S-MODE Science Report: Oct 25 - Nov 7, 2022

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Science Highlights:

We continued to sample the front and the evolving submesoscale instabilities during the final week of the campaign. This data set provides a really exciting new view of submesoscale ocean dynamics. It is new in many ways:

(1) We have remote sensing observations of the full life cycle of the development of submesoscale instabilities at an ocean front. We got spectacular imagery and quantitative observations from all of the airborne instruments (MASS, MOSES, PRISM, and DopplerScatt).

(2) We conducted a "W experiment", with three Lagrangian floats to test DopplerScatt-derived and MASS-derived estimates of vertical velocity, with encouraging preliminary results. Up to now, Lagrangian floats are the only proven way of measuring submesoscale vertical velocity signals. Extending this capability is a major goal of S-MODE.

(3) The in situ assets were well positioned this week, and through the last weeks of the campaign, collecting measurements that complement the aerial remote sensing measurements. The Saildrones held a tight formation crossing the front and instabilities many times; the Wave Gliders maintained a sub-mesoscale gradient array, collecting one of the first time-depth view of vorticity and divergence; the UW gliders and NAVO gliders provided the larger-scale context.

(4) The team on the research vessel (*M/V Bold Horizon*) collected high-resolution surveys of temperature, salinity and biophysical variables across the front and the instabilities.

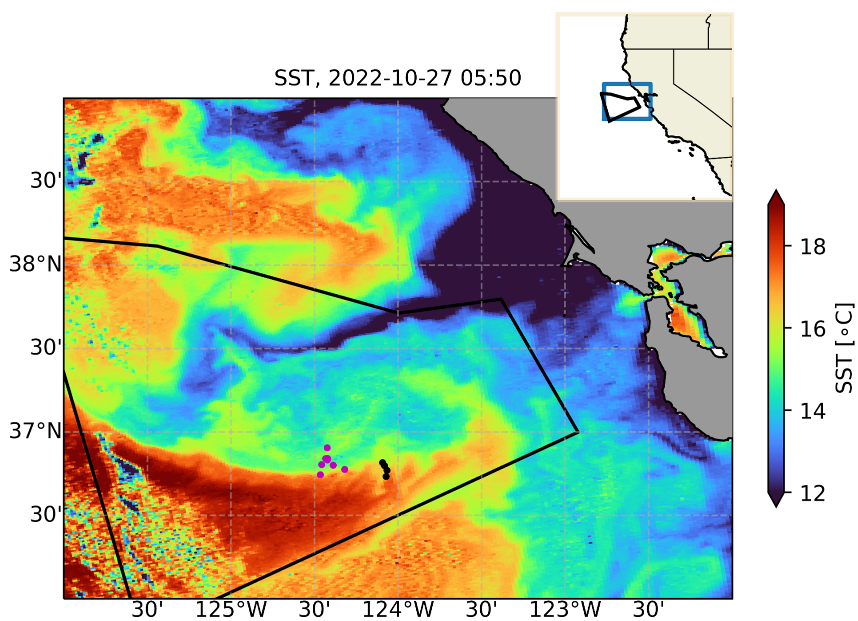

Fig. 1: Satellite sea surface temperature image on the final day of science flights. The dots mark the location of the Wave Gliders (pink) and Saildrones (black) around the time of the image. All of the S-MODE observational platforms made intensive measurements along this unstable front during this time period.

M/V Bold Horizon (Chief Scientist: Andrey Shcherbina, UW)

- During the last week of operations, *M/V Bold Horizon* continued EcoCTD mapping of the evolving frontal instabilities. A dense cold filament (possibly with a small embedded eddy) has been followed as it jutted towards the southern boundary of the S-MODE domain.
- Flow-through biological measurements quantifying hyperspectral inherent optical properties of absorption and scattering were continued throughout the surveys, in addition to chlorophyll fluorescence, beam attenuation and backscattering at three wavelengths (BB3). These measurements indicated that the optical properties of the water - likely reflecting different abundances and populations of phytoplankton - were correlated with the frontal structure.
- A high resolution CTD transect was conducted across the front (see Fig. 2 below), allowing targeted bottle measurements of nutrients, phytoplankton community, and pigments on subsurface features.
- The PySAS control box was damaged during the weekend weather, and so only hand-held radiometric measurements were collected from the deck with a focus on aircraft (MASS or PRISM) overflights.
- Three Lagrangian Floats were also deployed within the filament for a "W experiment" – shallow isopyncal drifts aimed specifically at comparison of upper-ocean vertical velocities (W) measured directly with those obtained from remote-sensing observations.
- The remainder of the Bold Horizon time in IOP-1 was dedicated to recovery of some of our more vulnerable autonomous assets – five Seagliders (UW), two Wave Gliders, and one malfunctioning NAVO Slocum Glider that was drifting helplessly some 200 miles off Santa Barbara.

