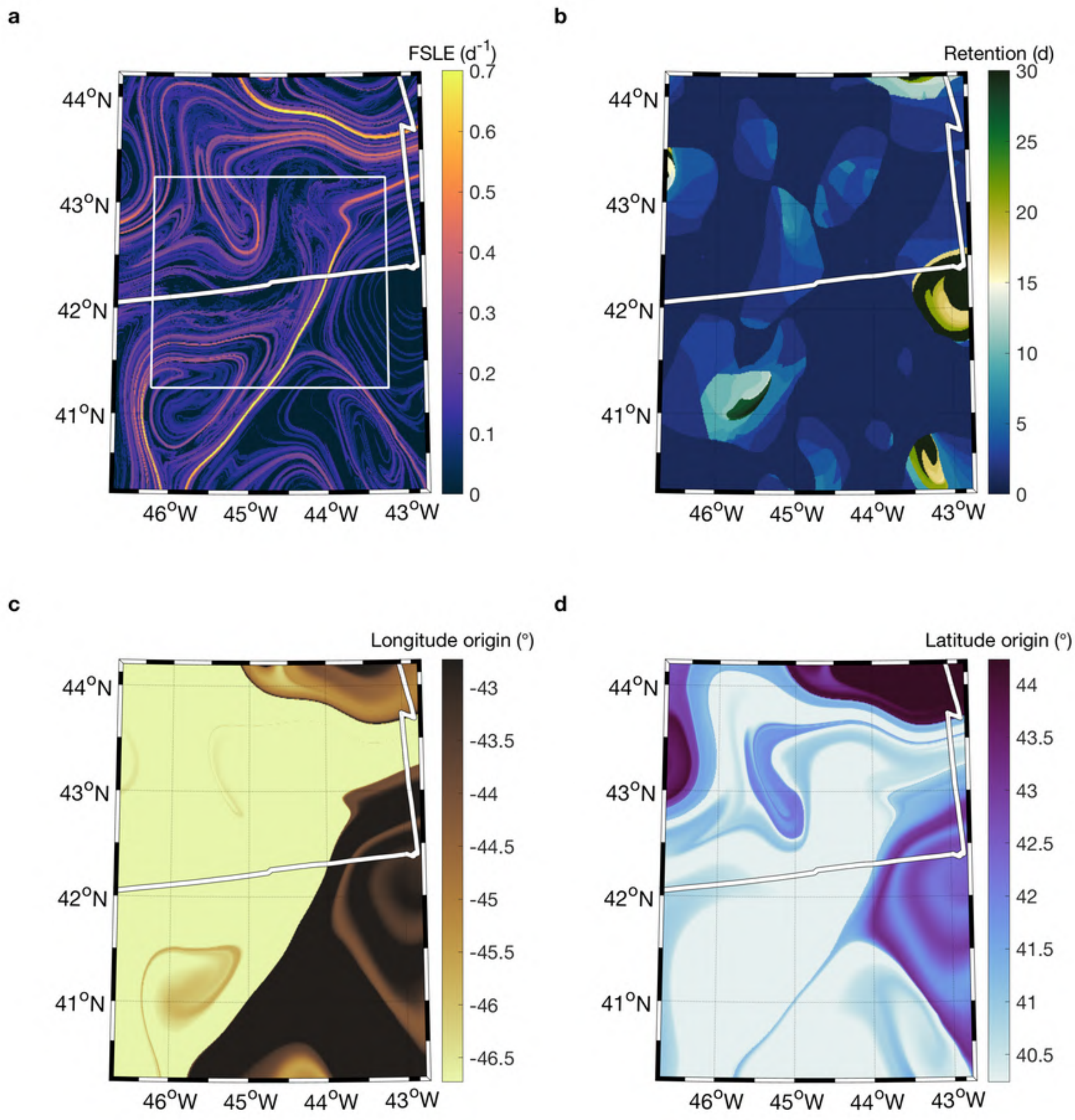

Figure S35. Same as Fig. S7.

3.3.2 S1 NAAMES-3

Station 1 was located within a retentive anticyclonic eddy. The strong signal in the gradient of SLA suggests strong geostrophic velocities that may have been able to trap water parcels and cause high retention within the eddy core (Figure S37 b)) and separate the eddy from the waters coming from the south-east (Figure S37 c) and d)). However, the deployed drifters did not stay within the eddy core, suggesting that the currents in the top 15m may have caused this eddy to "leak" water parcels near the surface.

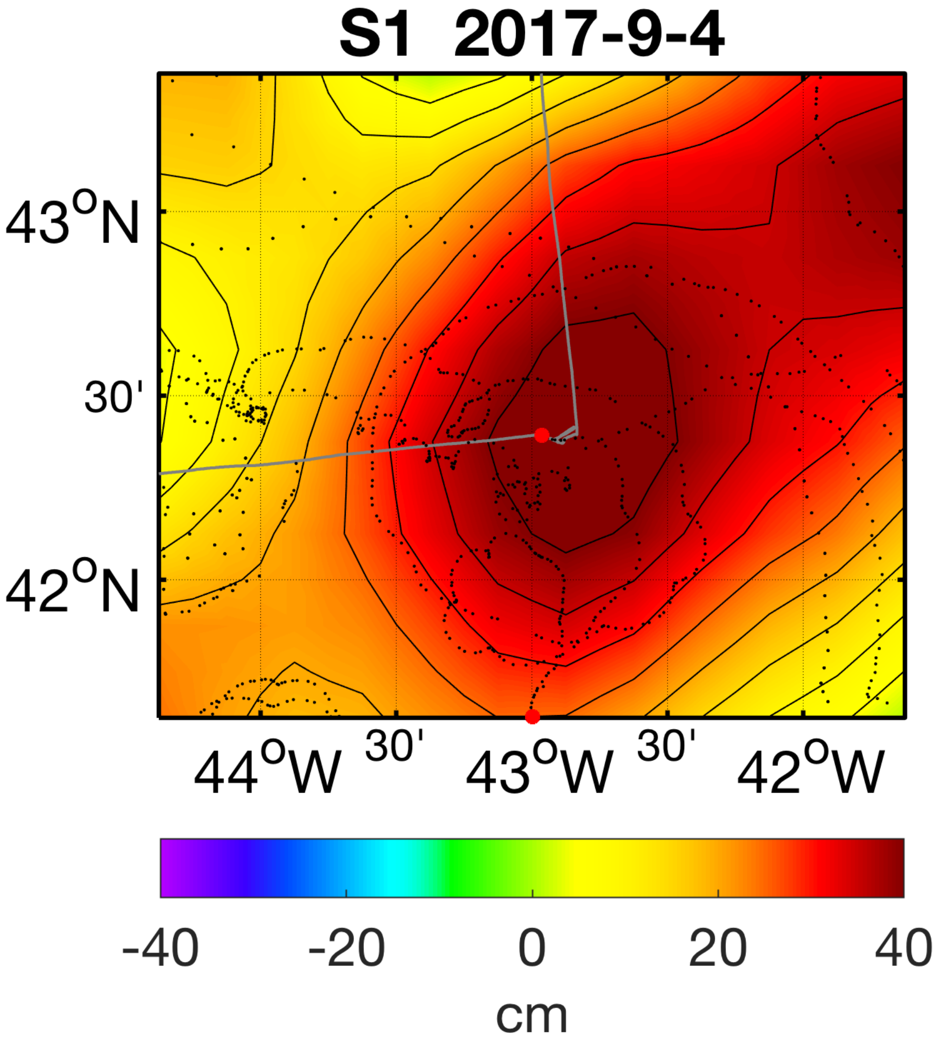

Figure S36. Same as Fig. S6.

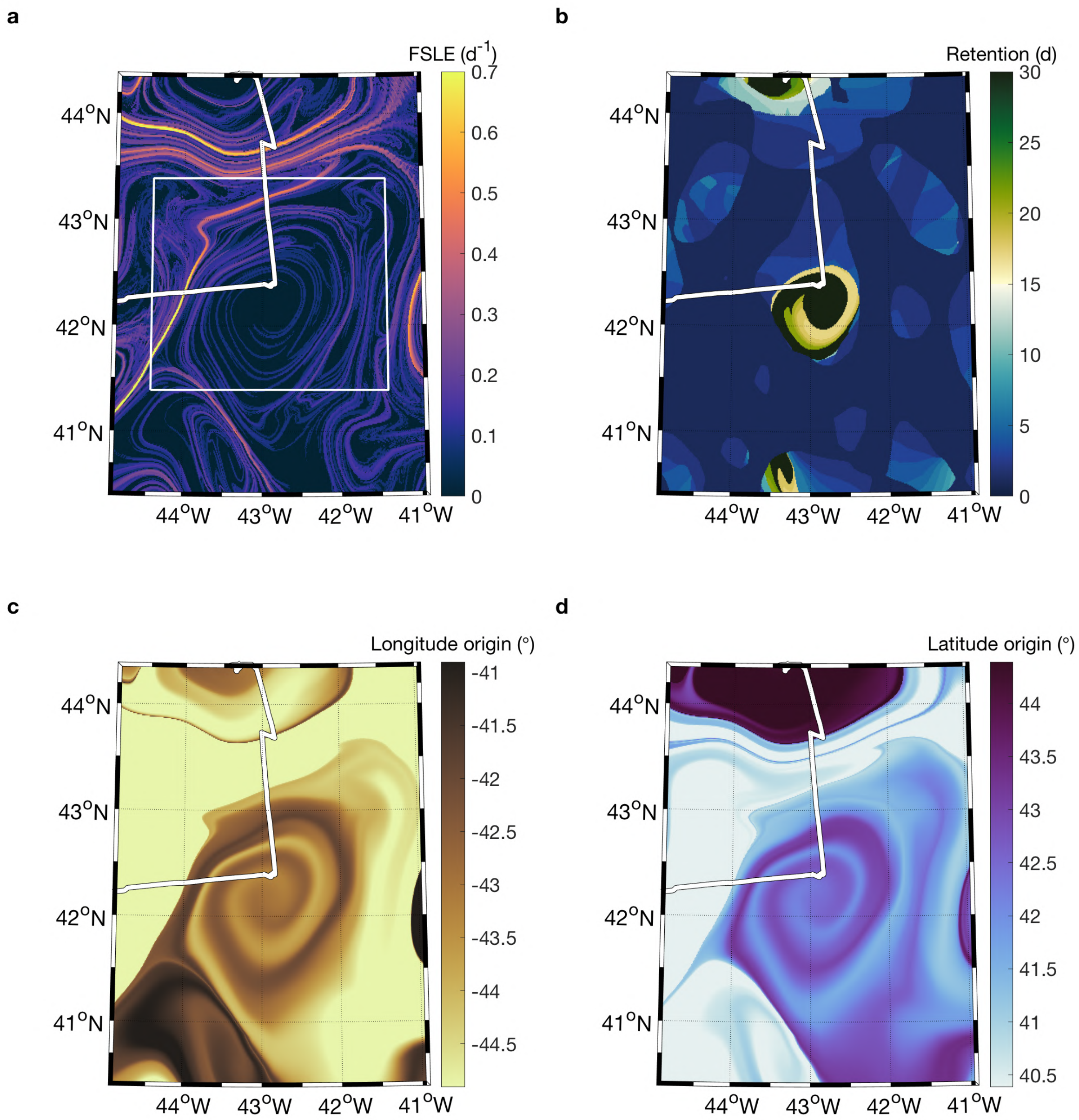

Figure S37. Same as Fig. S7.

3.3.3 S1.5 NAAMES-3

Station 1.5 was an in-between station. It was located between the two mesoscale eddies sampled as S1 and S2, an anticyclone and a cyclone respectively.

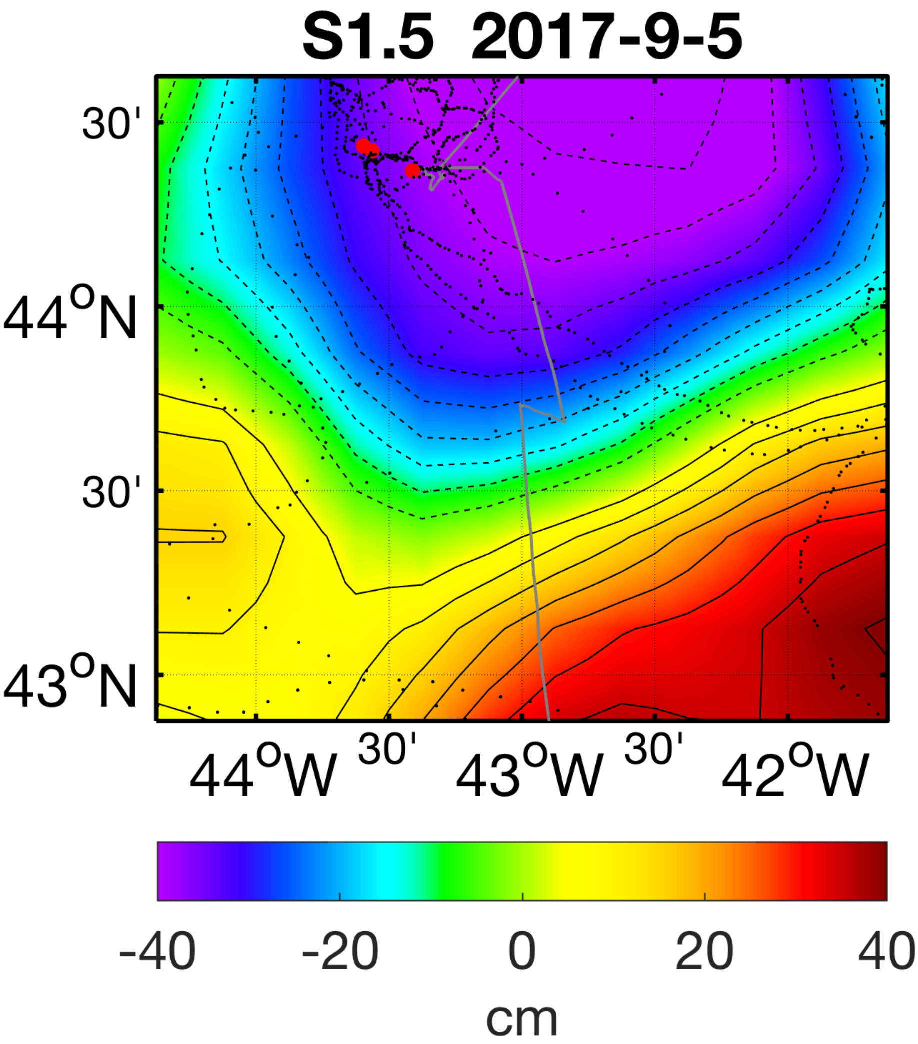

Figure S38. Same as Fig. S6.

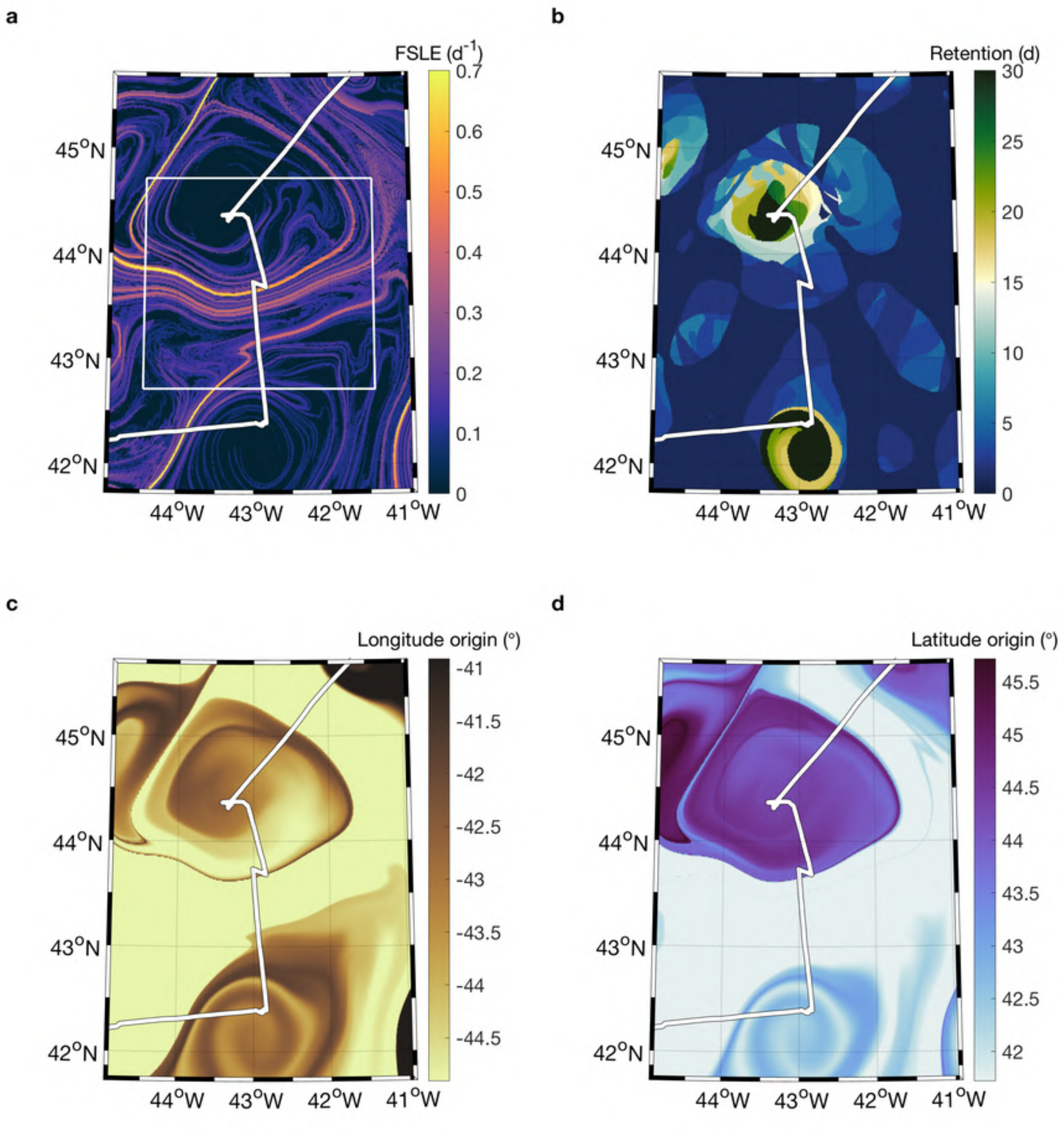

Figure S39. Same as Fig. S7.

