# Submesoscale Ocean Dynamics and Vertical Transport (S-MODE) Science Report
## April 17 - May 2, 2023

*Erin Czech, Eric D'Asaro, Tom Farrar, Mara Freilich, Luc Lenain, Jeroen Molemaker, Melissa Omand, Dragana Perkovic-Martin, Luc Rainville, Ernesto Rodriguez, Andrey Shcherbina, David Thompson, Alex Wineteer*

**Science Highlights (S-MODE Lead PI: Tom Farrar, Woods Hole Oceanographic Institution (WHOI); S-MODE Deputy PI: Eric D'Asaro, University of Washington)**

The final S-MODE campaign was a huge success! The combination of near-daily aerial remote sensing from three aircraft with the in situ measurements from the research vessel, the Lagrangian (water following) floats and drifters, and more than 20 uncrewed vehicles has given us an exciting new view of submesoscale ocean dynamics. We were fortunate to have very good large-scale conditions producing energetic submesoscale eddies, with strong physical and biological signals, that we were able to measure intensively with all of our different platforms.

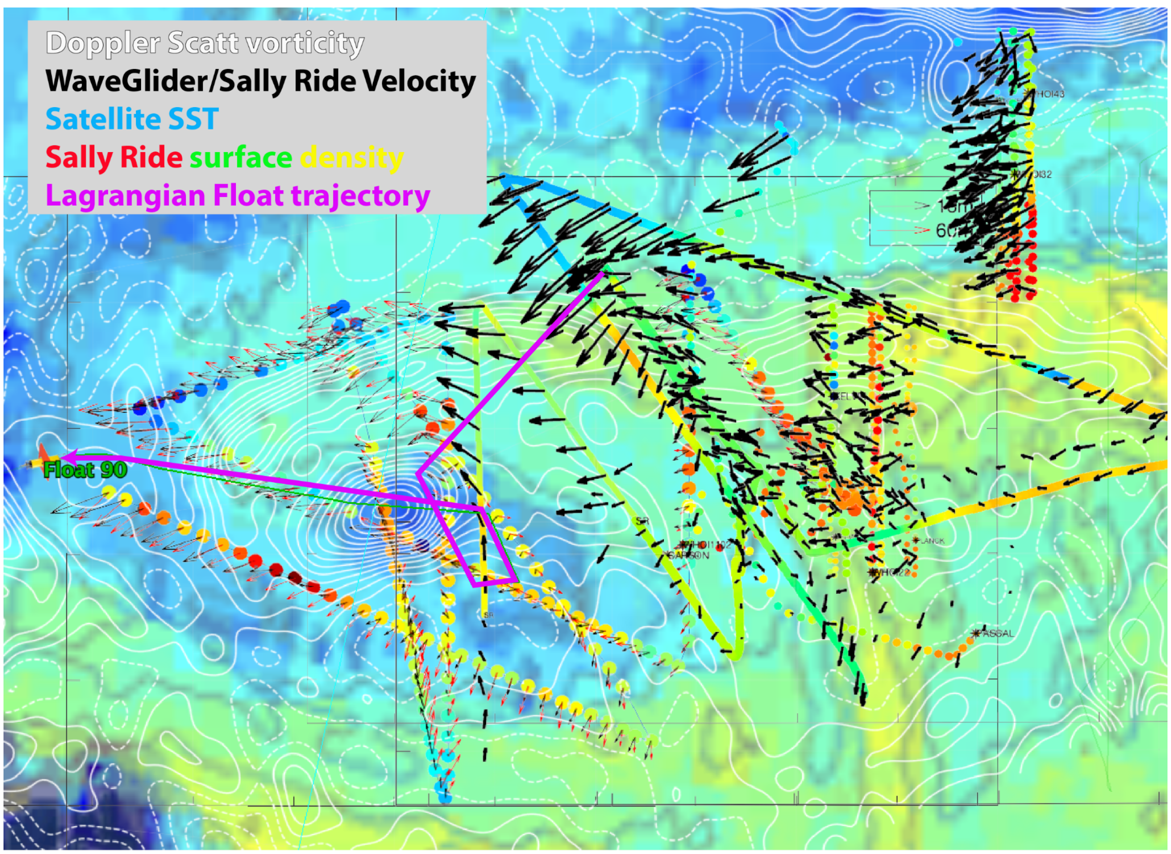



*Figure 1. The April 24, 2023 ocean state as determined by a combination of DopplerScatt, satellite, ship, and autonomous surface vehicle measurements*

The April 24 Lagrangian Float deployment illustrates the S-MODE sampling strategy. The figure above shows the ocean state as determined by a combination of DopplerScatt, satellite, ship, and autonomous surface vehicle measurements. It shows a cyclonic submesoscale ocean eddy which is stirring warm dense water (red/yellow/green) into a colder, lighter background (cyan/blue). Dopplerscatt vorticity (white contours) shows vorticities larger than 2f (rotating at twice the earth's rotation rate). Based on this information, a Lagrangian float was deployed into the dense water; its track is shown in magenta.

The bottom plot shows the depth of the float over the next three days. Since the float follows the water in three dimensions, its vertical motion is the vertical motion of the water. The float moved vertically by 40m with vertical velocities, averaged over a few hours, of 1-5 mm/s. A major goal of S-MODE is to understand the dynamics of these motions, their importance in setting the upper ocean state, and the ability to measure them from ocean surface velocity measurements.

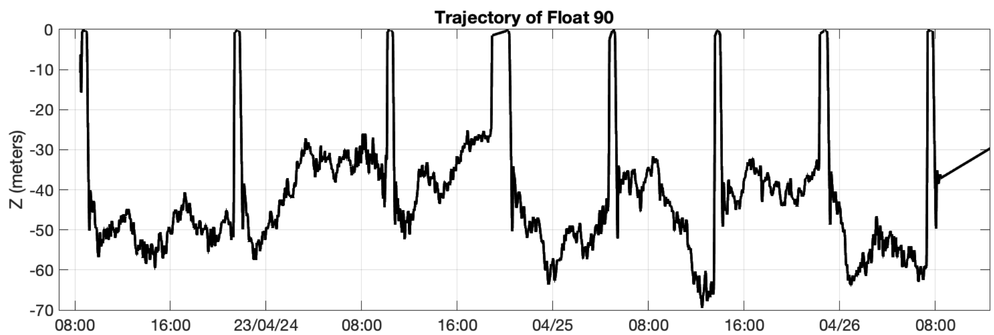



*Figure 2. Lagrangian Float 90 depth in meters from Apr 24-26, 2023.*

**DopplerScatt (PI: Dragana Perkovic-Martin, NASA JPL), MOSES (PI: Jeroen Molemaker, UCLA)**

JPL's Doppler Scatterometry (DopplerScatt) instrument and UCLA's Multiscale Observing System of the Ocean Surface (MOSES) completed a total of 22 flights during S-MODE's second Intensive Operations Period (IOP-2) over approximately 100 flight hours on NASA Armstrong Flight Research Center's B200 aircraft.