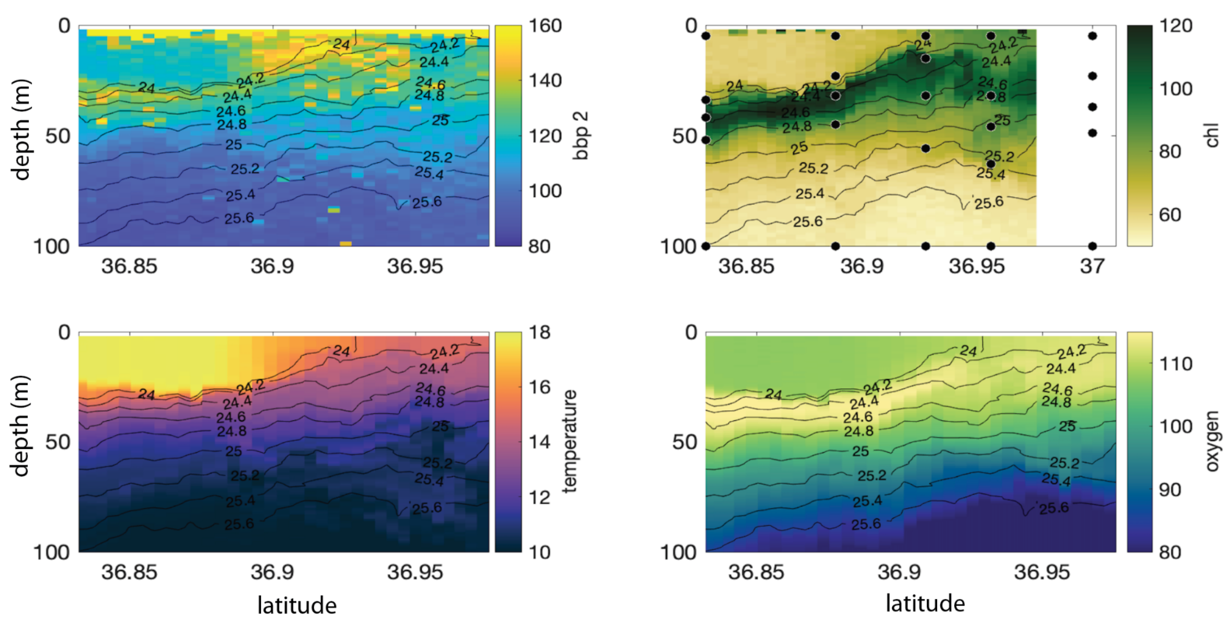

Fig. 2: a) Backscatter 2 (700nm) b) Chlorophyll fluorescence c) temperature and d) oxygen percent saturation from an EcoCTD transect across the front. The black dots in b show the locations of CTD bottle measurements during the high-resolution CTD transect.

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

- The final week of DopplerScatt operations has brought another five flights including a 2-flight day on October 26th. Over the duration of the IOP-1 campaign, DopplerScatt has collected approx. 78 hours of data.

Left: AFRC and JPL crew for the final flight on October 27th; Right: DopplerScatt operators with AFRC crew post final flight.

- During the final week of the campaign, DopplerScatt concentrated on mapping the evolution of the front, and mapped the progress of frontal instabilities and front meanders. The upper panel in Fig. 3 below, in the same area as was shown in previous reports, shows the growth of a large meander in the current field. The next panel presents MASS SST data (courtesy L. Lenain) overlaid on the relative vorticity field calculated from the DopplerScatt data.
- During the final week of the campaign, a joint side-experiment, called the W-experiment, to assess the feasibility of measuring vertical velocities (W) was conducted using the UW Lagrangian Floats (E. D'Asaro, PI), DopplerScatt, MOSES (J. Molemaker, PI), and MASS (L. Lenain, PI). The DopplerScatt contribution was to map the velocity field from which surface current divergence could be inferred and related to the vertical velocities observed directly by the Lagrangian floats. The intensive mapping was conducted over a period of three days and three flights, allowing sampling of the temporal evolution of the field. Luckily, these experiment days coincided with a significant fast change in the flow field, with associated large divergence and vorticity signatures. The figure below captures the magnitude of the changes seen over a period of less than 6 hours, and highlights the advantages of coincident MASS SST data collections to understand and validate the changes in the circulation. Further discussion of the W-experiment will be given in the Lagrangian Float section of this report.