3.3.4 S2 NAAMES-3

Station 2 was set at the center of a cyclonic eddy. This eddy appears from altimetry to be moderately retentive and is separated from the surrounding waters by strong transport fronts (highlighted by the high values of FSLEs in Figure S41 a)). The deployed drifters were entrained within the eddy core for several rotations before they exited the eddy.

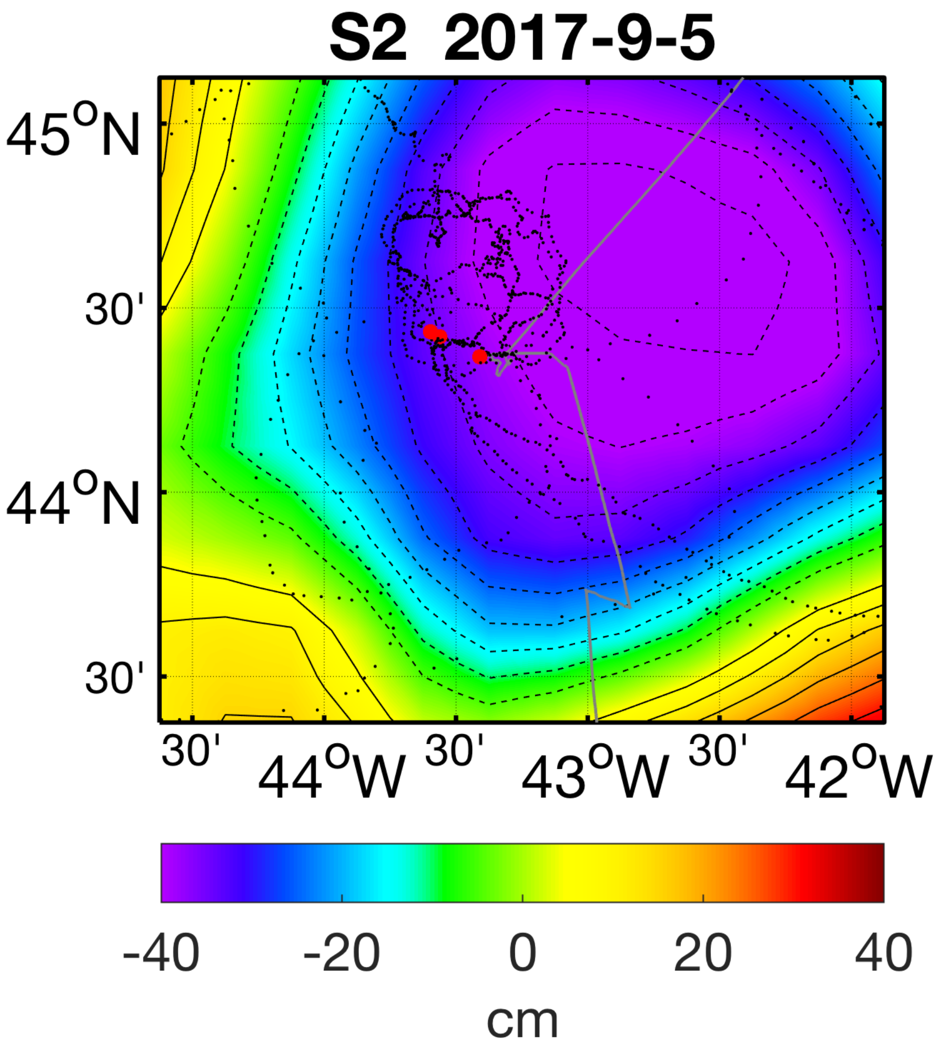

Figure S40. Same as Fig. S6.

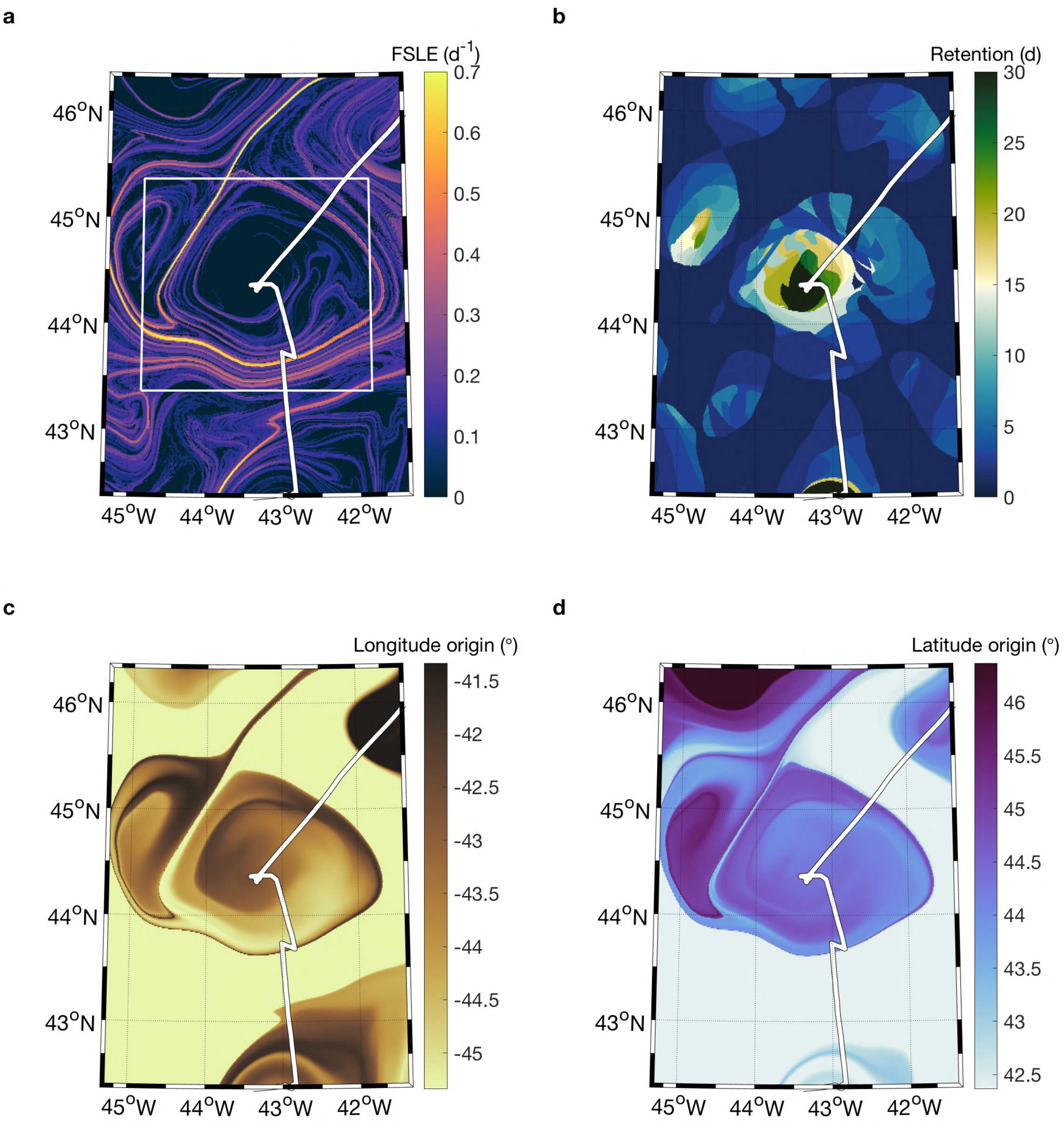

Figure S41. Same as Fig. S7.

3.3.5 S3 NAAMES-3

Station 3 was located at the center of a mode-water eddy (McGillicuddy et al., 2007). Mode-water eddies are a feature of the northwestern subtropical Atlantic: they rotate as anticyclones (*i.e.*, clockwise) and are indistinguishable from anticyclones from their altimetric signature (see Figure S42). However, their vertical structure is very different (as it was observed during the CTD casts): the main thermocline is deepened (as in anticyclones) whereas the seasonal thermocline is shoaled (as in cyclones). The result is a layer of relatively uniform water properties (mode-water) extending, in this case, down to 600 m. As a consequence, just as cyclones, mode-water eddies are expected to bring nutrients into the euphotic zone during their formation and intensification phases. This specific mode-water eddy appeared particularly retentive in the layer dominated by geostrophic velocities and was separated from the surrounding waters by strong transport fronts (Figures S43 and S43).

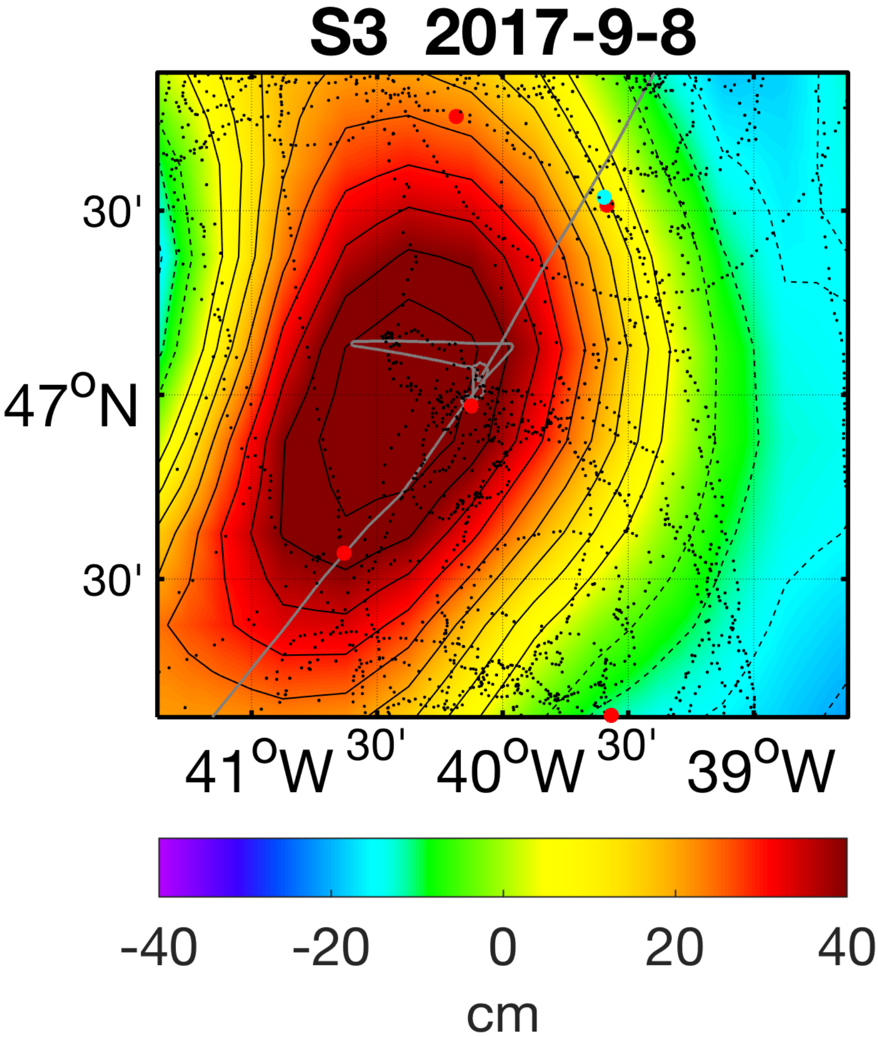

Figure S42. Same as Fig. S6.

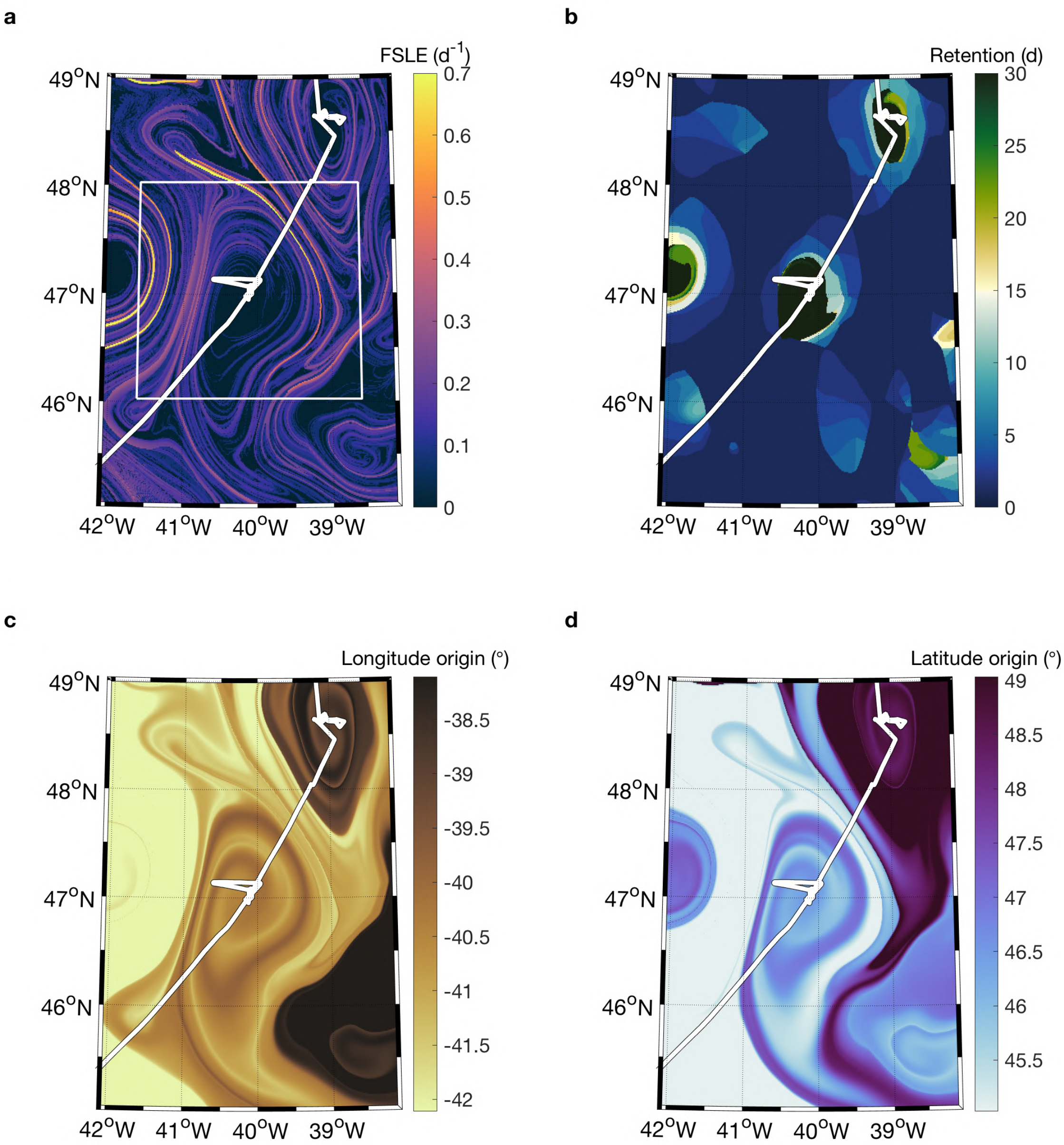

Figure S43. Same as Fig. S7.