*Figure 3. DopplerScatt operators swap day; Left to right: Hernan Posada (AFRC), Ruzbeh Akbar (JPL), Alex Wineteer (JPL), Delphine Hypolite (UCLA), Federica Polverari (JPL), Scott Howe (AFRC), and Hector Torres Gutierrez (JPL).*

In this period, the DopplerScatt team has concentrated data collections to observe two phenomena: 1) a "sub-mesoscale eddy street" produced by the interaction of open ocean water and the fresh water from the San Francisco Bay (see Figure 2) and 2) a three-step process of merging sub-mesoscale eddies.

An "eddy street" is commonly observed in satellite images of chlorophyll-a (green pigment associated with microscopic plants), due to its nutrient rich water from the bay that drives phytoplankton blooms. However, measuring the velocity field of the "eddy street" is challenging, requiring two-dimensional observations at high-resolution. DopplerScatt's observations from April 18$^{th}$ produced a vorticity map (Figure 2, right panel) normalized by the Coriolis parameter (a proxy of the spinning of an element of fluid relative to the rotation of the Earth at a given latitude), which at a latitude of 37$^{o}$ N corresponds to a period of 19.94 hr. In this image, each small eddy (red circles in Figure 2) spins 3 times faster than the Coriolis parameter, corresponding to a period of 6.6 hr. Besides its importance to ocean biology, the "eddy street" also represents a pathway for kinetic energy dissipation of the larger scale flow. In other words, it is the link between large-scale circulation and micro-turbulence. DopplerScatt observations of the "submesoscale eddy street" offer the opportunity to better understand the role of fine-scale oceanic motions, not only on the ocean dynamics, but also on the ocean biology.

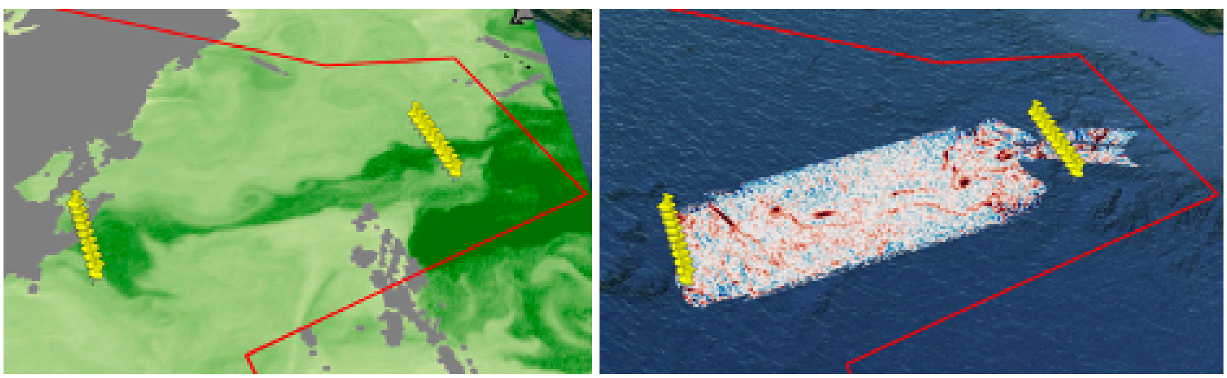


*Figure 4. Left: Sentinel-3 image of chlorophyll on April 17th with DopplerScatt waypoints overlaid (darker green indicates higher chlorophyll concentration). Right: DopplerScatt vorticity image from April 17th collection overlaid with waypoints for April 18th collection. Red outline in both images is the boundary of the S-MODE IOP-2 operations area.*

Several days of DopplerScatt observations of the area (April 19-22) revealed the eddy evolution shown in Figure 3 (red arrow).  The rapidly changing small-scale eddy (10 km diameter) is evidence that it is poorly constrained by the Earth's rotation. Theoretical and numerical studies have predicted vertical velocities of the order of 100 m/day confined to small-scale features; submesoscale structures, like this eddy, represent the most efficient pathway for heat, tracers and gas from the upper ocean to the ocean interior. S-MODE's plethora of in-water assets are concentrated in the small-scale eddy, following its trajectory based on DopplerScatt observations. The goal is to test the hypothesis that submesoscale structures are key players in the vertical exchange in the upper ocean layer.

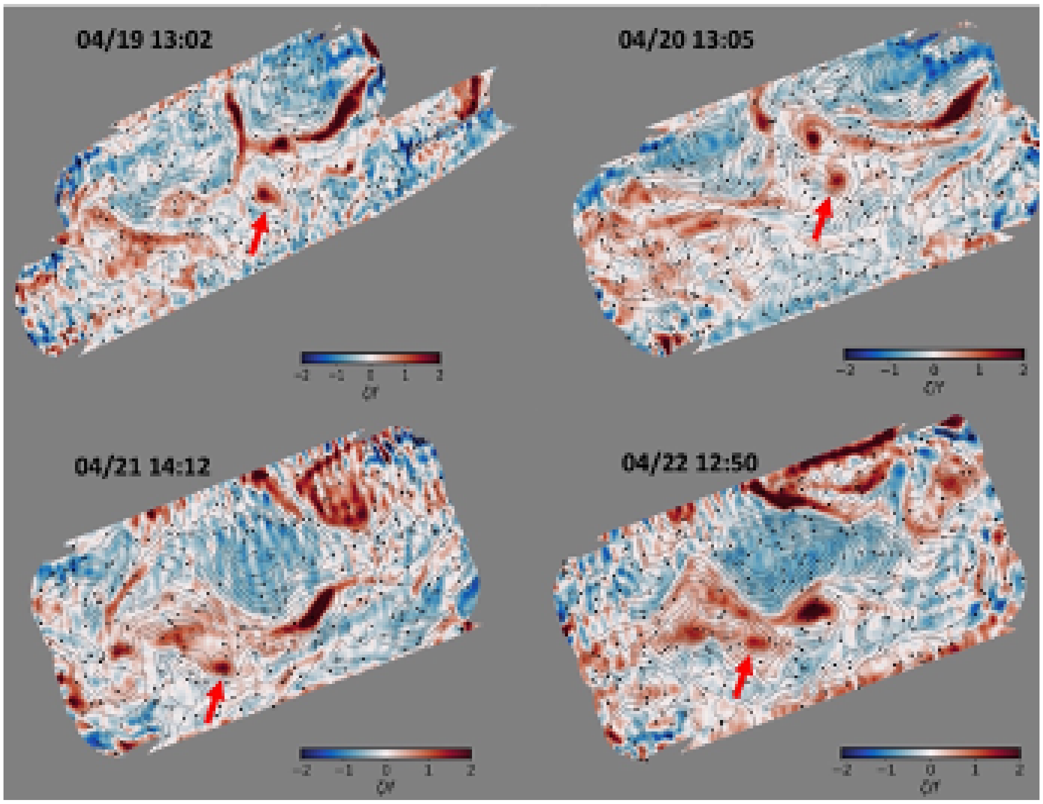



*Figure 5. Sub-mesoscale eddy evolution over four days of DopplerScatt observations. The red arrow marks the position of the small-scale eddy tracked by in-water assets. Streamlines represent DopplerScatt estimated high-pass ocean currents relative to a cutoff wavelength of 15 km.*