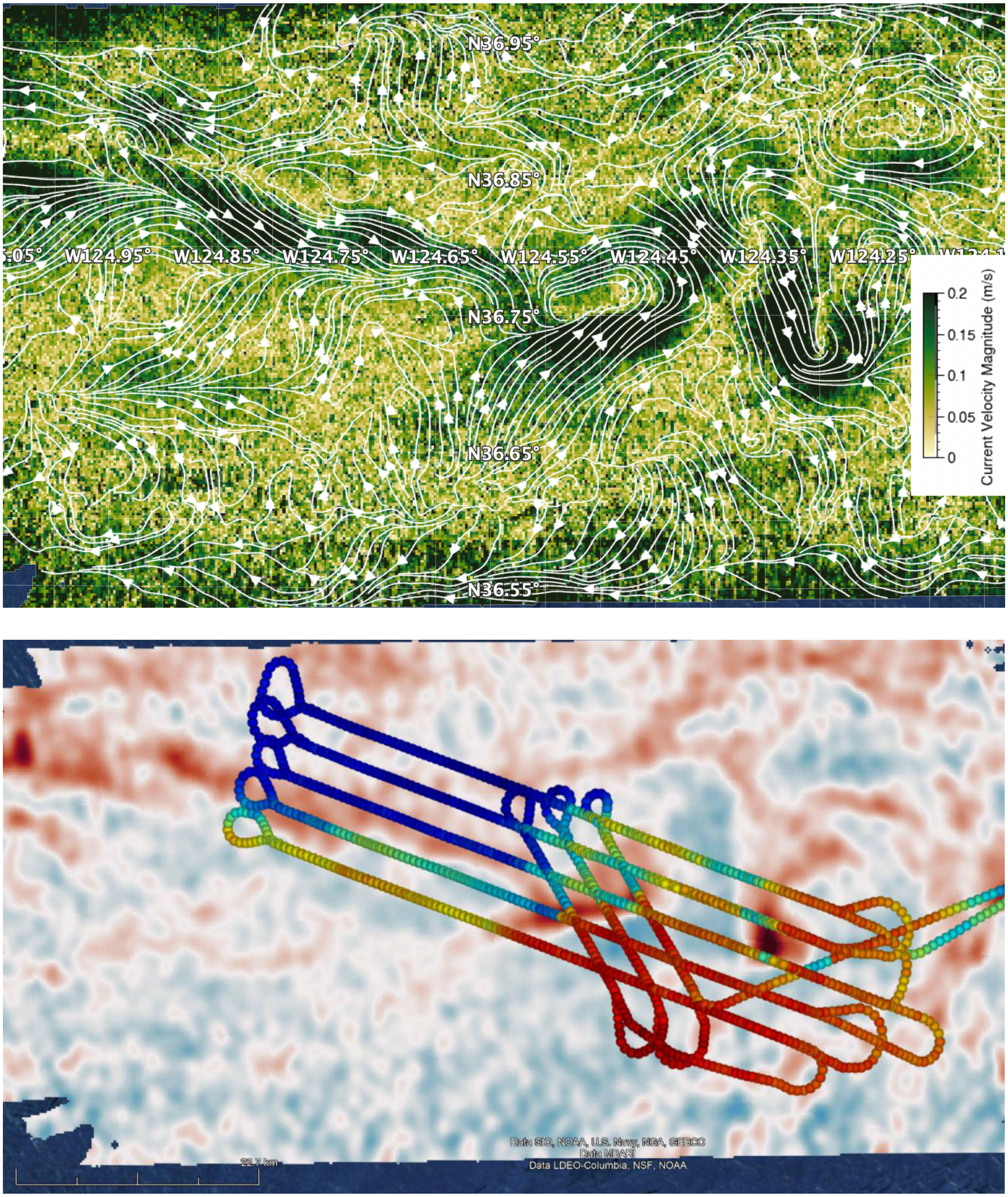

Fig. 3: DopplerScatt submesoscale currents (scales smaller than 15 km) showing the development of significant meanders as a result of the evolution of the instabilities showcased in the previous report (upper panel). Computing dynamical variables, like the relative vorticity shown above, from DopplerScatt currents and overlaying them with Sea Surface Temperature (SST) data from the SIO MASS instrument aids in the understanding of missing processes at the evolving front (lower panel).