3.3.6 S3.5 NAAMES-3

This “in-between” station was located between the mode water eddy sampled at Station 3 and the small retentive cyclone sampled at station 4.

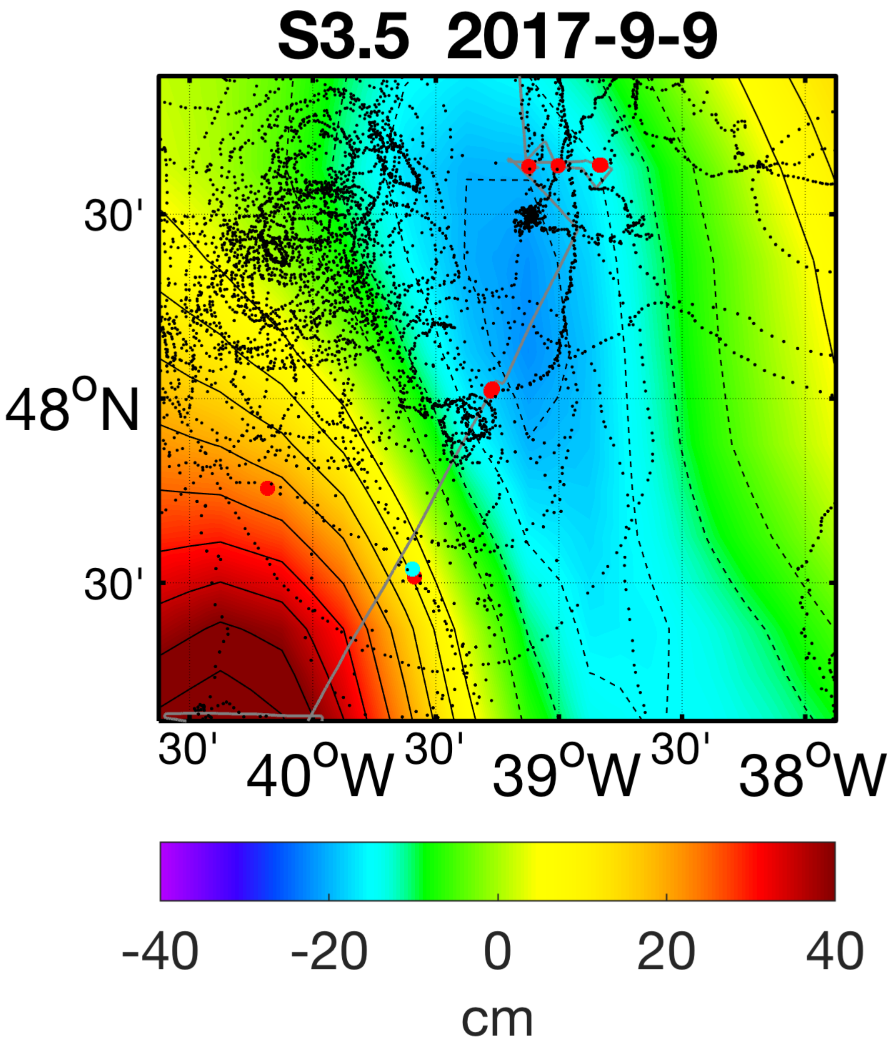

Figure S44. Same as Fig. S6.

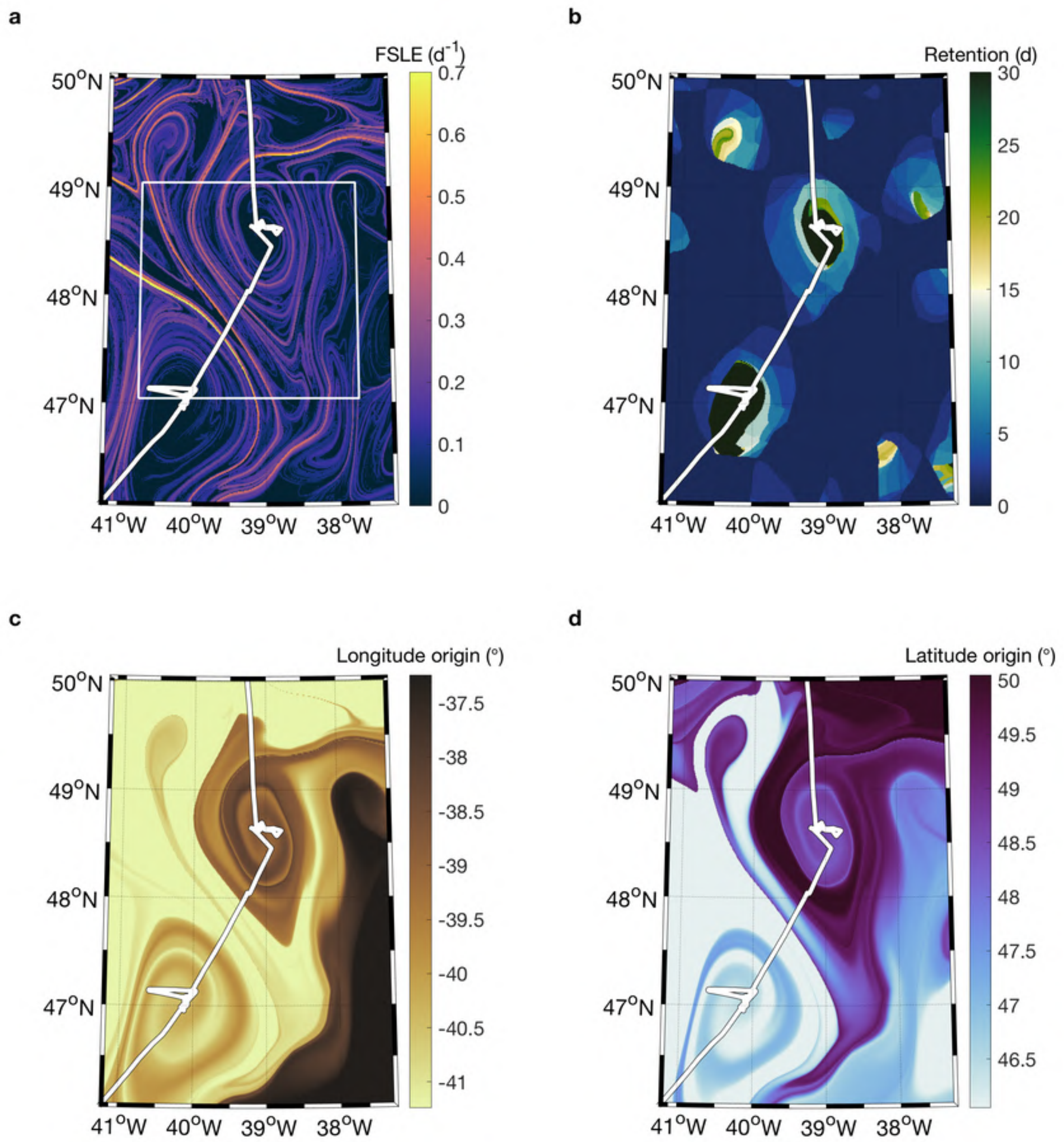

Figure S45. Same as Fig. S7.

3.3.7 S4 NAAMES-3

We aimed at locating Station 4 at the center of a small, but strongly retentive cyclone. Locating the center of this very small cyclone was extremely difficult and the station may have been located in the proximity of the eddy center, but likely a few kilometers away. The drifters did not appear to be trapped by the eddy when they were deployed. However, the trajectories of some of them suggest, from a preliminary analysis, that they may have ended up trapped in an eddy after a short time (likely the eddy sampled in Station 4).

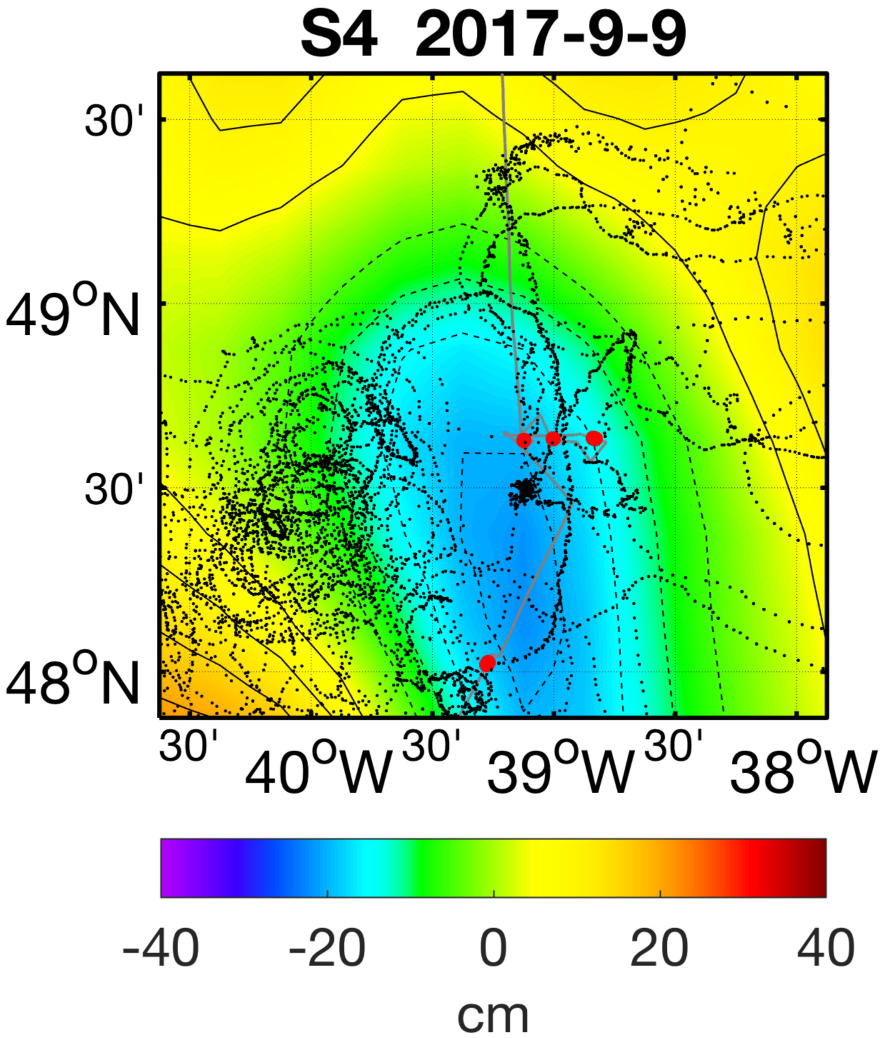

Figure S46. Same as Fig. S6.

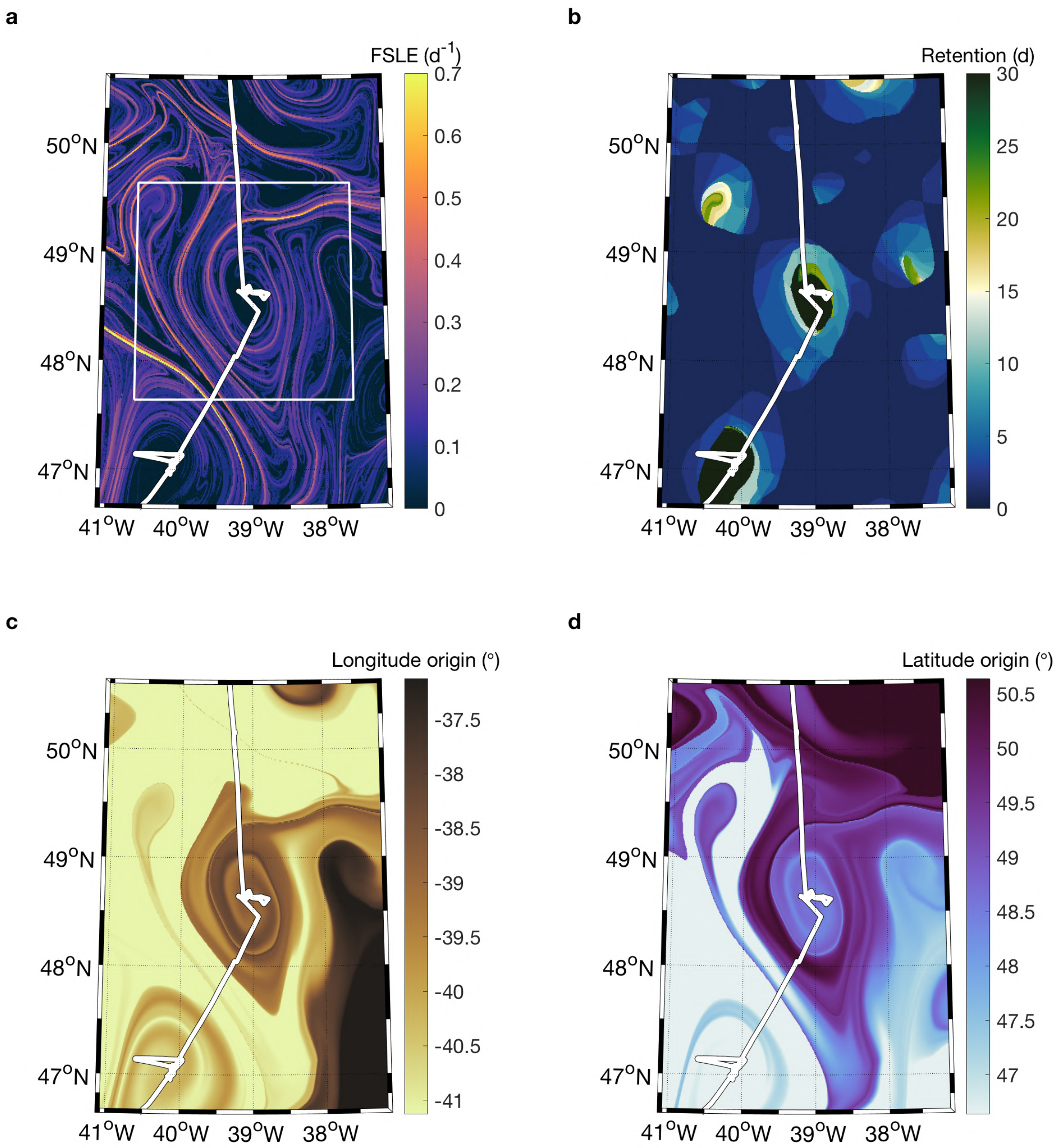

Figure S47. Same as Fig. S7.

3.3.8 S4.5 NAAMES-3

This "in-between" station was not located in the close proximity of any mesoscale feature.

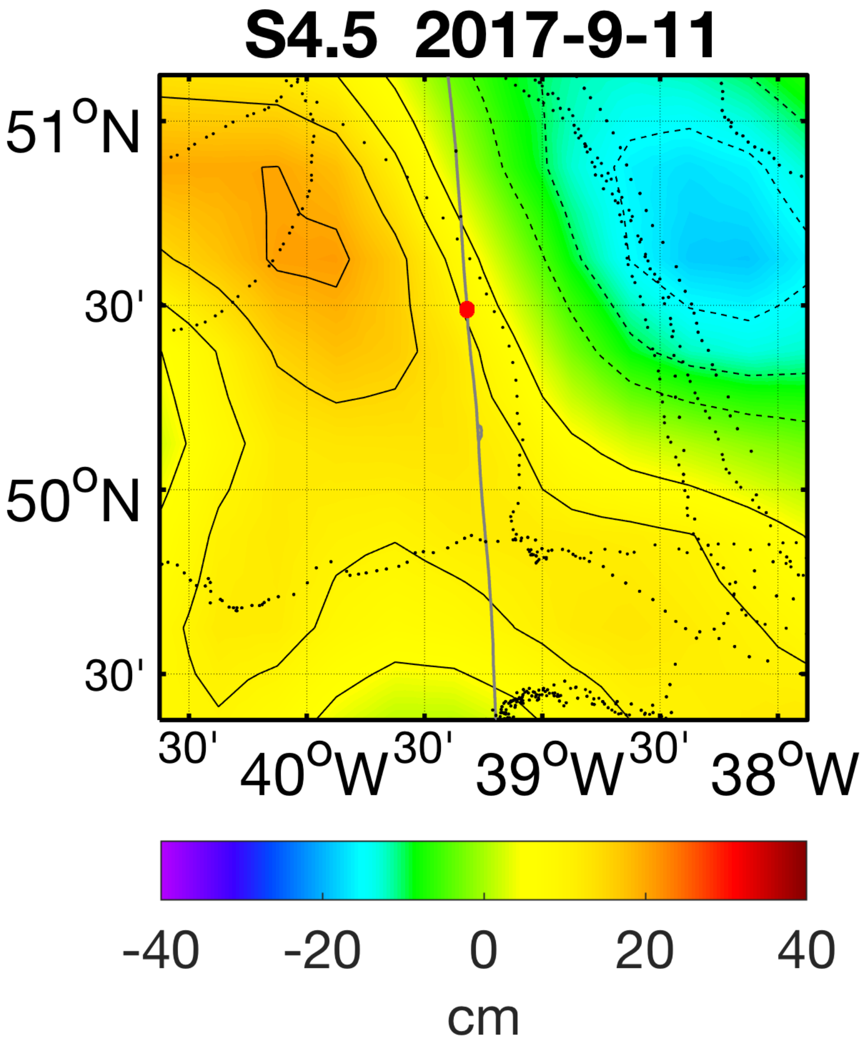

Figure S48. Same as Fig. S6.