One of the most fascinating characteristics which can be observed is the merging of small-scale eddies "giving birth" to a larger single eddy. The merging of large-scale eddies (100-300 km in size) has been observed by altimeters. These large eddies evolve on time scales from a few weeks to months and can be observed by satellite assets. However, observing the merging of small-scale eddies (approx. 10-km in size) is difficult as they evolve on time scales of a few days. To observe a merging event, the S-MODE team used the DopplerScatt instrument, capable of surveying a region of ~100 km x 100 km in a few hours. DopplerScatt observed **the three-step process of the merging event** (Figure 4): **attraction, collision, and merging.** These observations give a unique opportunity for understanding of the oceanic conditions necessary for this event to occur. S-MDOE science team will however have another unique opportunity, to connect the kinematics of the ocean surface currents with the ocean interior, by correlating DopplerScatt data with co-located in situ measurements of temperature, salinity, chlorophyll and currents at depth. The goal will be to determine the impact of the small-scale merging event on the vertical exchange of climate and biological variables in the upper ocean.

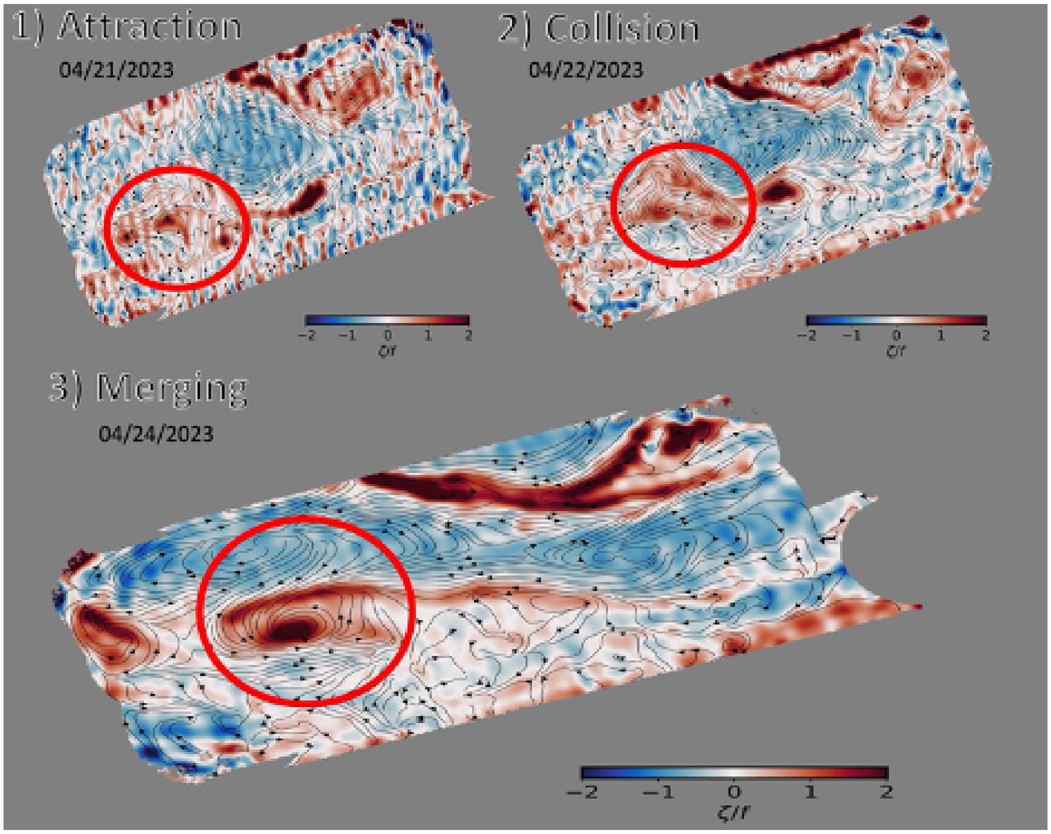



*Figure 6. DopplerScatt vorticity map over three days displays the three parts of the small-scale merging event: Attraction (04/21/2023), Collision (04/22/2023), and Merging (04/24/2023). The red circle marks the area of merging.*

DopplerScatt's measurements of wind velocity confirmed the impact of small-scale ocean features on the wind field (Figure 5). This tight connection between small-scale ocean structures and small-scale wind anomalies has a profound implication for the Earth's climate system: strong air-sea couplings provide a mechanism for tracer exchange between the ocean and the atmosphere. Heat and carbon dioxide may find their way into the ocean through these processes being observed by S-MODE assets.

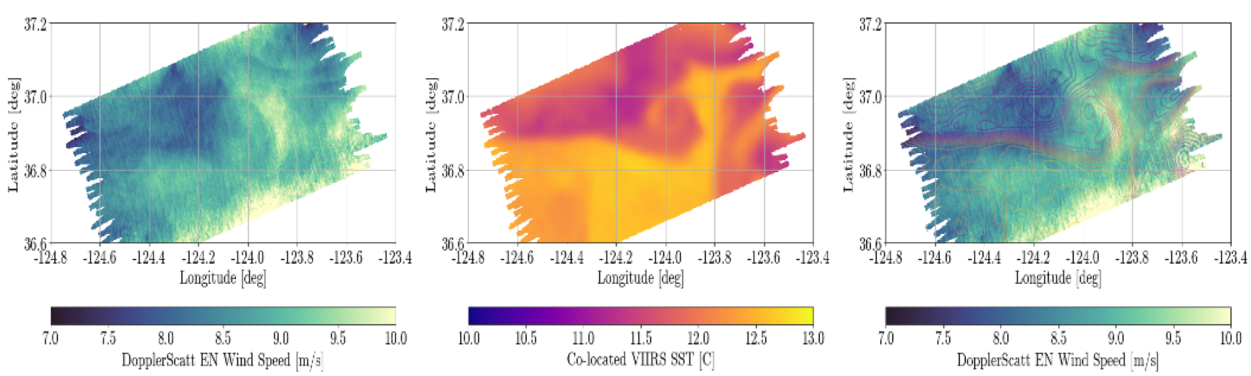



*Figure 7. Left: DopplerScatt equivalent neutral winds on April 20. Middle: Co-located Sea Surface Temperature (SST) satellite measurements. Right: DopplerScatt equivalent neutral winds (color) and SST (contours).*

**R/V Sally Ride (Chief Scientist: Andrey Shcherbina, University of Washington)**

Over the past week, R/V Sally Ride conducted in-situ observations of the submesoscale eddy field arising from the coastal outflow instability. We relied on shipboard and towed instrumentation to observe detailed three-dimensional subsurface structure of the features seen in remote sensing data. The observations reveal the complex interplay of temperature and salinity variations that drive vigorous eddying and mixing of the inflowing fresh water.