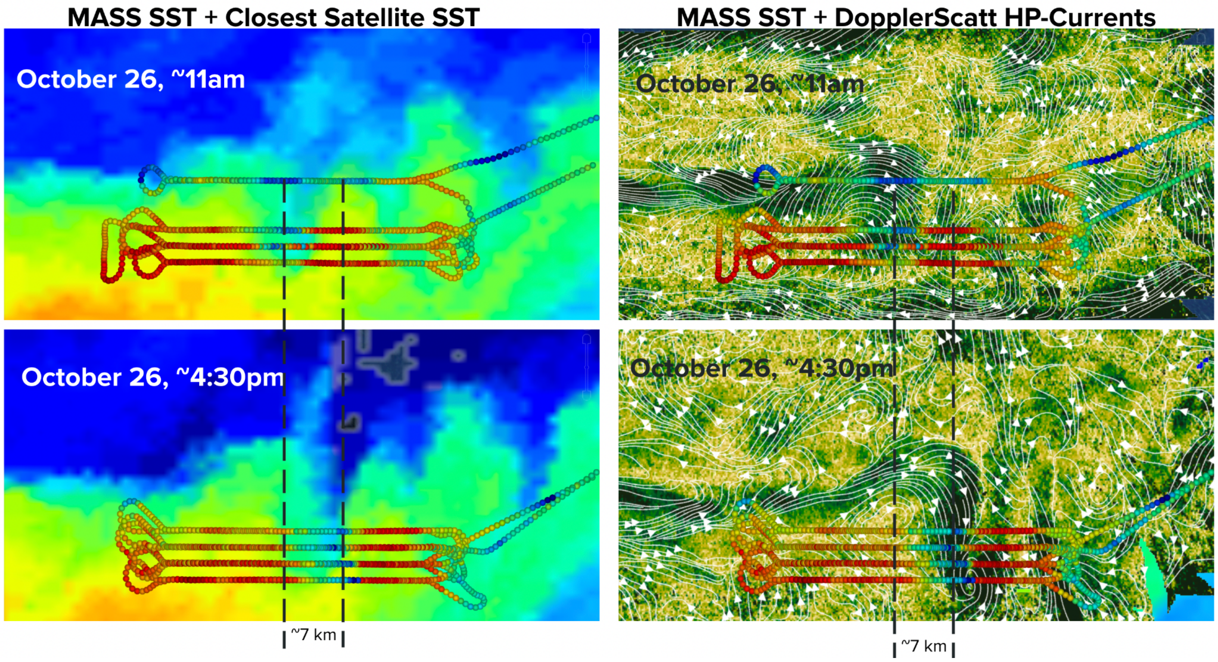

Fig. 4: Changes in the surface current field from DopplerScatt submesoscale currents (right column) over a period of less than 5 hours, where a ~7 km movement in the high-speed ridge was observed. The changes were associated with the extension of a cold filament in the southward direction, and eastward advection by the large-scale currents. The cold water movement can be seen at low-resolution in the left-hand column from satellite SST, and at much higher resolution from coincident MASS SST overpasses, which validated the surface current front displacement observed by DopplerScatt and showed the very narrow filament of cold water moving east and south. MASS data are also overlaid on the DopplerScatt current field, showing the cold water intrusion associated with a narrow jet of south-flowing submesoscale currents.