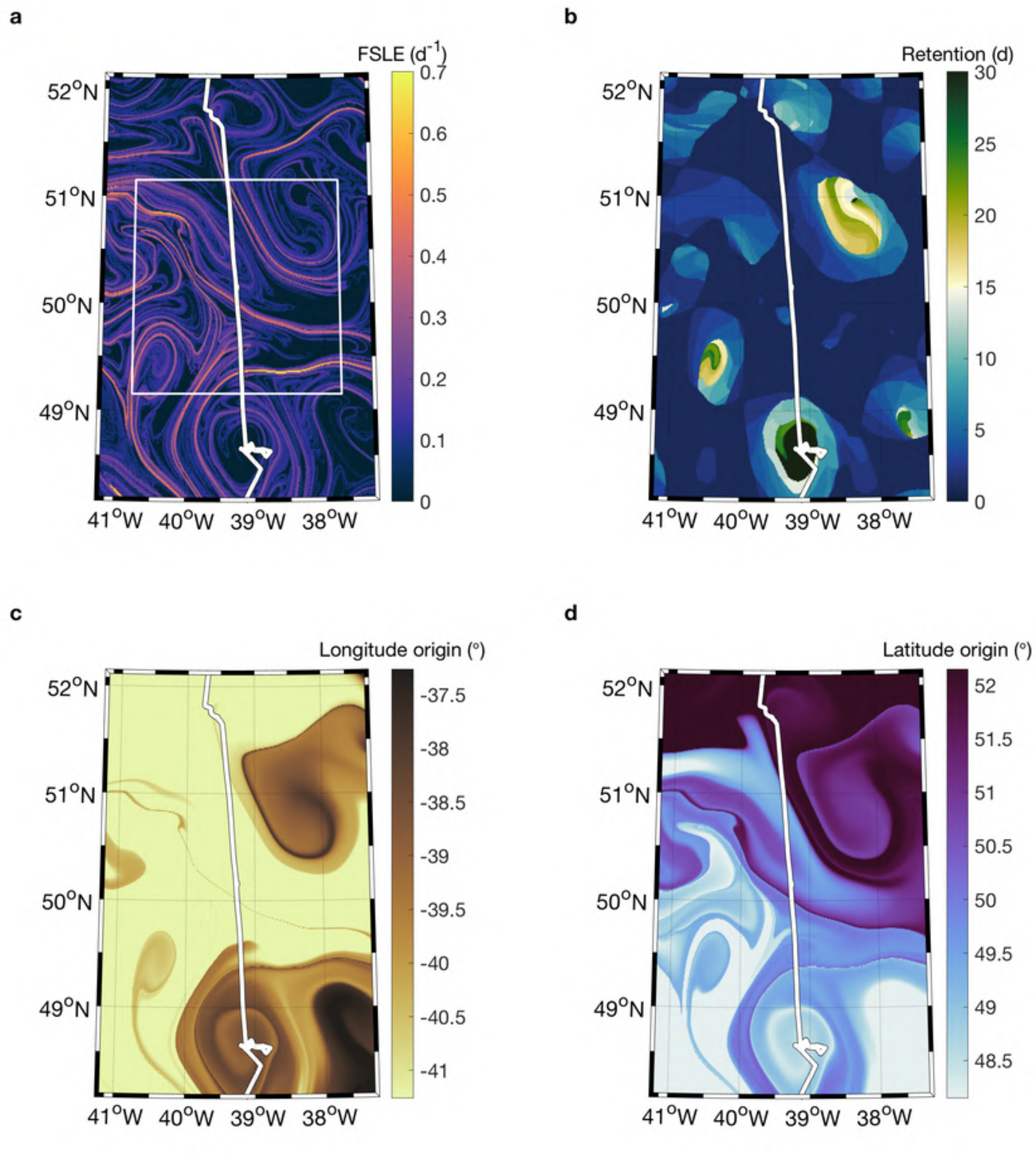

Figure S49. Same as Fig. S7.

3.3.9 S5 NAAMES-3

Station 5 was chosen as a “non-eddy station” and it appears to be in relatively uniform waters in the proximity of a weak recirculation structure.

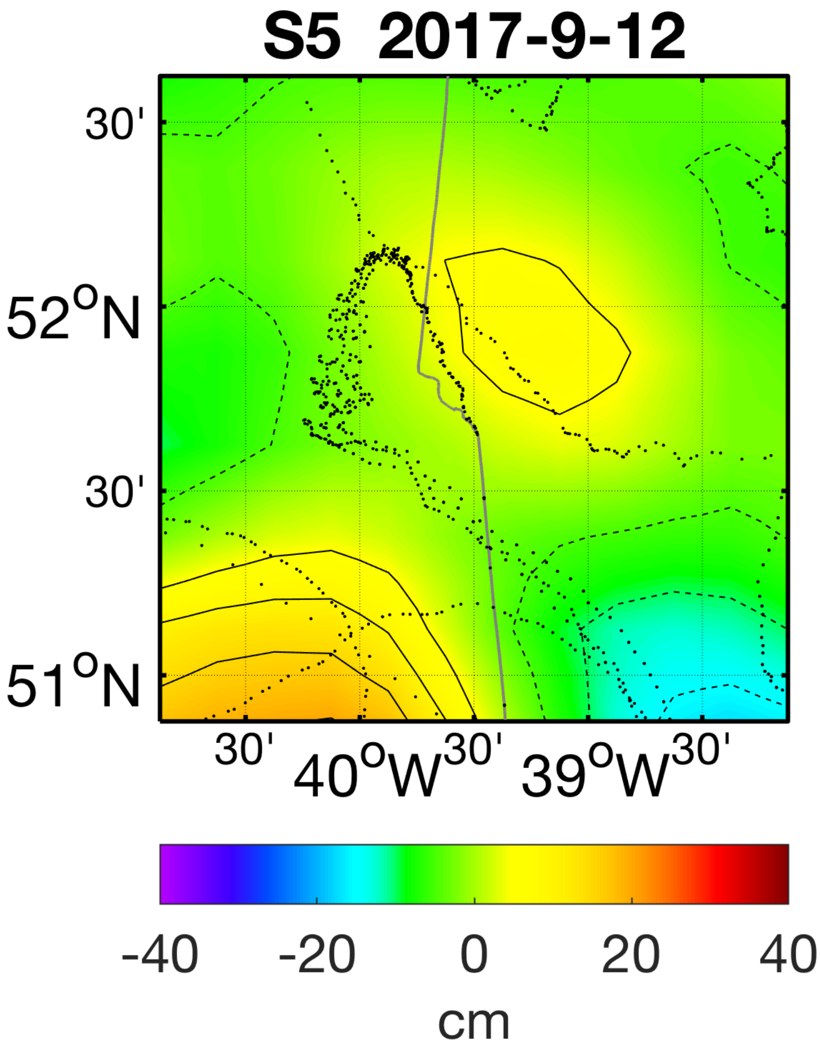

Figure S50. Same as Fig. S6.

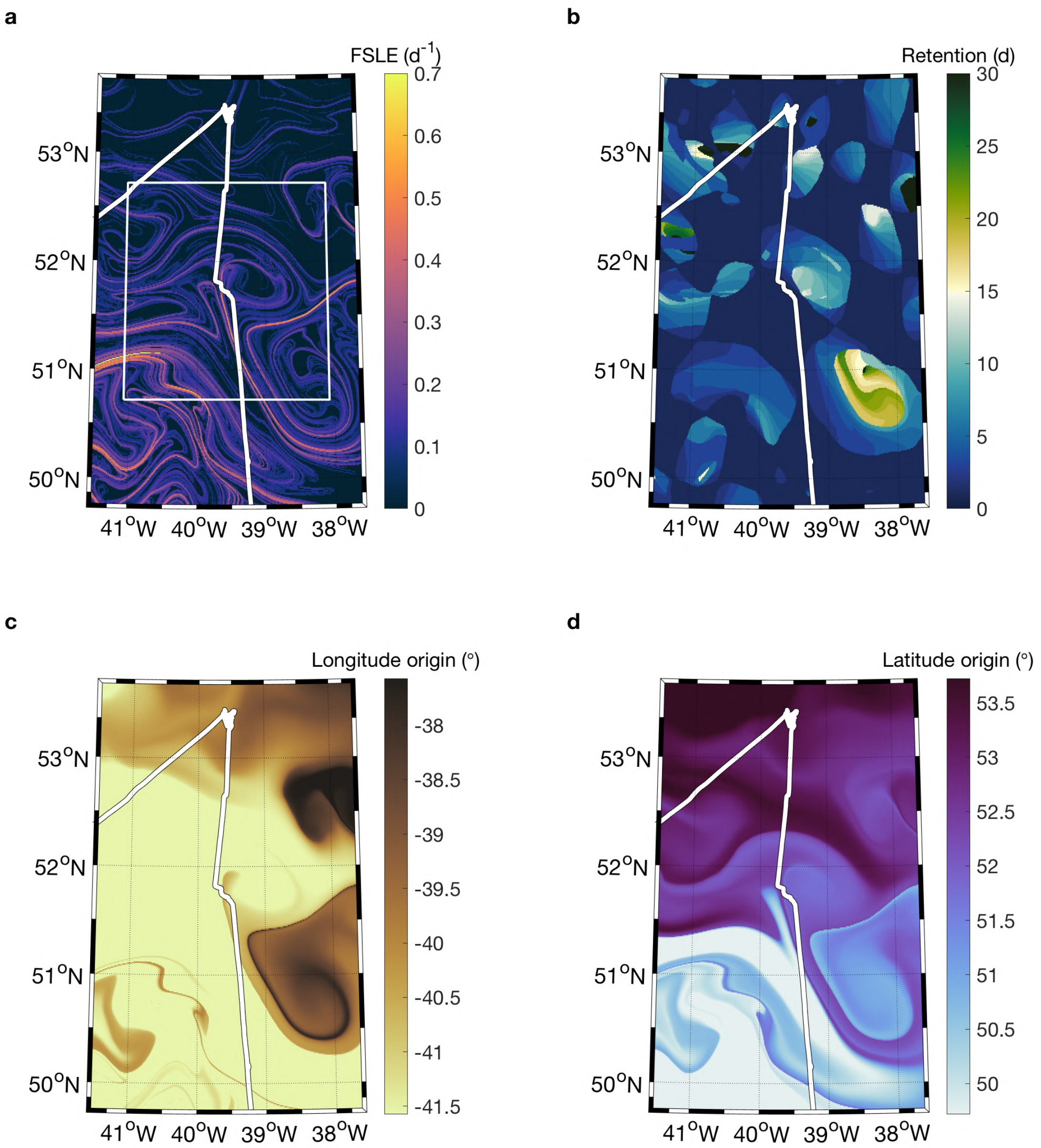

Figure S51. Same as Fig. S7.

3.3.10 S5.5 NAAMES-3

This was an “in-between” station.

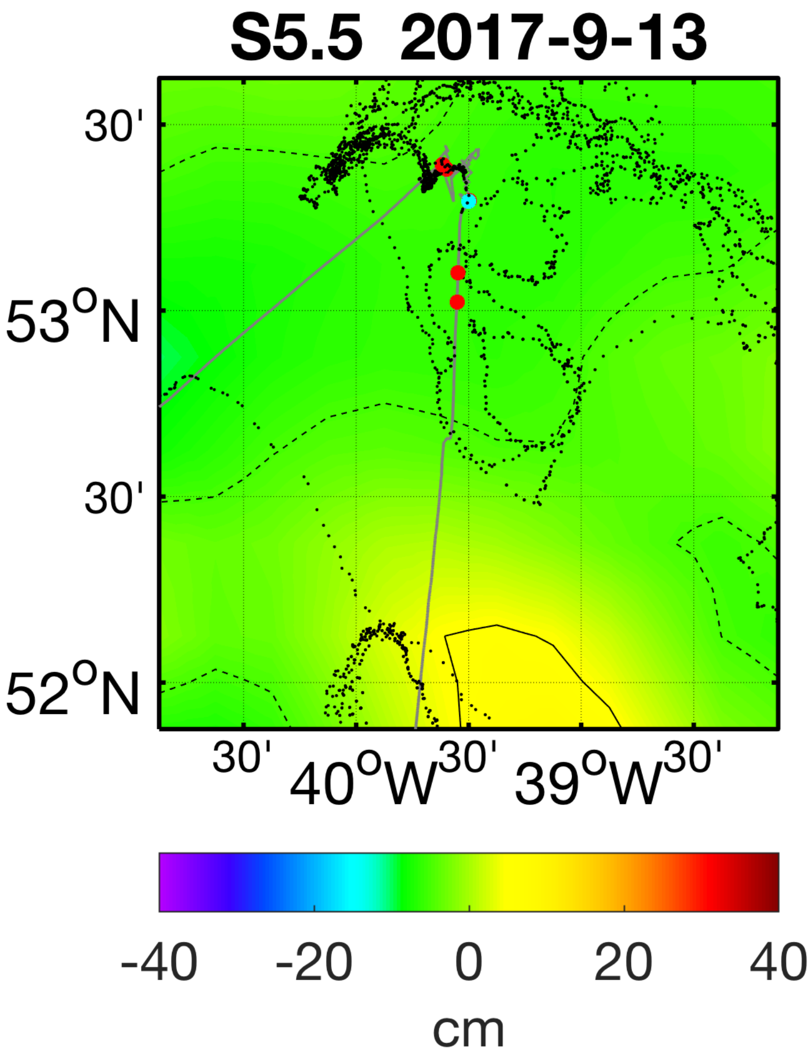

Figure S52. Same as Fig. S6.

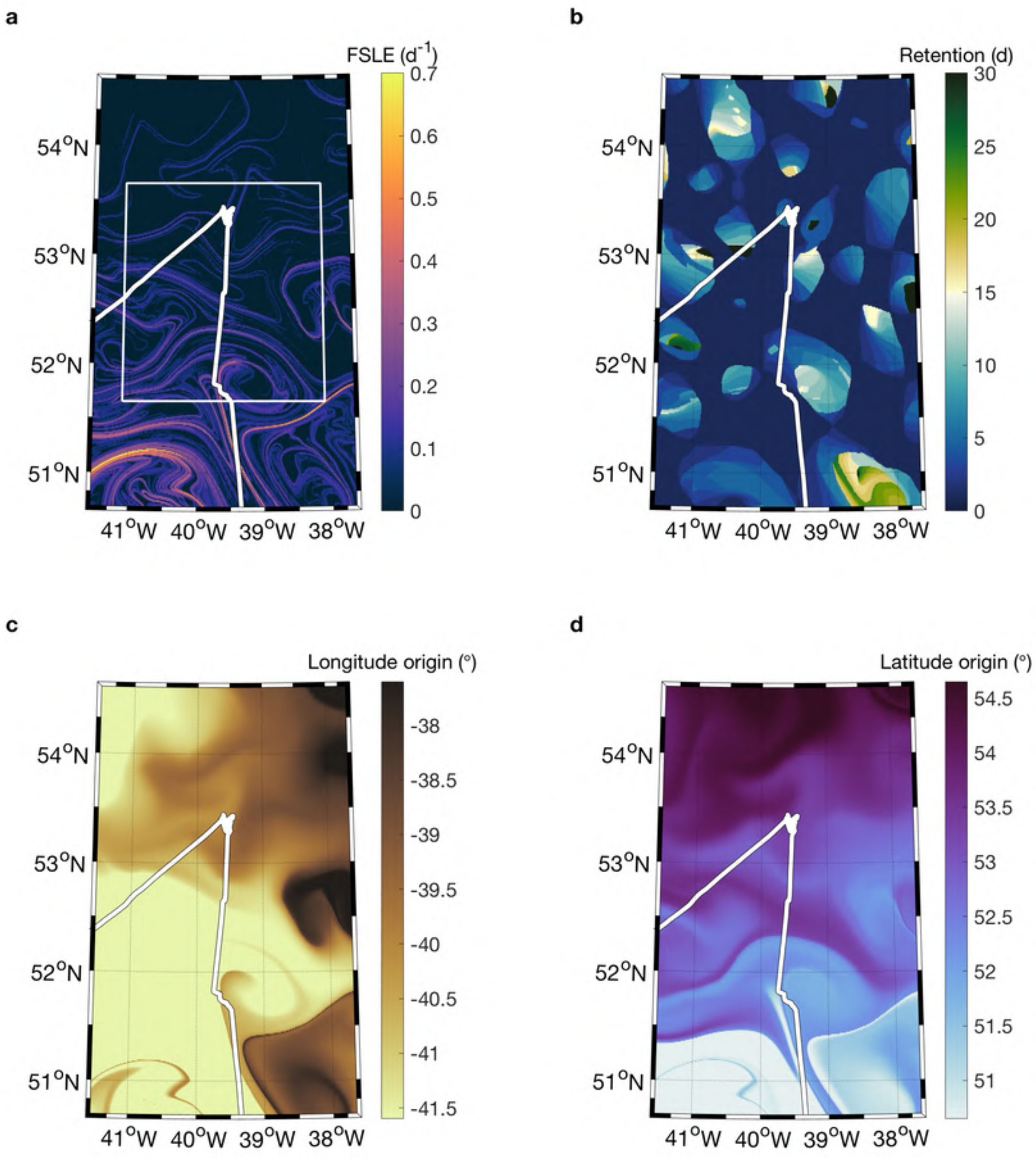

Figure S53. Same as Fig. S7.