R/V Sally Ride conducted several deployments of Lagrangian Floats designed to follow the three-dimensional flows in the upper ocean. These deployments are critical for understanding the vertical velocities and vertical exchange processes associated with submesoscale features.

Since the start of the cruise, almost a hundred surface drifters have been released in the study area from R/V Sally Ride. These drifters will continue to track the pathways of the water masses that we sampled as they are incorporated into the broader California Current system.

**Biological sampling on the Sally Ride (PI: Melissa Omand, University of Rhode Island (URI); with Mara Freilich, Scripps Institution of Oceanography (SIO); Kelly Luis, NASA JPL; Sarah Lang, URI; Roger P Kelly, URI; Dante Capone, SIO)**

Biological community composition and optical properties were characterized in situ using instruments the science seawater intake (flow through system include imaging of phytoplankton by an Imaging FlowCytobot (IFCB), Figure 6a), discrete bottle samples from the flow through system, discrete water samples from Conductivity, Temperature, and Depth (CTD) casts, and above-water and in-water radiometric sampling. An Underwater Vision Profiler (UVP-6) attached to the CTD Rosette captured large cells, microzooplankton (Figure 6b) and particles. These samples will be used to answer science questions about the interactions between submesoscale dynamics and biology, as well as to develop biogeochemical proxies from bio-optics.

The URI team collected and processed discrete bottle samples from the underway system and CTD rosette. These were analyzed on board for Chlorophyll-a pigment concentration and stored for High Performance Liquid Chromotography (HPLC) analysis by the NASA Ocean Biology and Biogeochemistry (OBB) group (309). Samples for particulate organic carbon (283) and dissolved inorganic nutrients (216) were collected and stored frozen for analysis at URI. Three CTD transects were conducted along a surveyed line, typically containing 4-5 casts (Figure 7). CTD casts were also conducted in a Lagrangian frame following the floats and drifters deployed in dense water near the feature of interest. For example, the biological sampling tracked the evolution of biological communities in the submesoscale features that DopplerScatt observed merging from April 19-24. Samples were collected for Chl, HPLC, nutrients, DNA, flow cytometry. The SIO team conducted high resolution community sampling to study submesoscale biological variability (145 surface samples), and incubated CTD water at various light levels to assess growth and grazing rates (161 CTD samples and 30 grazing rates). Kelly Luis operated the PySAS hyperspectral radiometers on the bow and the hand-held radiometer during PRISM and MASS overflights.

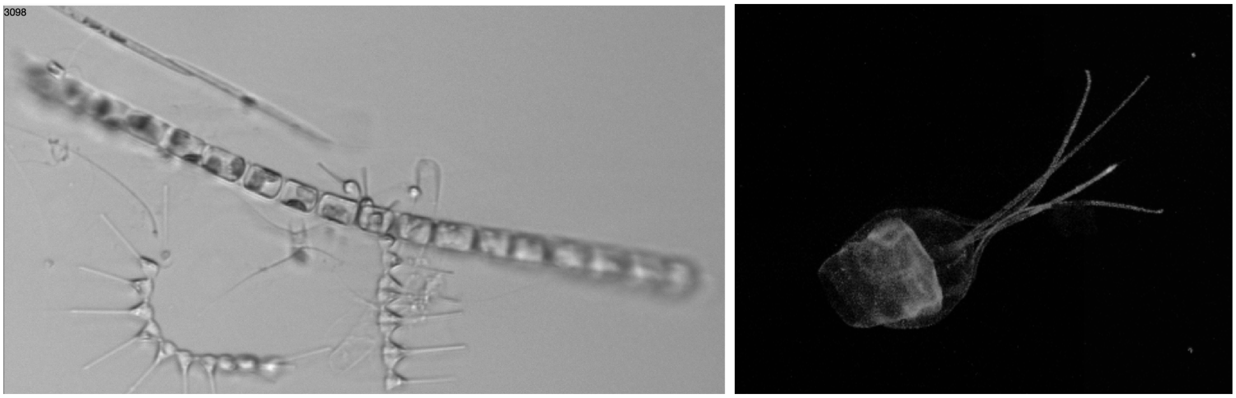



*Figure 8. Example images of phytoplankton from the IFCB and microzooplankton from the UVP-6.*