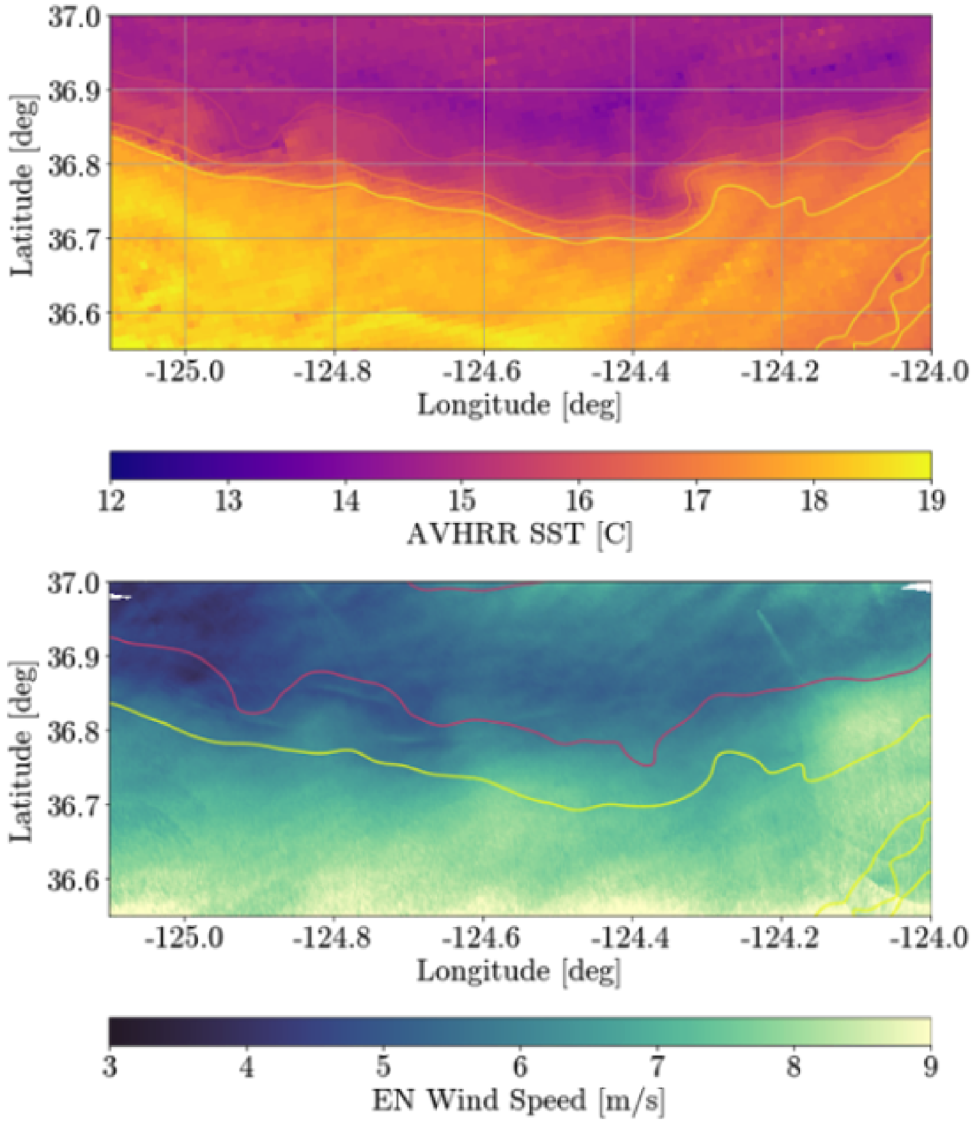

Fig. 5: DopplerScatt observed the influence of sea surface temperature and surface currents on the EN wind field. To the South, AVHRR sea surface temperature (top pane) shows the warm side of the front with growing instabilities. In the bottom pane, DopplerScatt wind speed shows rapid changes from low wind speed over the cold side of the front to higher winds on the warm side of the front. At an even finer scale, the instabilities shown in AVHRR SST are visible modulating the EN winds (left side of bottom pane, follow the red SST contour) at ~1 km scales. This coupling is very strong, and will be seen in even greater detail once this quicklook analysis is performed using coincident MOSES/MASS SST instead of satellite measurements.

MASS (PI: Luc Lenain, Scripps)

This week concluded the MASS flight operations after successfully conducting more than 13 research flights and several calibration flights. Under cloud-free, or conditions with cloud base sufficiently high for the Twin Otter to fly under, we conducted coordinated flights with the other two aircraft and in-situ assets to survey the mesoscale front and associated submesoscale features discussed in earlier parts of this report.

PRISM (PI: David Thompson, JPL)

PRISM flew two sorties, on October 26 and 27. These expanded our previous sampling strategy, augmenting the mosaic coverage with multiple repeated overflights over key flightlines. The resulting maps show not only the extent and patterns of phytoplankton, but also track its temporal evolution over short timescales. The initial data quality, evidenced by quicklook chlorophyll-a products shown below, looks good with almost no cloud coverage. Future versions of the product, incorporating glint and atmospheric correction, will improve the uniformity of these mosaics. However, the mosaics will never match perfectly along the seams due to the constant motion of the measured water masses.