3.3.11 S6 NAAMES-3

Station 6 was the northernmost station sampled during this expedition. It was chosen because of its proximity to a float and displayed no signature in SLA. The drifters deployed at this station were advected east likely by the large scale wind-driven circulation of this region.

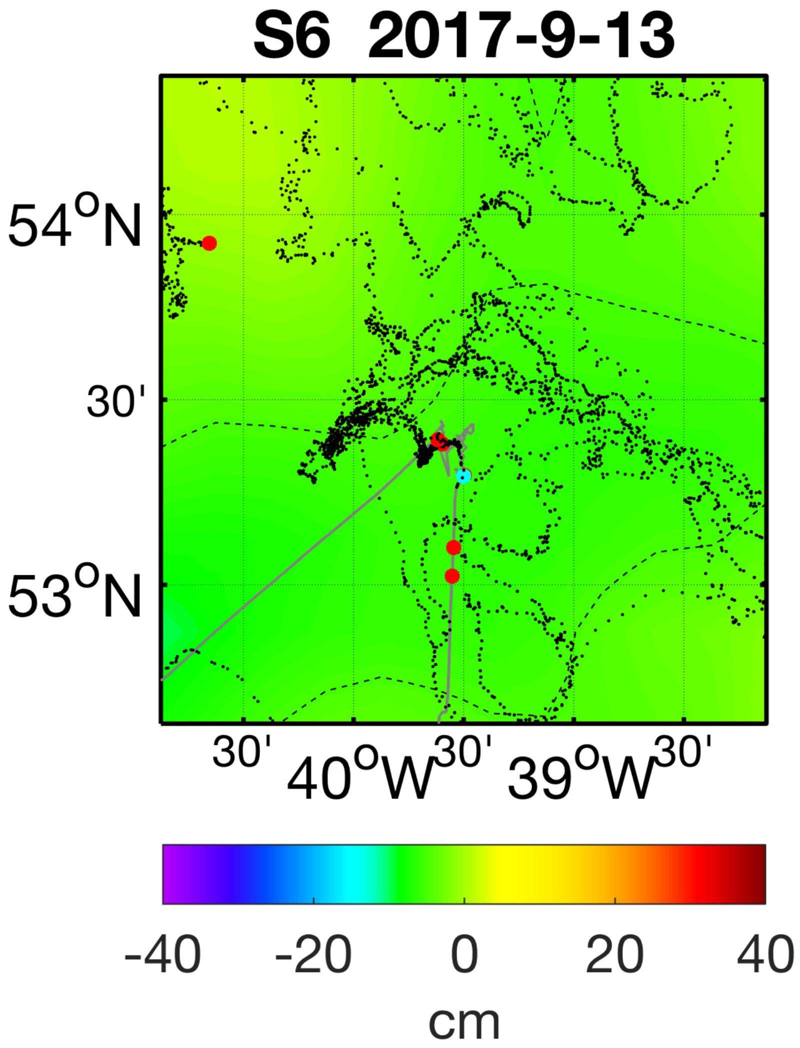

Figure S54. Same as Fig. S6.

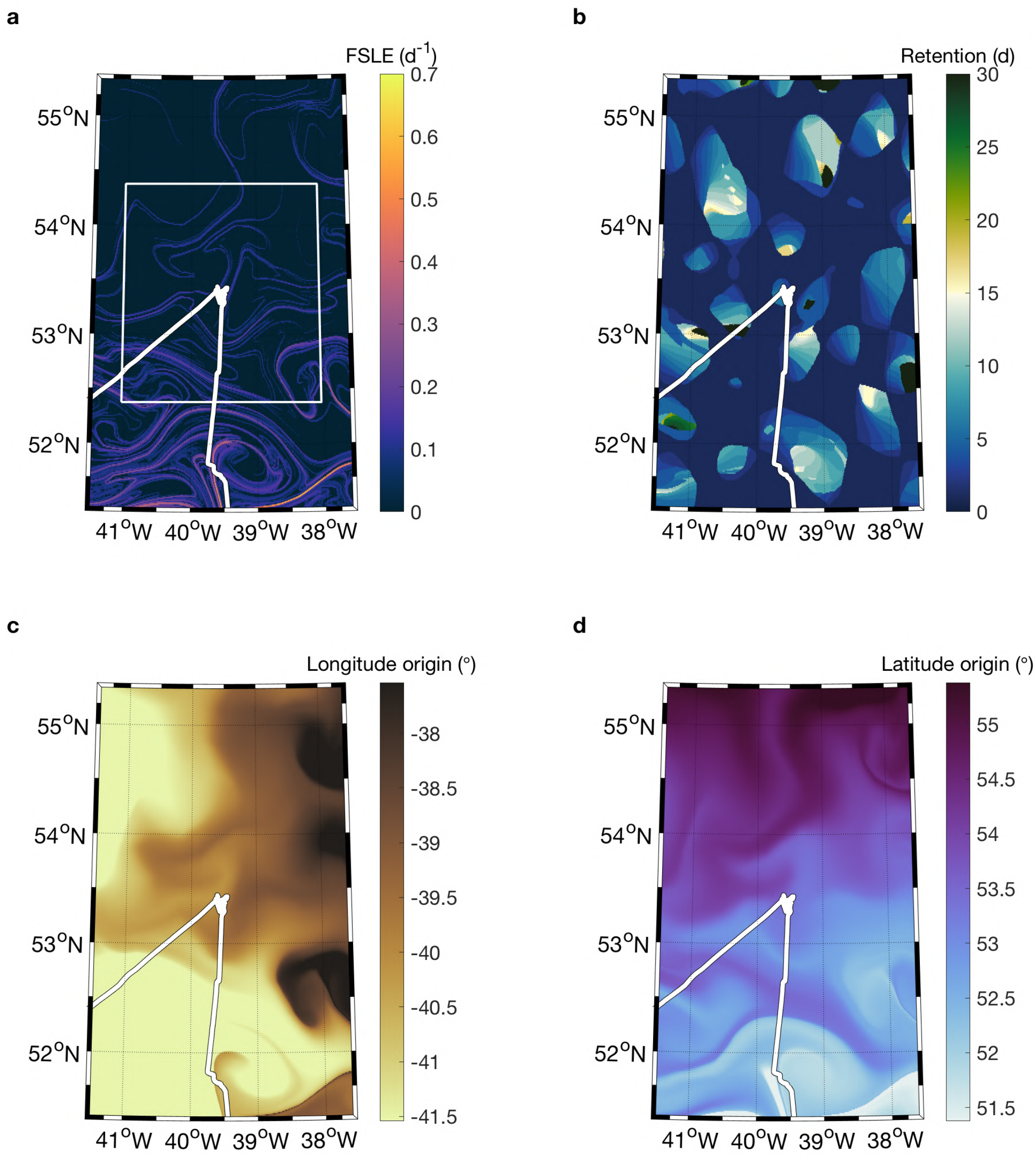

Figure S55. Same as Fig. S7.

3.4 NAAMES 4 - 2018

3.4.1 S1 NAAMES-4

As most stations during the NAAMES 4 expedition, this station was determined to be in the vicinity of a float. The station is not located in an eddy, but it is relatively close to a frontal structure (that was crossed before reaching the station) separating waters coming from the north (where the station was actually located) and waters from the south (corresponding to the region crossed just before reaching station).

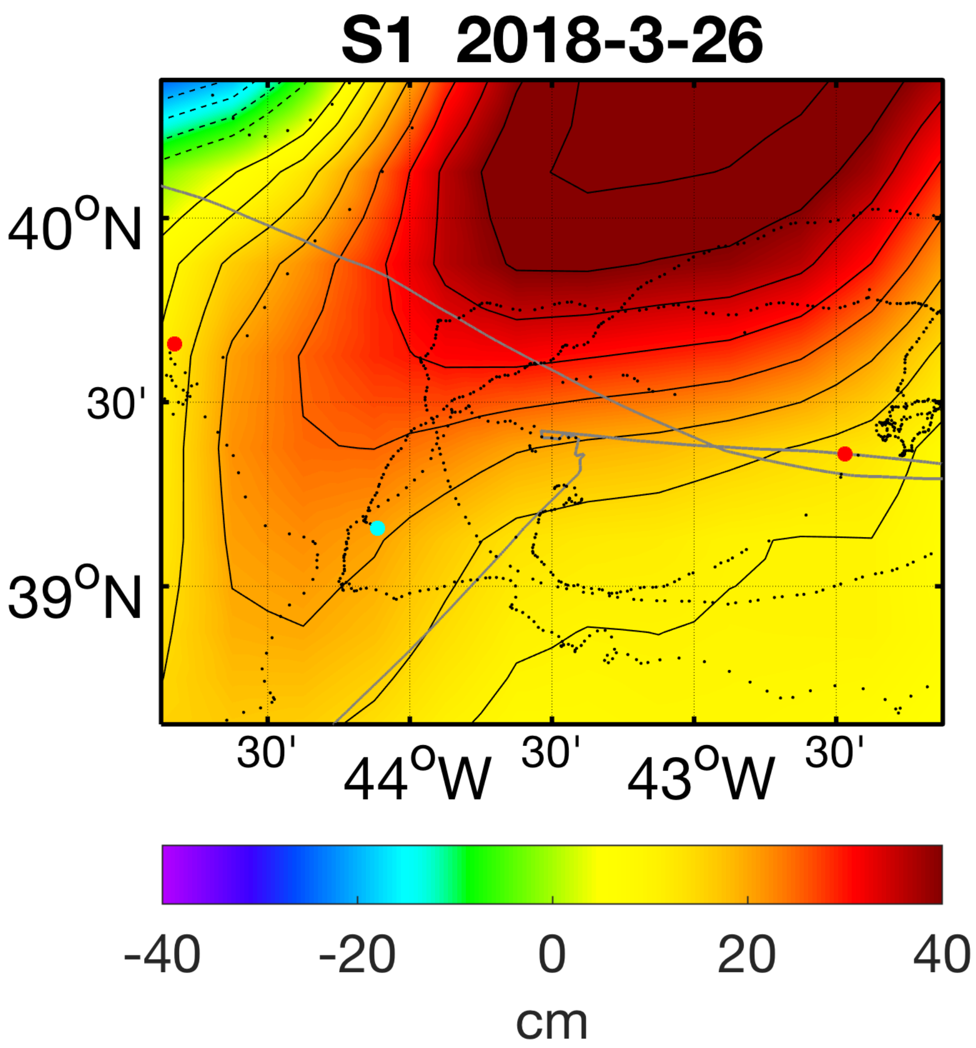

Figure S56. Same as Fig. S6.

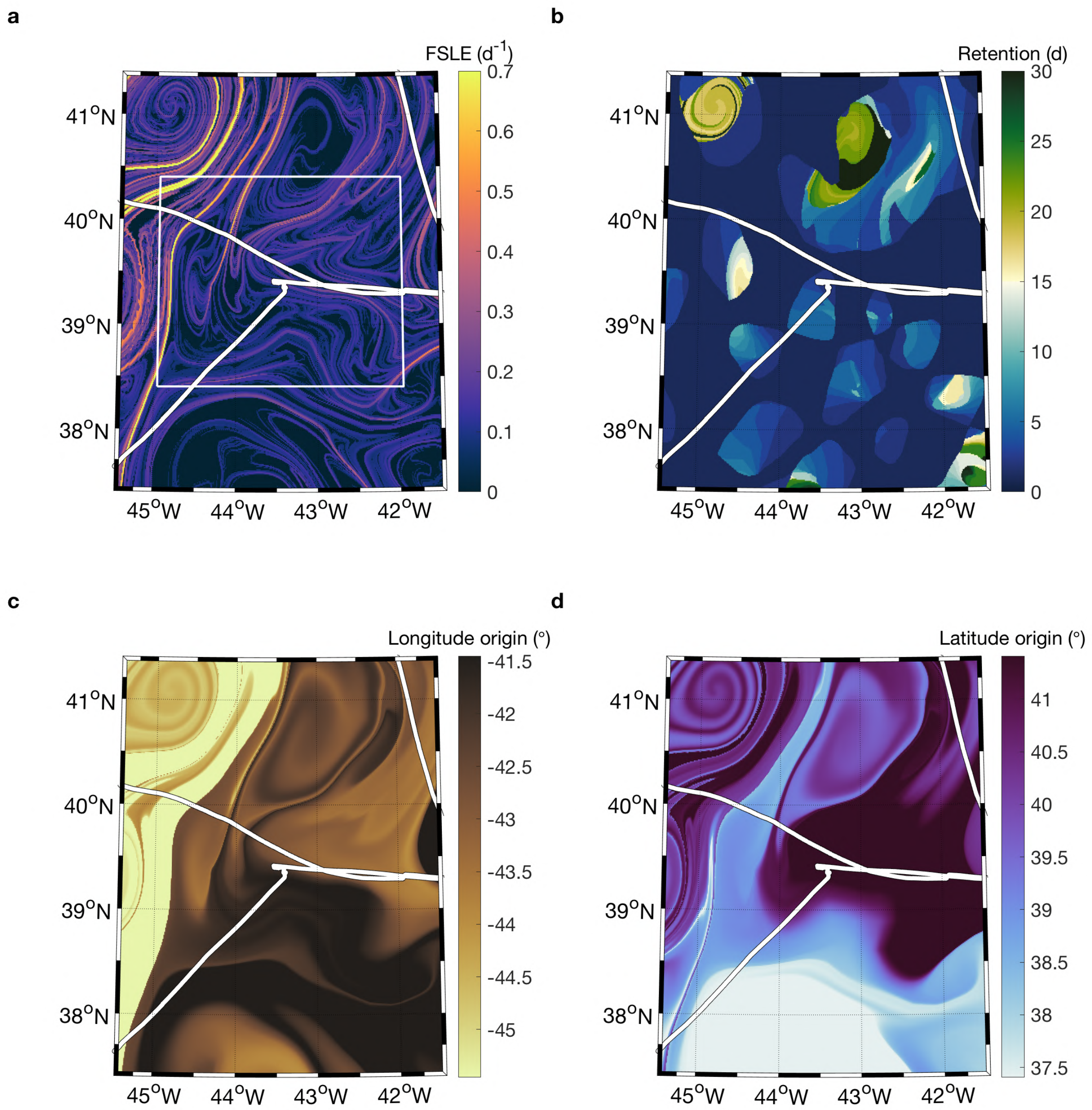

Figure S57. Same as Fig. S7.

3.4.2 S2 NAAMES-4

This station was chosen to be in the proximity of a float and happened to be located between two weakly retentive mesoscale eddies (Figure S59 b)). A Lagrangian drifter was deployed at this location and the ship returned at the drifters' location for station 2-Return-to-Drifter (2RD). This station did not appear to be located within an eddy. However, the trajectory of the deployed drifter (and potentially the evolution of the bio-Argo float) appears to be influenced by the cyclone located north of the station.