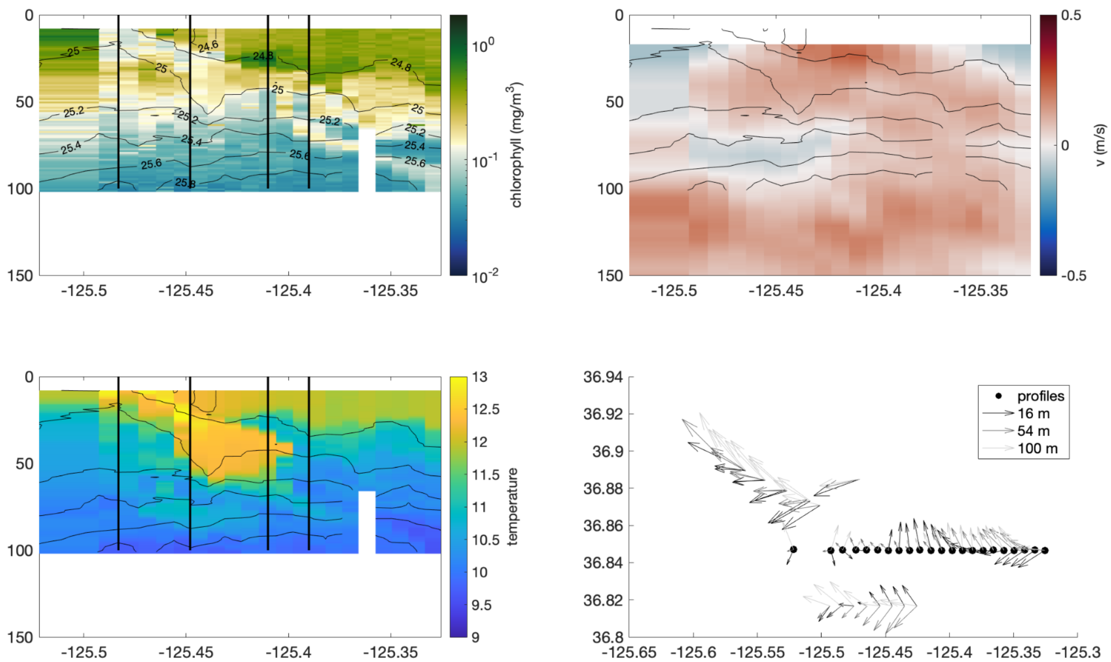
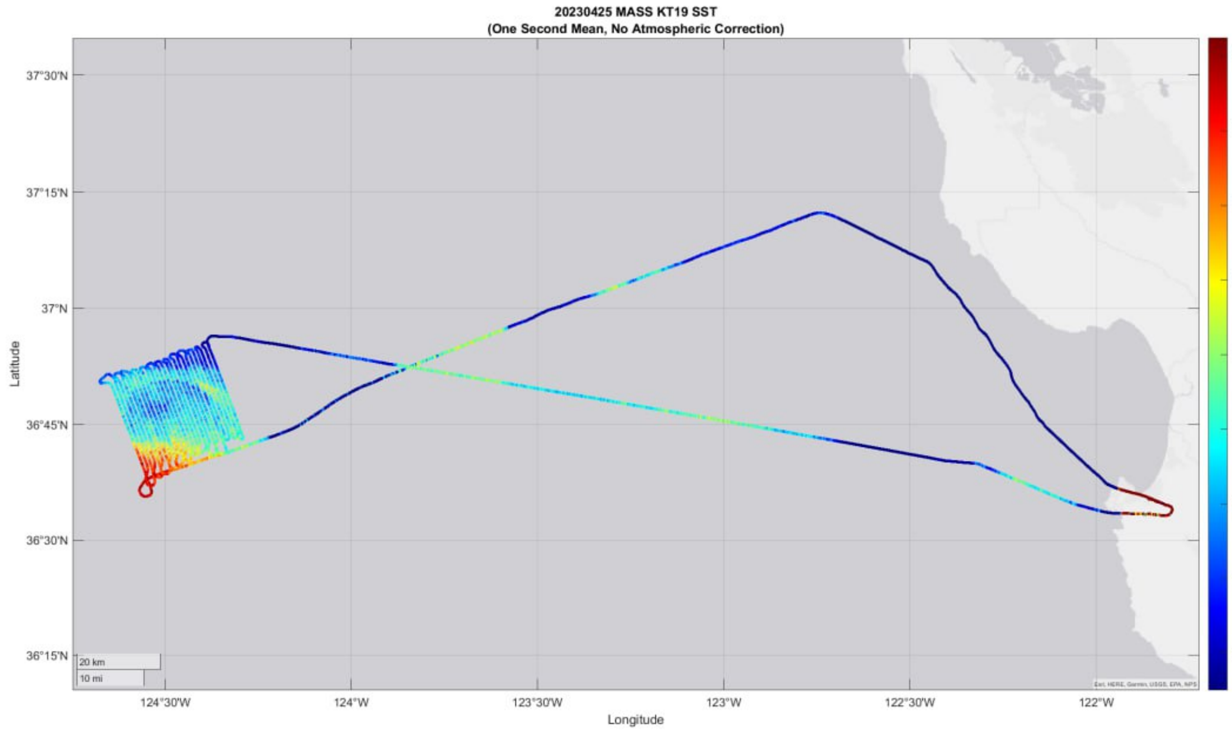



*Figure 9. An EcoCTD transect with locations of the third CTD transect. Top left: Chl fluorescence, Top right: "V" velocity, Lower left: Temperature and Lower right: locations of the EcoCTD profiles with velocity vectors at 16m, 54m and 100m indicated.*

**MASS (PI: Luc Lenain, SIO)**

The SIO Modular Aerial Sensing System (MASS) completed its 12th and final flight on April 26, 2023 collecting more than 80 flight-hours of observations in the S-MODE operations area. All instrument systems operated nominally, collecting one of the richest datasets to date by the MASS instrument of collocated near surface currents, sea surface temperature (SST), hyperspectral and visible imagery, and directional properties of surface waves and ocean topography. The low level flight capability of the instrumented Twin Otter turned out to be crucial for target tracking during periods of time where cloud coverage prohibited optical imagery (SST and Chlorophyll concentration in particular) from orbital or suborbital platforms.