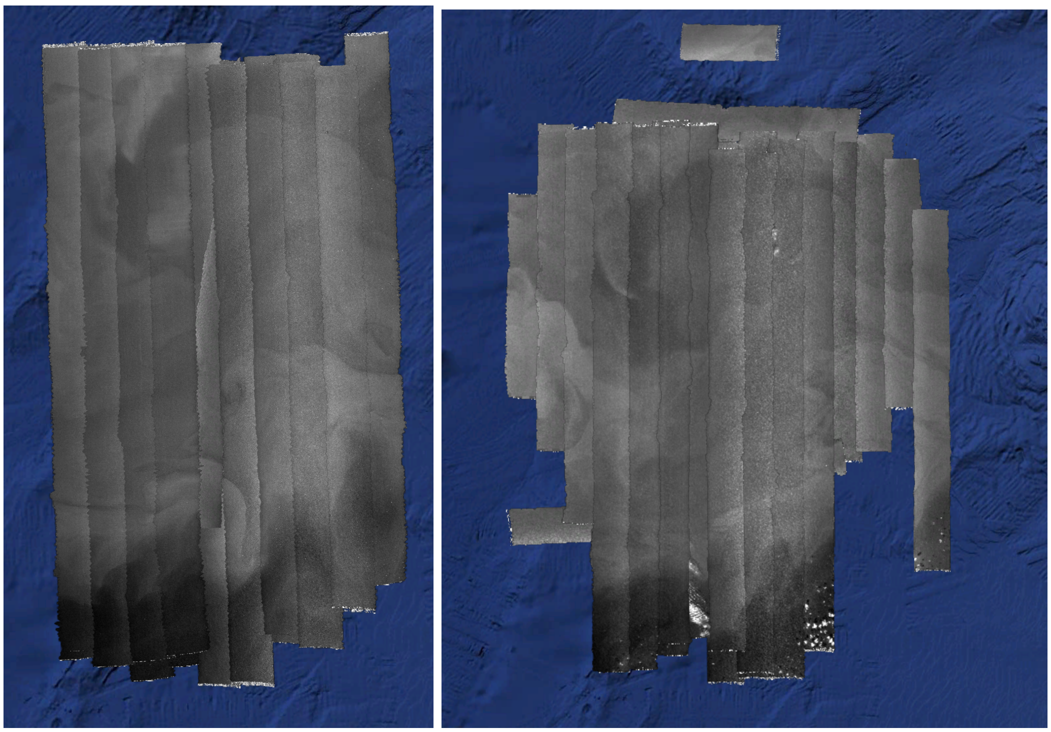

Fig. 6: Left: PRISM image mosaic of "quicklook" chlorophyll index products (no glint or atmospheric correction yet), acquired on 26 October. Right: PRISM quicklook acquired on 27 October. Both contain multiple repeats over key flightlines.

Left: PRISM hangar calibration activity. Calibration is performed in a darkened hangar to minimize lighting variability. Right: PRISM and G-III team.

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

All eight Wave Gliders continued to collect observations of air-sea interaction and upper-ocean processes this week in close coordination with the research vessel and aircraft. Two of the vehicles were recovered by the *M/V Bold Horizon* before it departed the operations area. The other six vehicles headed to Santa Cruz, CA after the end of the experiment to be recovered from a local charter vessel, the F/V Shana Rae on November 7 2022, concluding a 7+ weeks long deployment.

Wave Glider recovery on November 7 2022 from the F/V Shana Rae. Note the biofouling after the 7+ weeks long deployment.