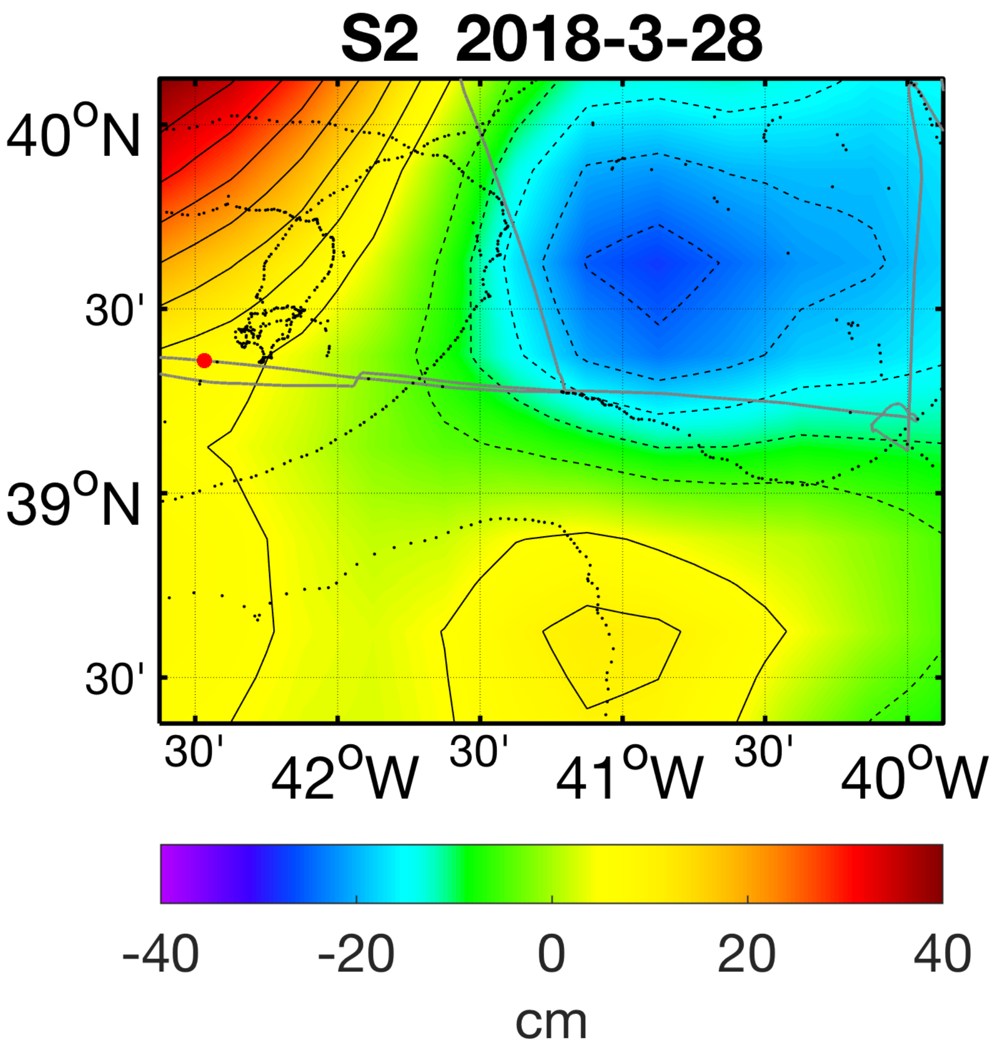

Figure S58. Same as Fig. S6.

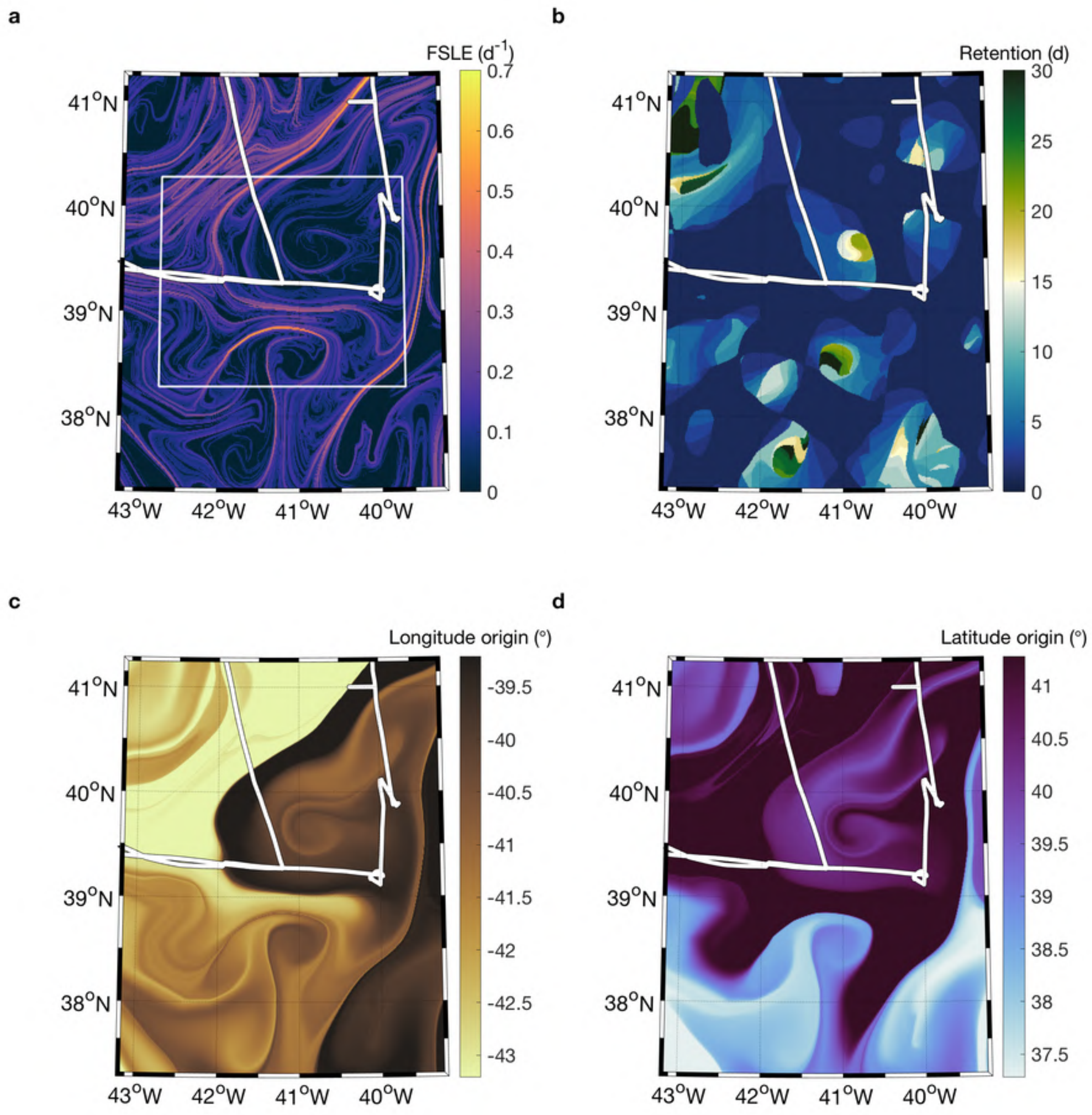

Figure S59. Same as Fig. S7.

3.4.3 S2.5 NAAMES-4

This "in-between" station was located in a minor circulation feature characterized by water parcels that were stationary in the last two weeks but were surrounded by waters coming from the south-west (Figure S61).

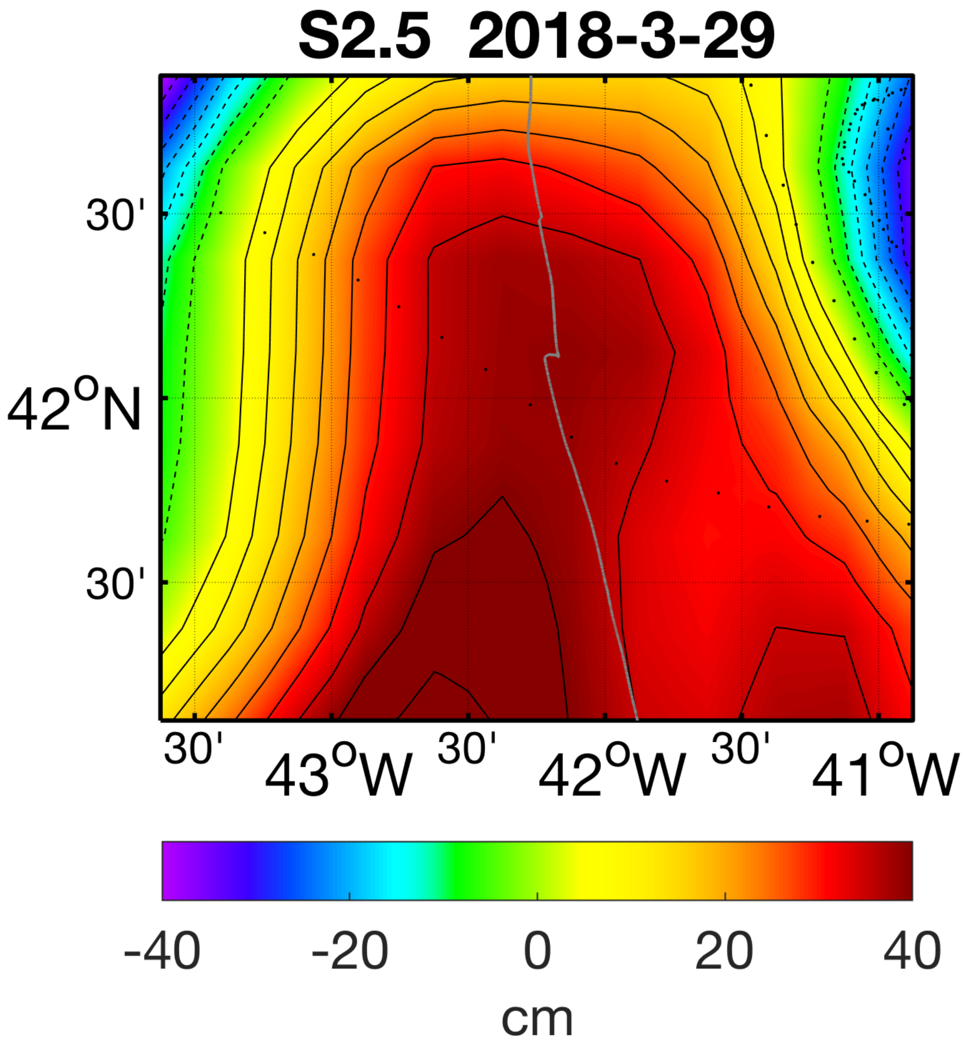

Figure S60. Same as Fig. S6.

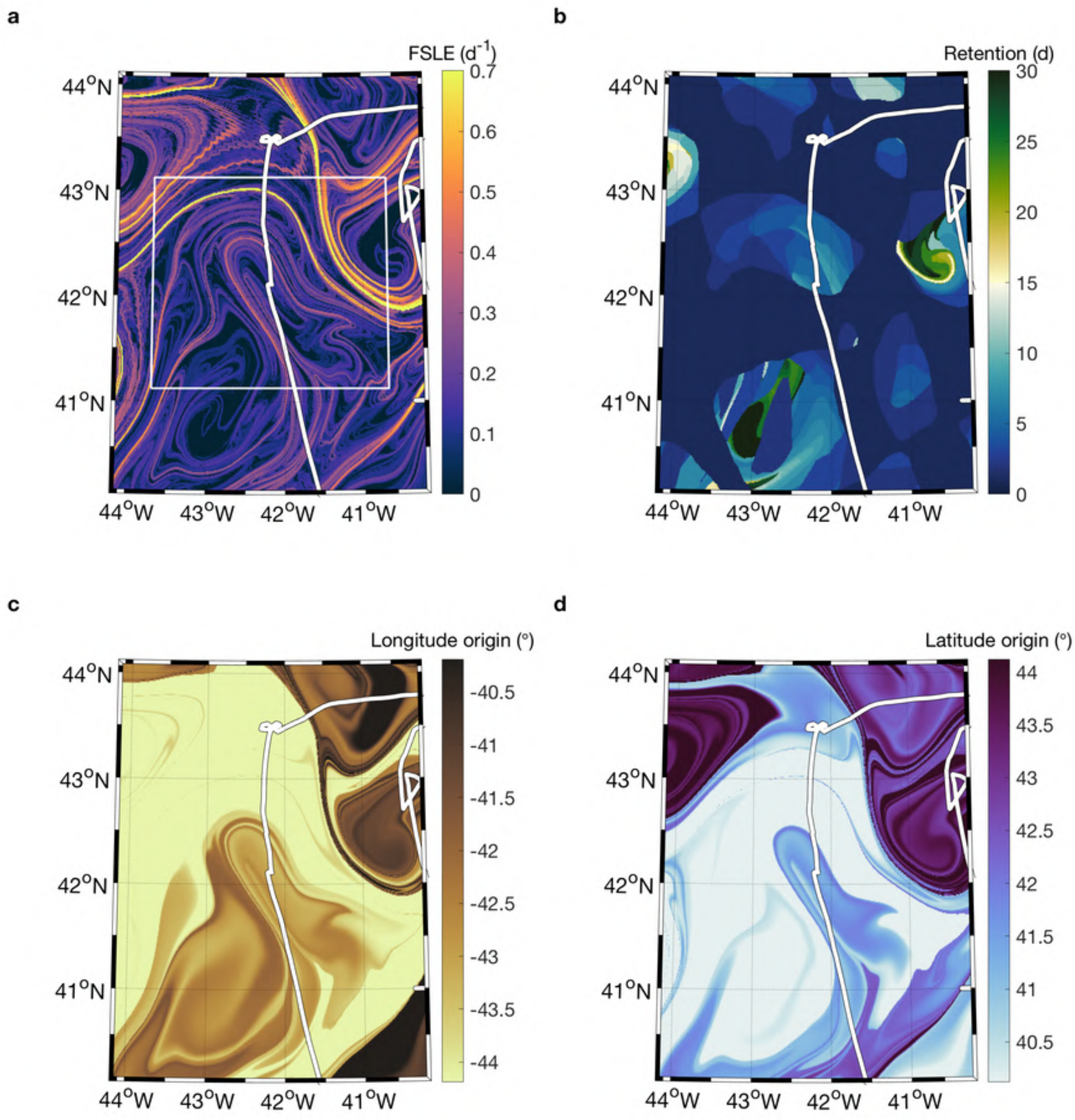

Figure S61. Same as Fig. S7.

3.4.4 S3 NAAMES-4

Station 3 was chosen because of its proximity to a float.

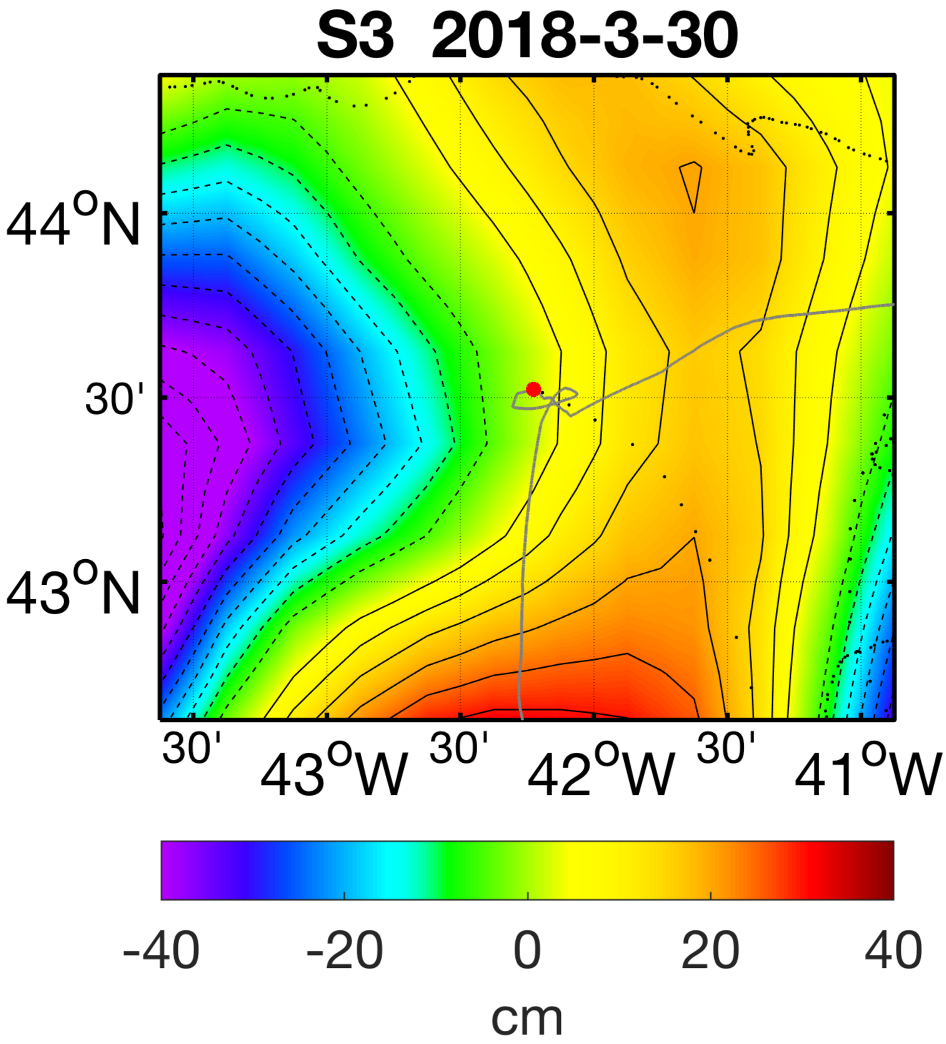

Figure S62. Same as Fig. S6.