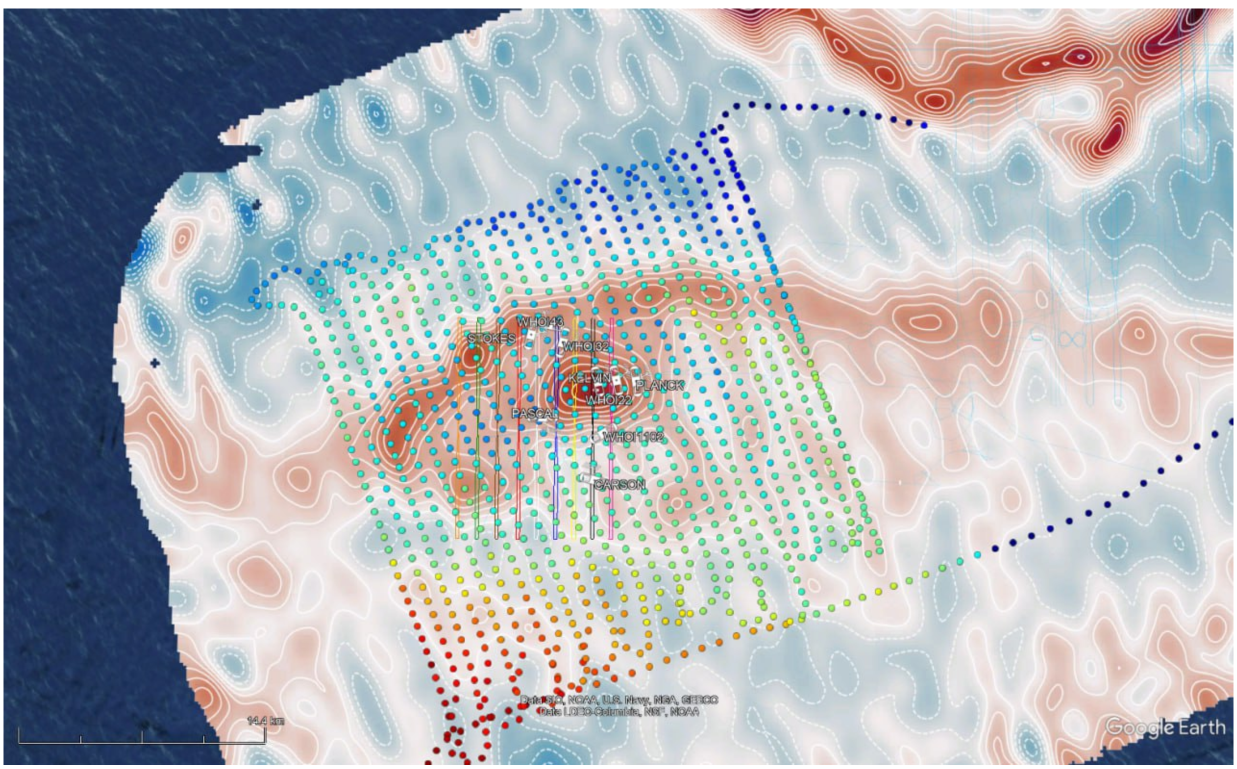




*Figure 10. (top) Example of along track SST collected from MASS during a cloudy day, flying at 1500 ft below the cloud base on April 25, 2023. (bottom) MASS SST overlaid on top of DopplerScatt derived vertical vorticity, also showing the Wave Glider track, all targeting a small scale eddy.*

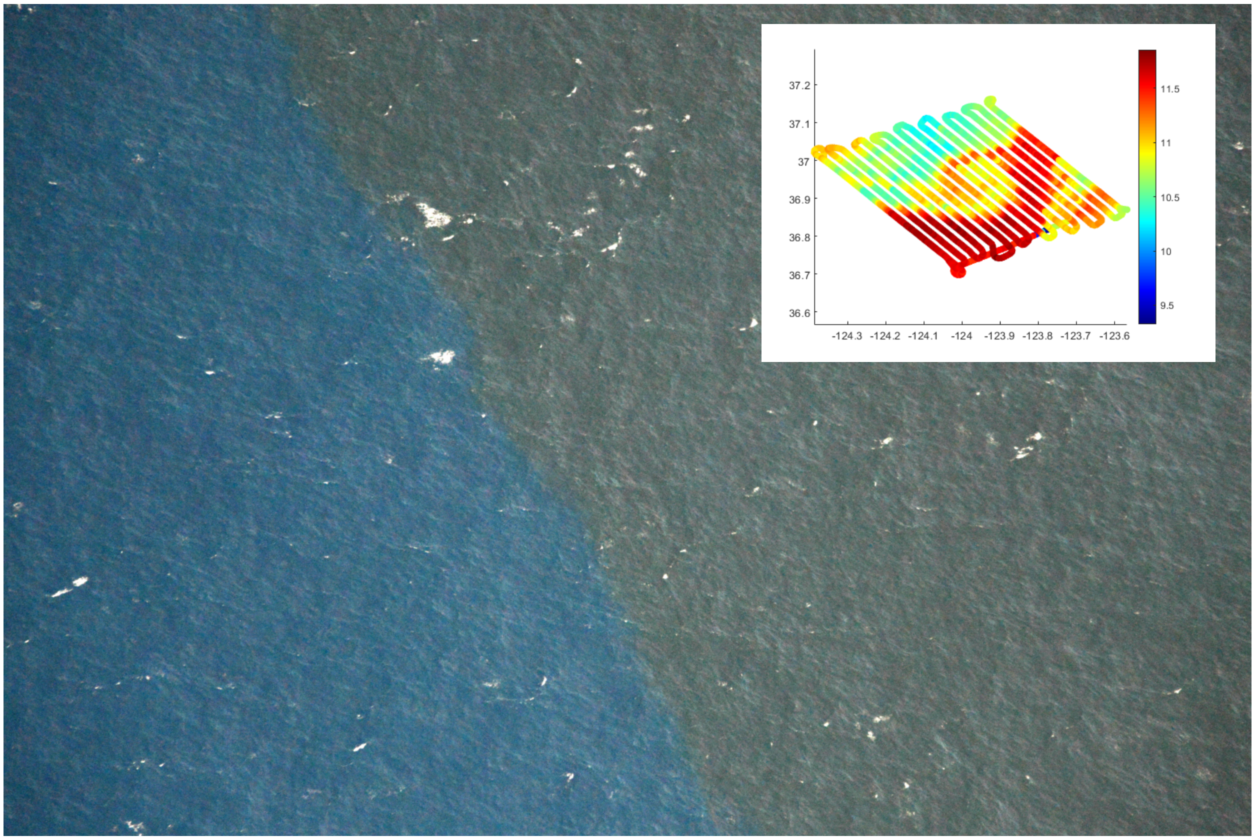



*Figure 11. Front crossing on April 19, 2023 showing significant change in ocean color properties at one of the SST fronts of the eddy observed by MASS (see insert)*.

**PRISM (PI: David Thompson, NASA JPL)**

JPL's Portable Remote Imaging Spectrometer (PRISM) flew multiple sorties under variable conditions, with 24-hour deliveries of quicklook KML chlorophyll index maps. The team's go/no-go and down day decision making meant that NASA's Langley Research Center (LaRC) G-III aircraft took advantage of every realistic clear sky opportunity during the campaign. The April 18 flight had some high-altitude cirrus and haze, resulting in complete coverage but only medium data quality. April 20 and 21 proved cloudier than forecast, so it was not possible to cover the entire area of interest and the team returned early to base. However, there were mostly clear skies over the target area on April 19 and 28, and our initial data assessment indicates good quality spectra for these mosaics.

The image below shows a calibrated chlorophyll-a map from April 27. The color scale ranges from 0 (blue) to 2.0 ug / L of chlorophyll-a. The primary features of interest are all resolved in chlorophyll gradients. Features down to sub-kilometer scale are clearly resolved. The right panel shows an initial estimate of particulate organic carbon concentrations for the same scene.

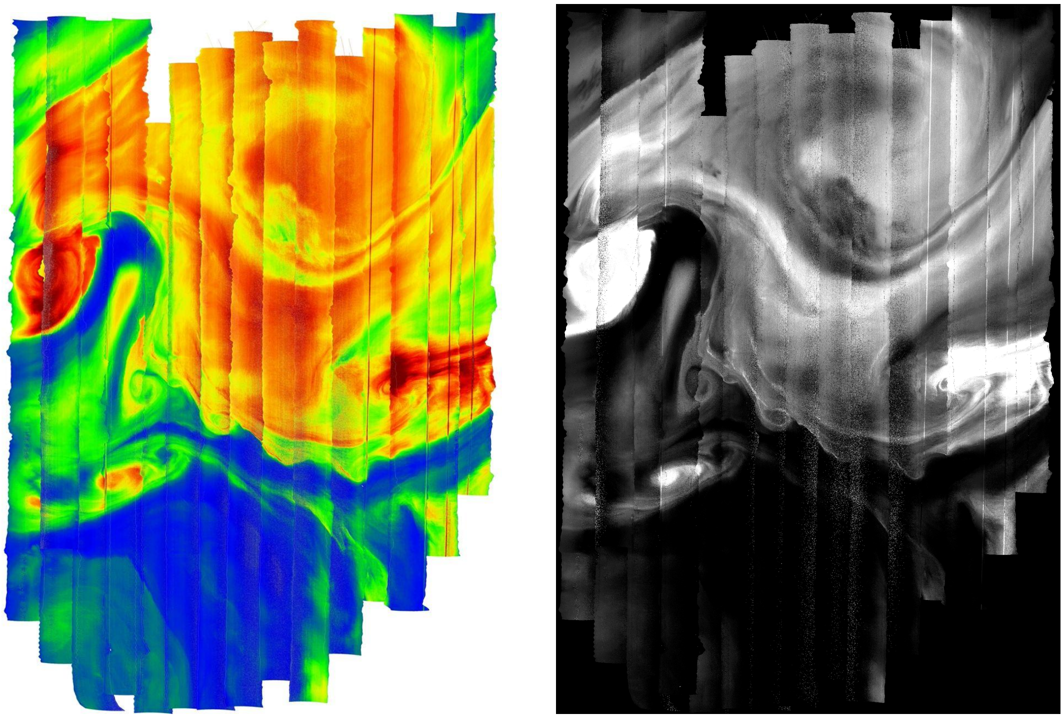


*Figure 12. (Left) First draft PRISM Chlorophyll-a map from April 27, 2023. The color scale runs from 0 (blue) to 2 (red) ug/L. (Right) Particulate organic carbon (POC). The intensity scale runs from 0 (dark) to 300 (bright) ug/L.*

The full spectrum contains additional information on POC and phytoplankton functional type. The figure below shows examples of spectra from different parts of the April 27 scene, indicating the shift in the absorption peak and overall shape of the water-leaving reflectance spectrum. Further refinements to calibration and glint correction are ongoing, but it already promises to be a rich dataset.

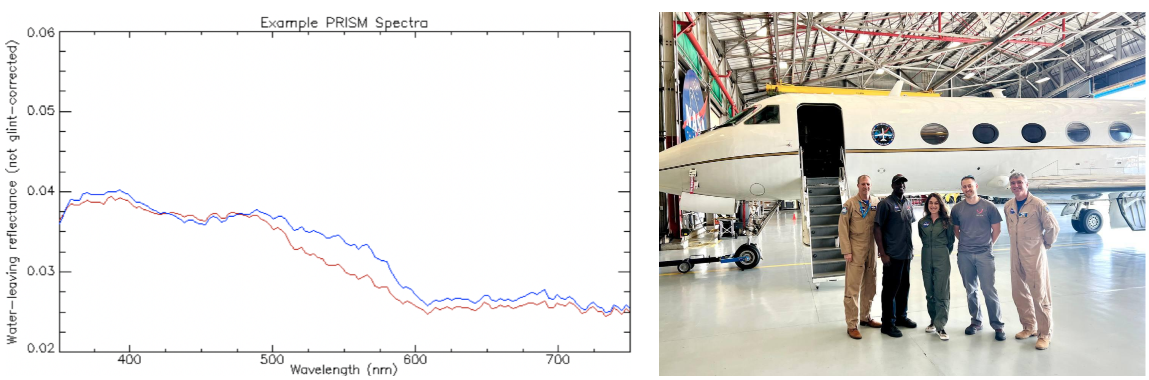



*Figure 13. (Left) Exemplar April 27 water-leaving reflectance spectra inside and outside of high-chlorophyll areas, showing a shift in the absorption band depth at 450 nm. (Right) The JPL PRISM and LaRC G-III team.*

**Wave Gliders (PIs: Tom Farrar, WHOI; Luc Lenain, SIO)**

All nine of the SIO and WHOI Wave Gliders deployed as part of the project successfully surveyed the S-MODE operations area since their deployment at the end of March 2023. The Wave Gliders are currently heading back to Monterey Bay, CA, where they will be recovered next week.

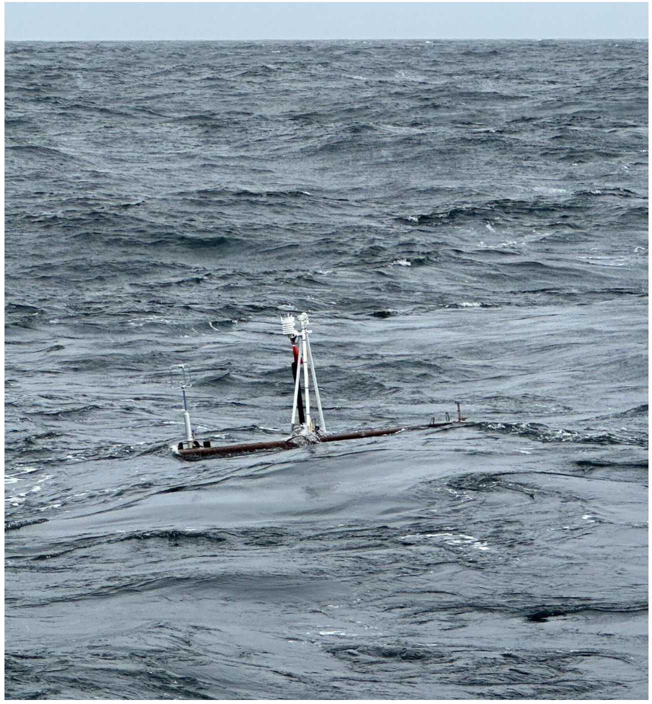


*Figure 14. One of the instrumented Wave Gliders as it passes near the R/V Sally Ride.*