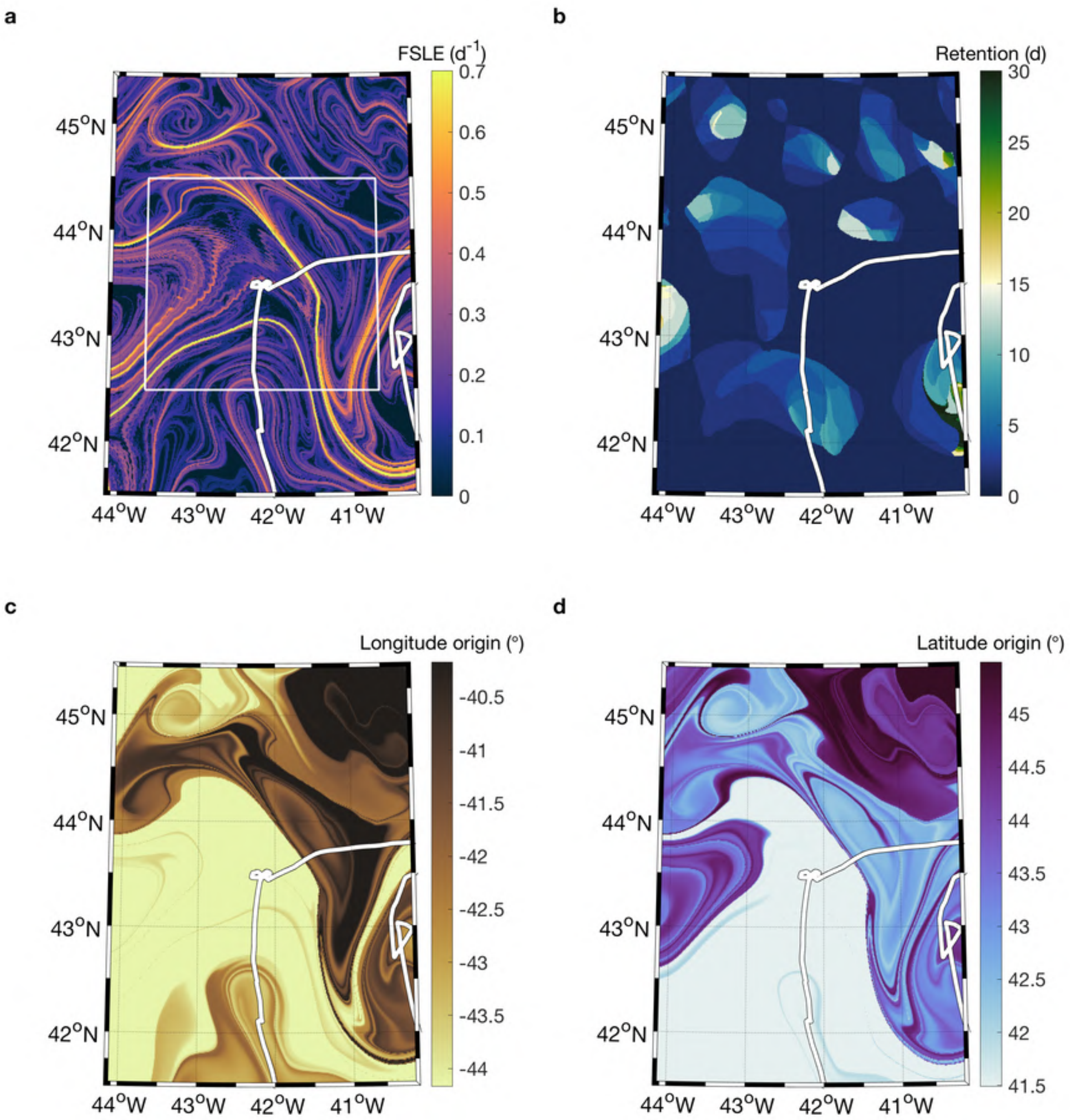

Figure S63. Same as Fig. S7.

3.4.5 S4 NAAMES-4

This station was chosen because of its proximity to a float. It was the northernmost station sampled during this cruise. Lagrangian re-analyses indicate that the sampled water is likely to have been advected from the north.(Figure S65 d)).

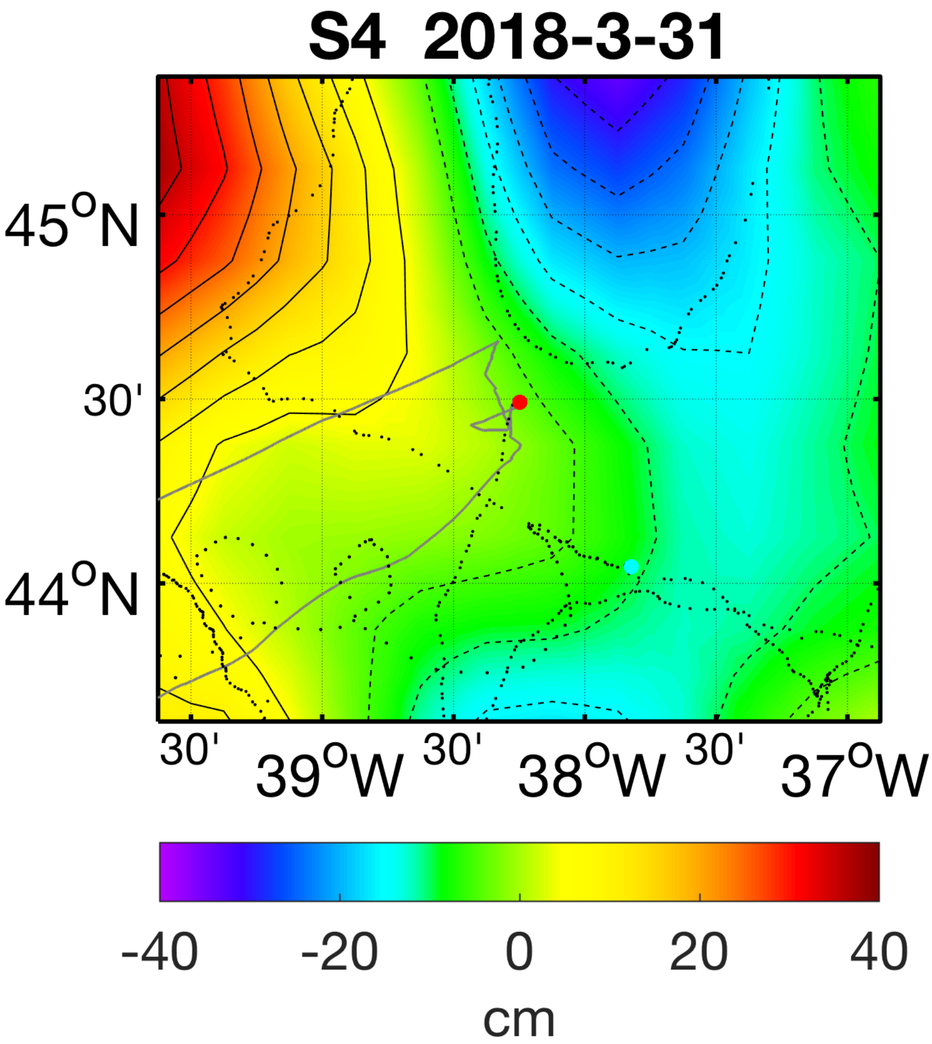

Figure S64. Same as Fig. S6.

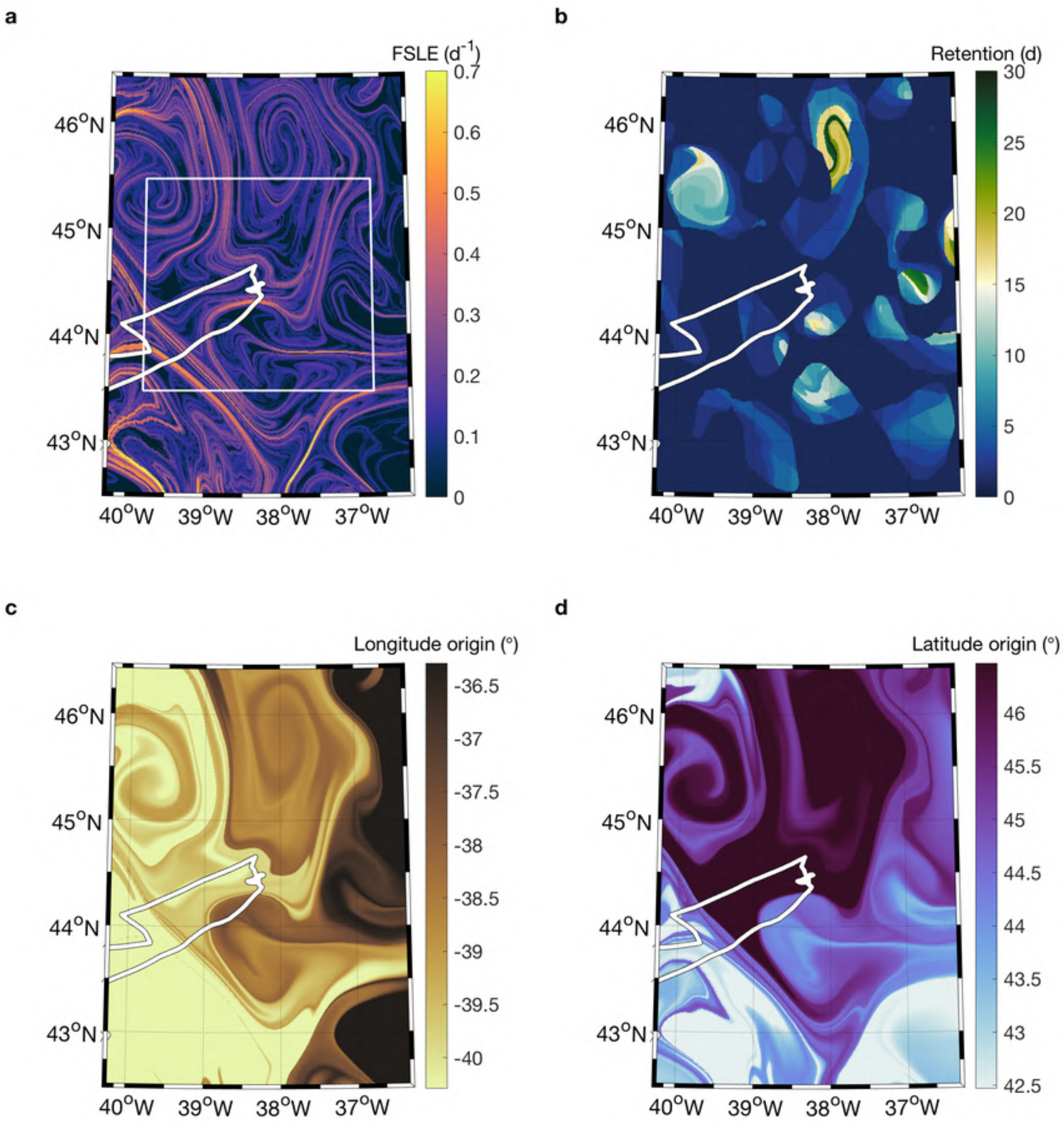

Figure S65. Same as Fig. S7.

3.4.6 SE4 NAAMES-4

This short station was part of an intensive eddy sampling conducted using the flow-through system and the Acoustic Doppler Current Profiler (ADCP). Station E4 was supposed to be located at the center of a cyclonic eddy. The station was likely located at the eddy periphery of this weakly retentive eddy (Figure S65 b)).

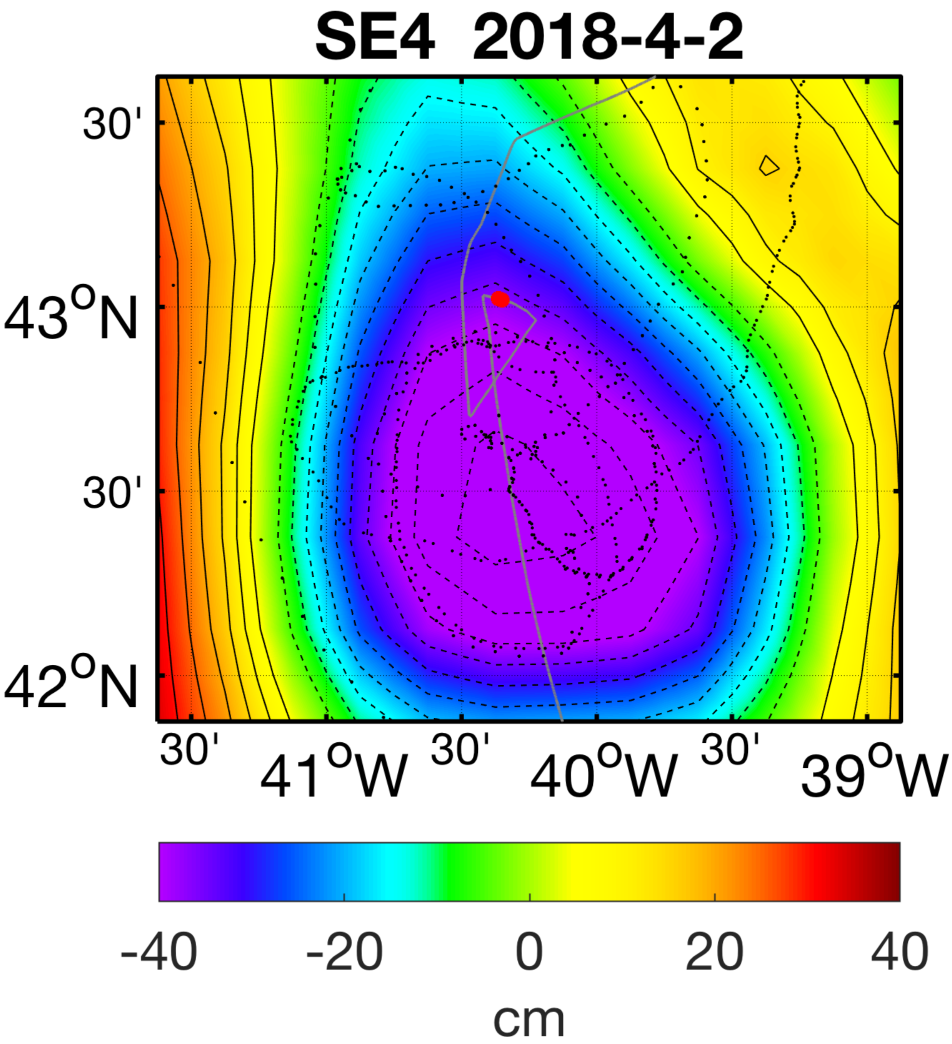

Figure S66. Same as Fig. S6.