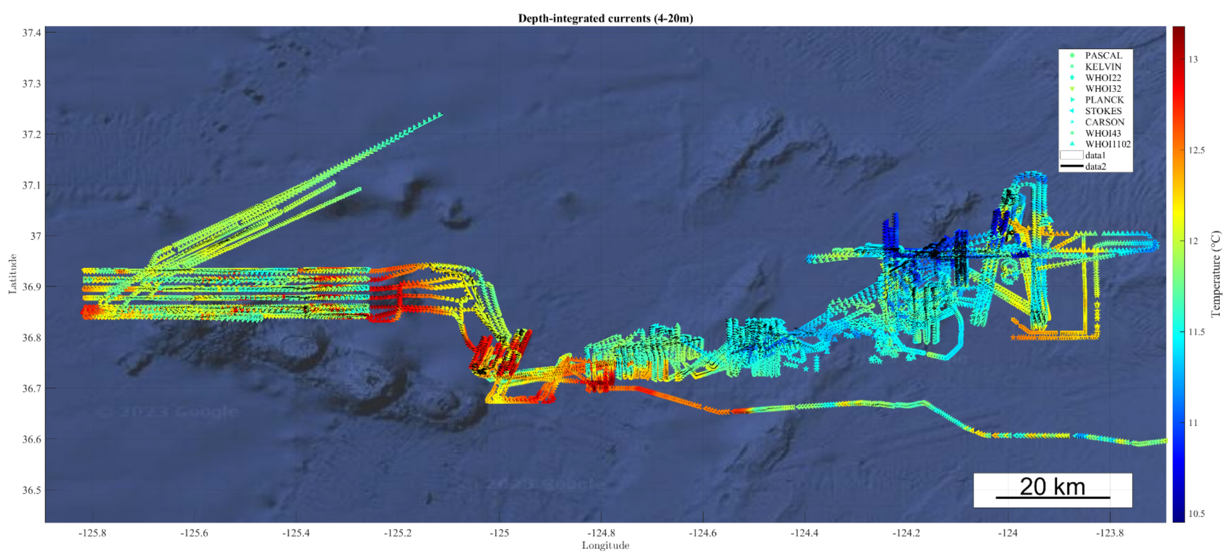



*Figure 15. Surface temperature and currents collected from all nine wave gliders during the S-MODE IOP-2 campaign.*

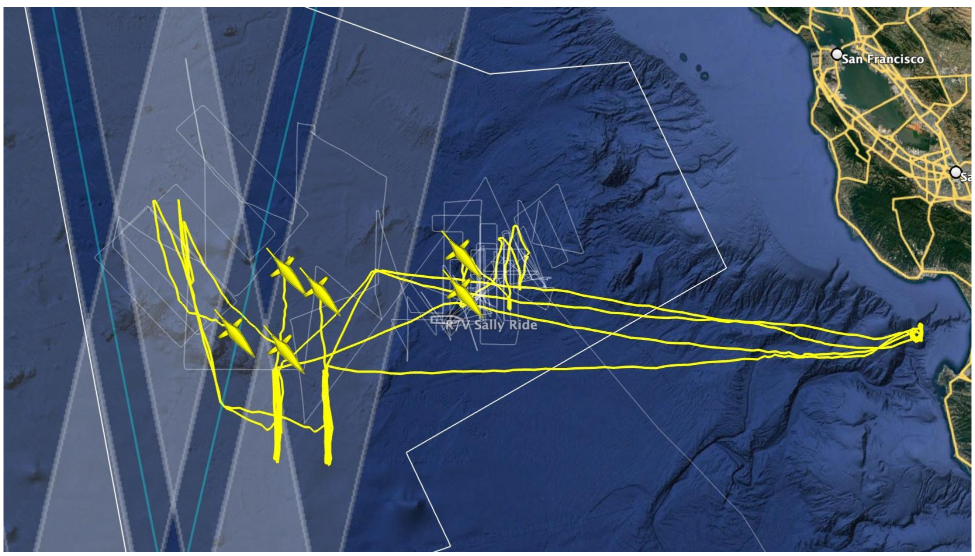
**Seagliders (PI: Luc Rainville, University of Washington)**

Four autonomous underwater Seagliders were deployed on 7 March 2023 from the charter Shana Rae, out of Santa Cruz. These Seagliders transited offshore, arriving in the operation area around 20 March.

For a two-week period, until the arrival of R/V Sally Ride on 11 April, the Seagliders occupied two 40-km meridional sections near 36° 30'N 125°W, across a strong SST gradient and within the SWOT satellite footprint. As the ship started sampling in the operation area, two gliders (SG247 and SG219) transited to sample a longer section across the large surface height gradient in the western portion of the S-MODE domain, near 37°N 125° 30'W.

On 17 April, the ship and other autonomous platforms started sampling an eddy on the eastern side of the domain, near 37°N 124°W. Two additional Seagliders (SG180 and SG237) were deployed there. These two gliders closely coordinated sampling with the Wave Gliders, in addition to the ship and other S-MODE instruments. This array slowly moved westward, towards the other four Seagliders.

SG247 and SG220, moved back to the other two Seagliders (SG219 and SG248), with adjusted pattern to capture the 'downstream' properties of the region sampled intensively by in-situ instruments and aircraft.



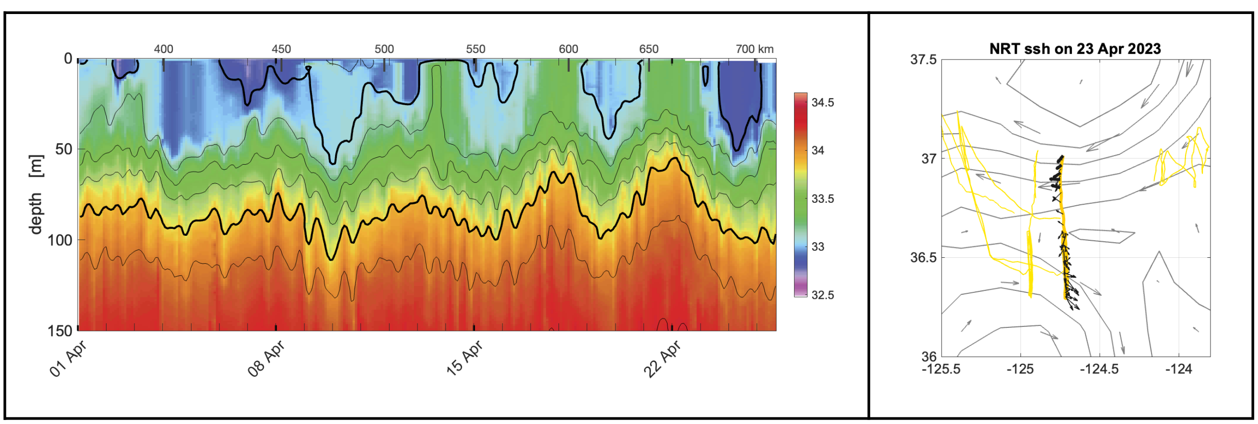




*Figure 16. Depth-time series of absolute salinity from SG248 in April 2023, back and forth along a meridional section (dark orange in the map). Isopycnals are contoured in black (0.1-intervals, 0.5 kg m$^{-3}$ in bold). Note that only the top 150m are shown (gliders sample to 1000m). Cumulative distance since deployment is labeled on top.*