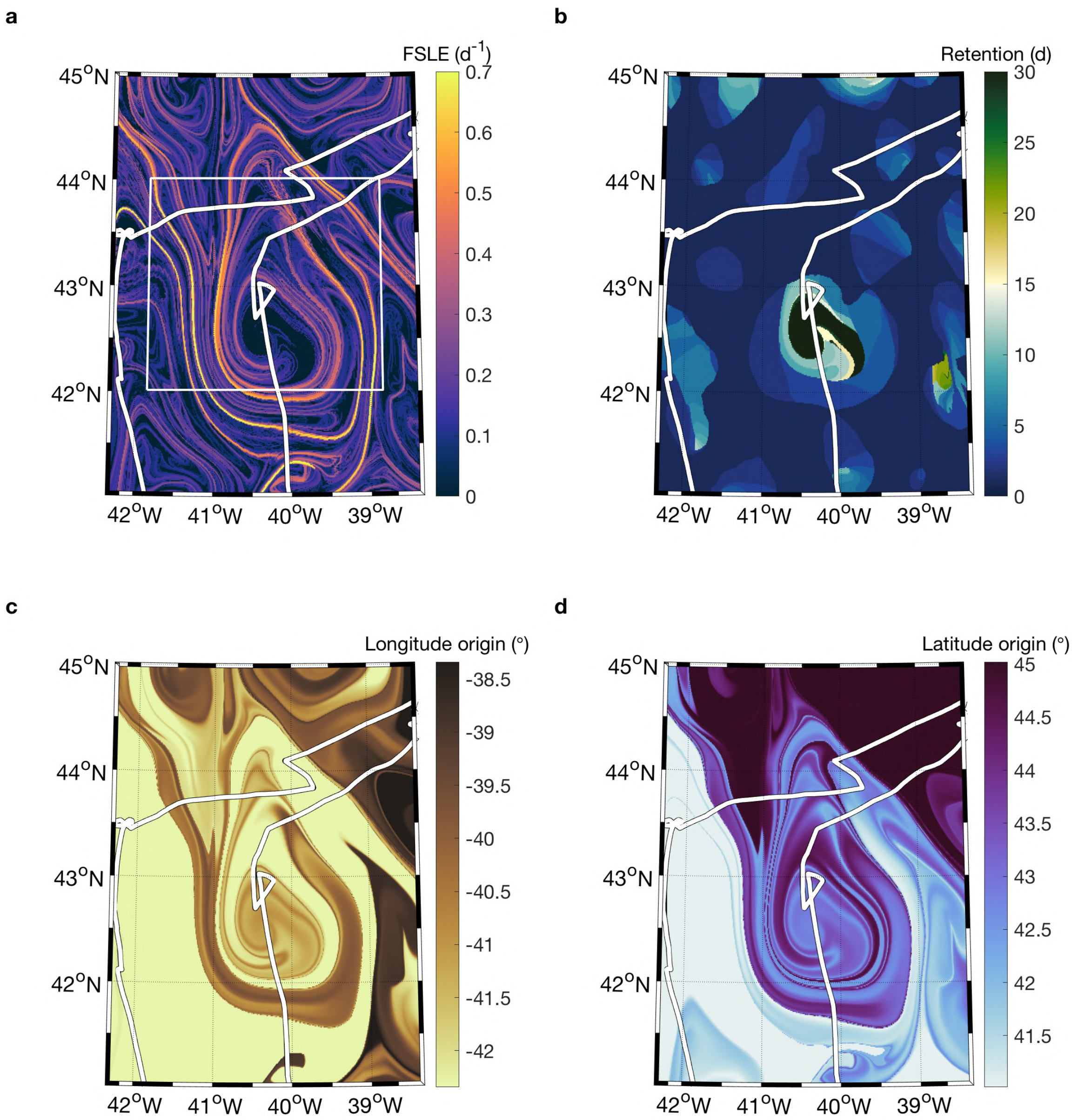

Figure S67. Same as Fig. S6.

3.4.7 S2RD NAAMES-4

Station 2 Return-to-Drifter was located at the updated position of the drifter deployed during the occupation of Station 2.

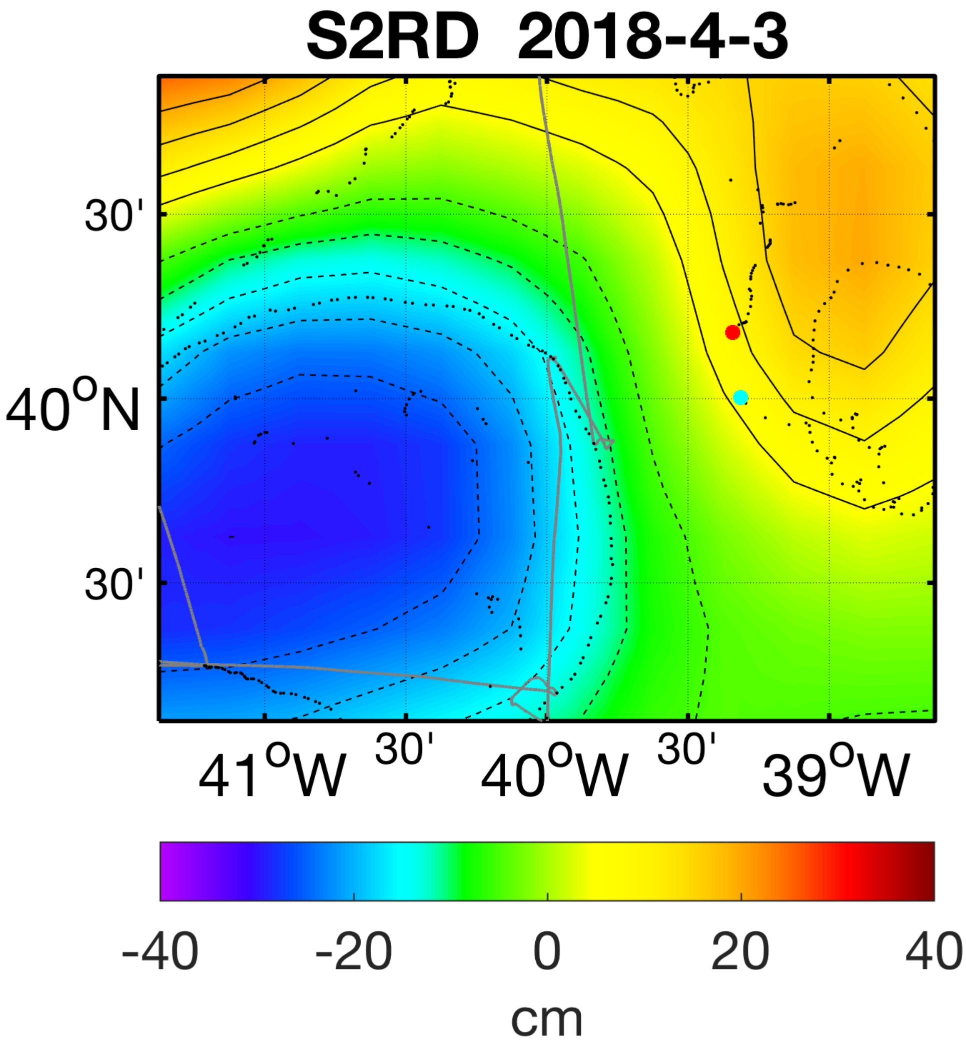

Figure S68. Same as Fig. S6.

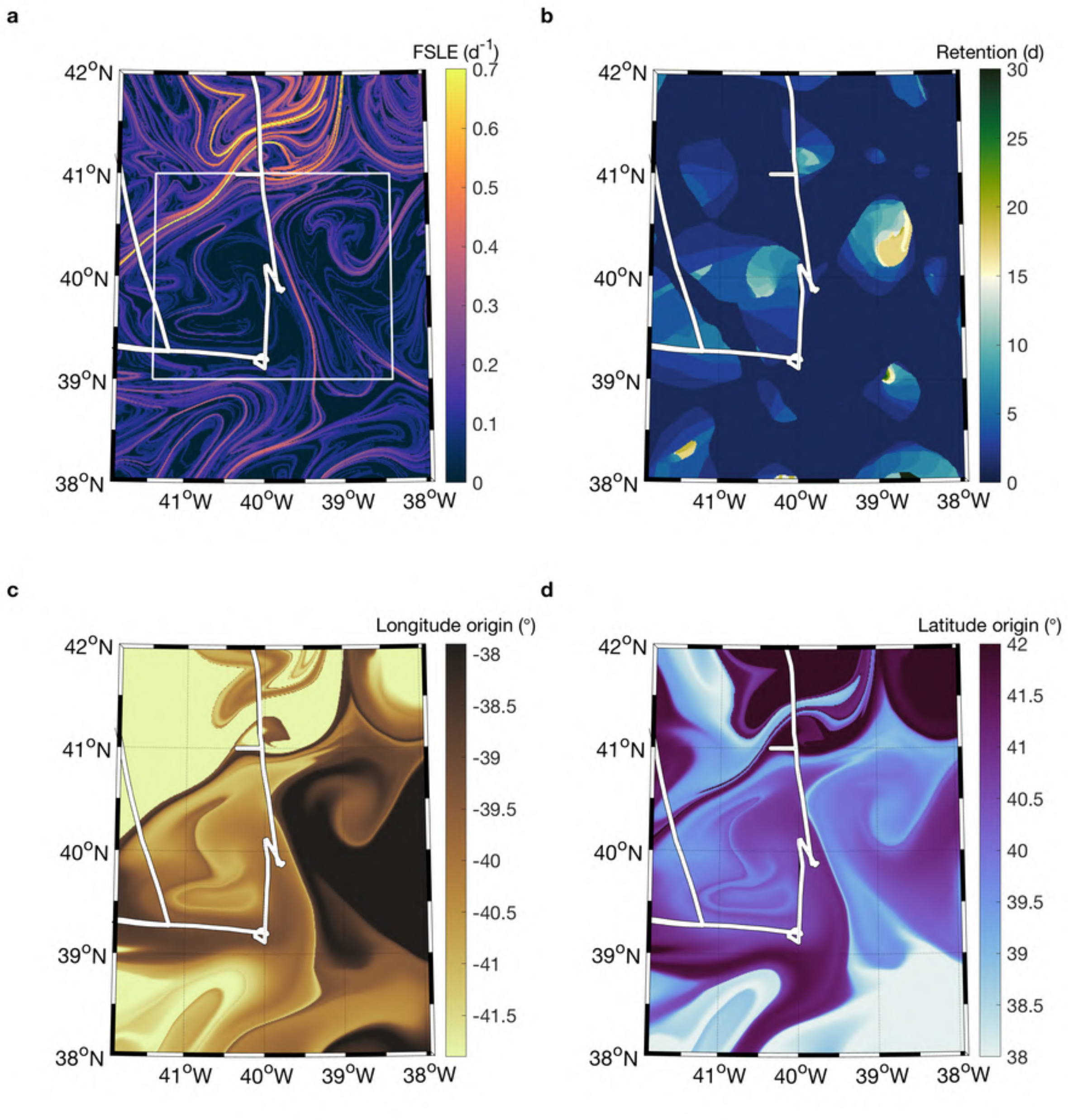

Figure S69. Same as Fig. S7.

3.4.8 S2RF NAAMES-4

Station 2 Return-to-Float was located at the updated position of the float used to identify Station 2.

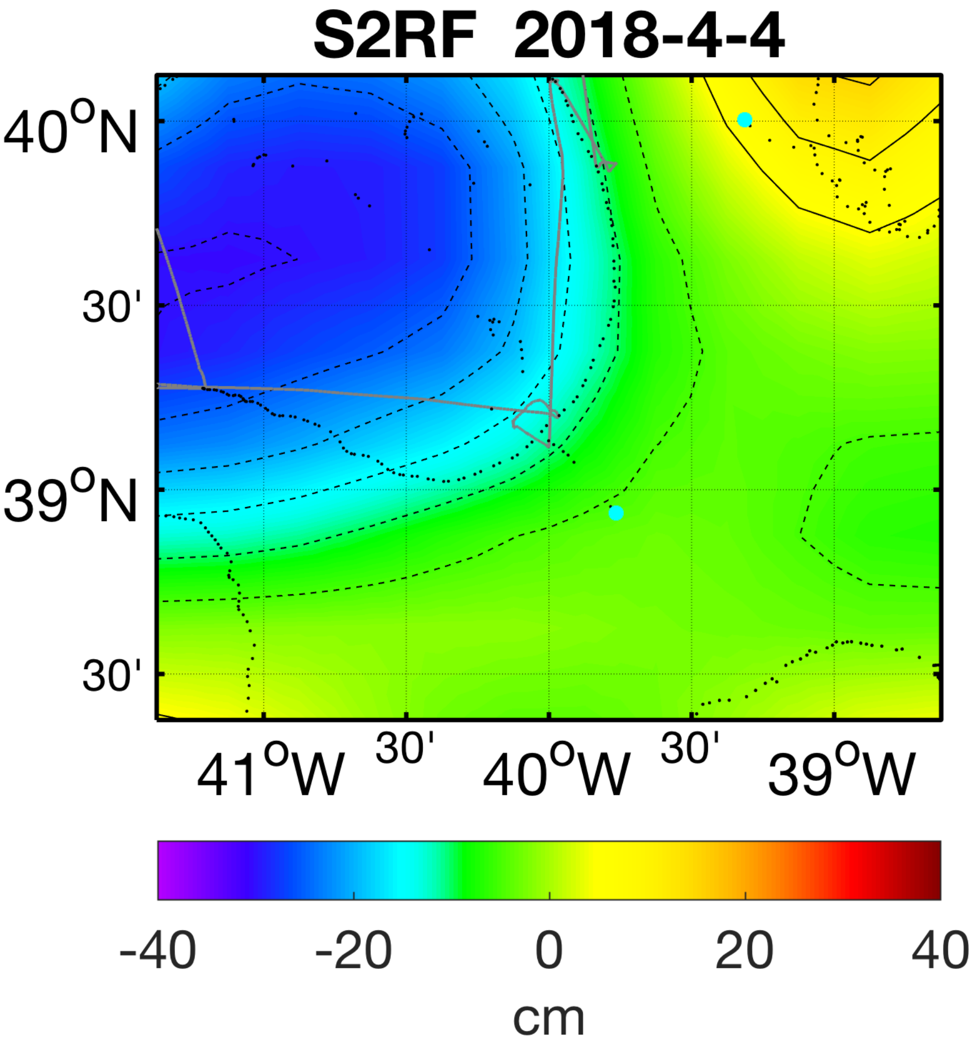

Figure S70. Same as Fig. S6.

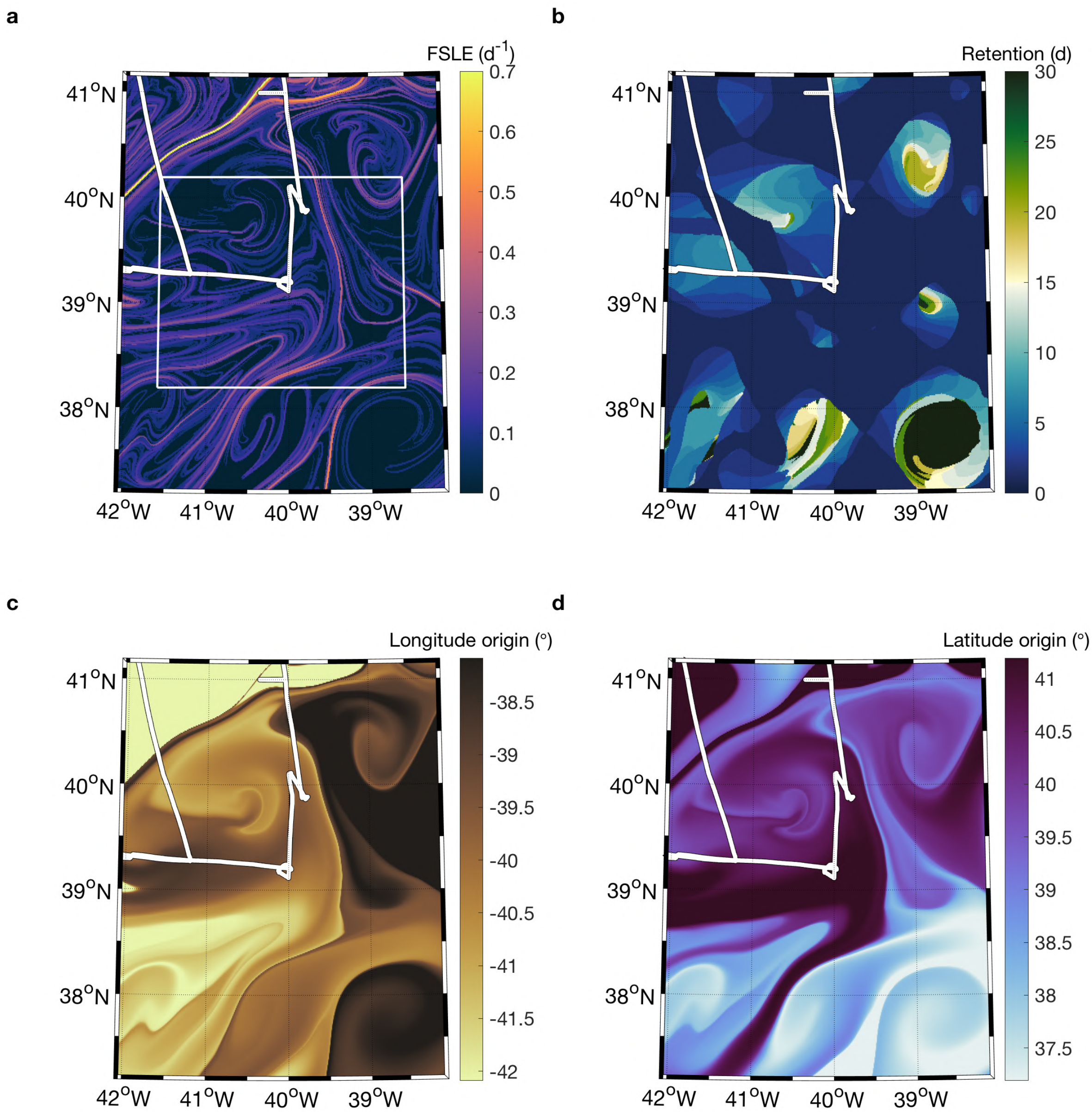

Figure S71. Same as Fig. S7.

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