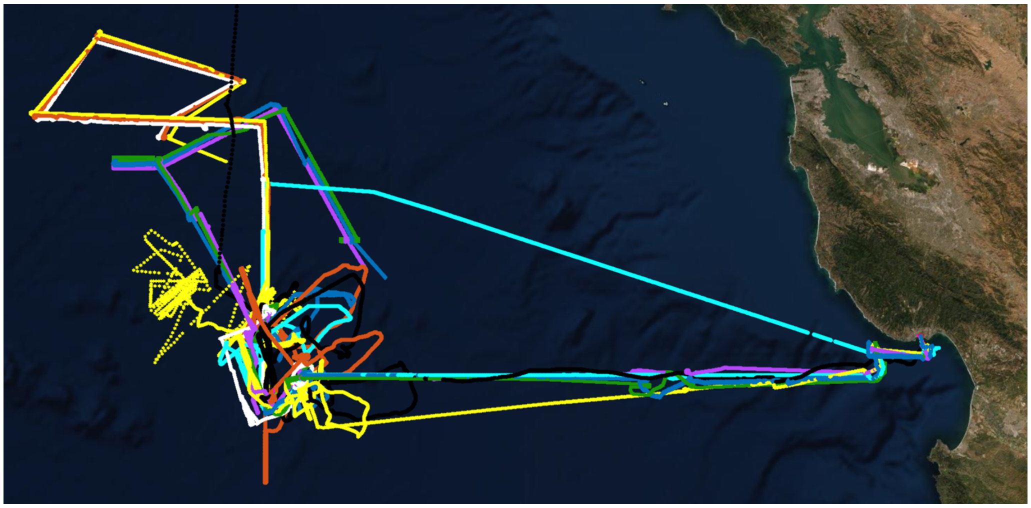

Fig. 7: Trajectory of all 8 Wave Gliders for the duration of their deployment.

Lagrangian Floats (PI: Eric D'Asaro, UW)

All three Lagrangian floats were deployed in a 'W experiment' from October 26-28 designed to compare direct and indirect measurement of vertical velocity 'W', a major goal of S-MODE. The floats were deployed near the main S-MODE front and measured downwelling velocities of about 1.4 mm/s (125 m/day) while remaining on the same density surface to about 1m. Compared with a nearby density section made by the *M/V Bold Horizon*, this implies that the floats were sliding down the sloping density surface, with compression occurring below the floats and stretching above them. This is consistent with the observations of surface convergence by DopplerScatt and nearby surface drifters.

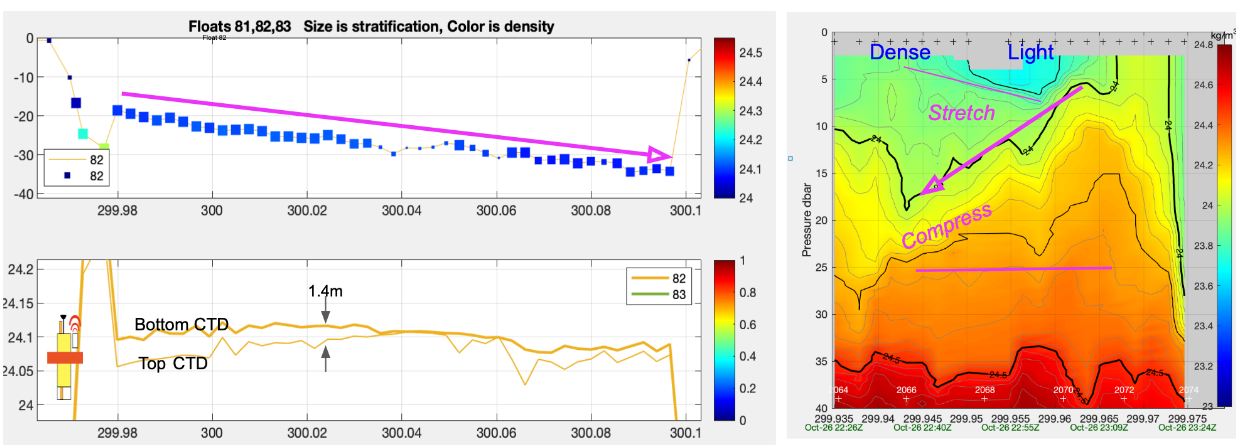

FIg. 8: Plots of Lagrangian Float data from 'W Experiment'

Saildrones (PI: Cesar Rocha, UConn)

The Saildrones spent the last few days of the campaign sailing in submesoscale formation the eastern part of the front to continuously measure velocity gradients near and across the front. The vehicles crossed the trailing edge of a mature instability identified in satellite and MOSES SST and DopplerScatt velocity. For the last 14 hours of the Saildrone campaign, which ended on October 27 at 1500z, we broke the formation and took advantage of great sailing conditions to conduct a quasi-synoptic survey of the mature instabilities, which propagated downstream (eastward), as seen in the figure below.

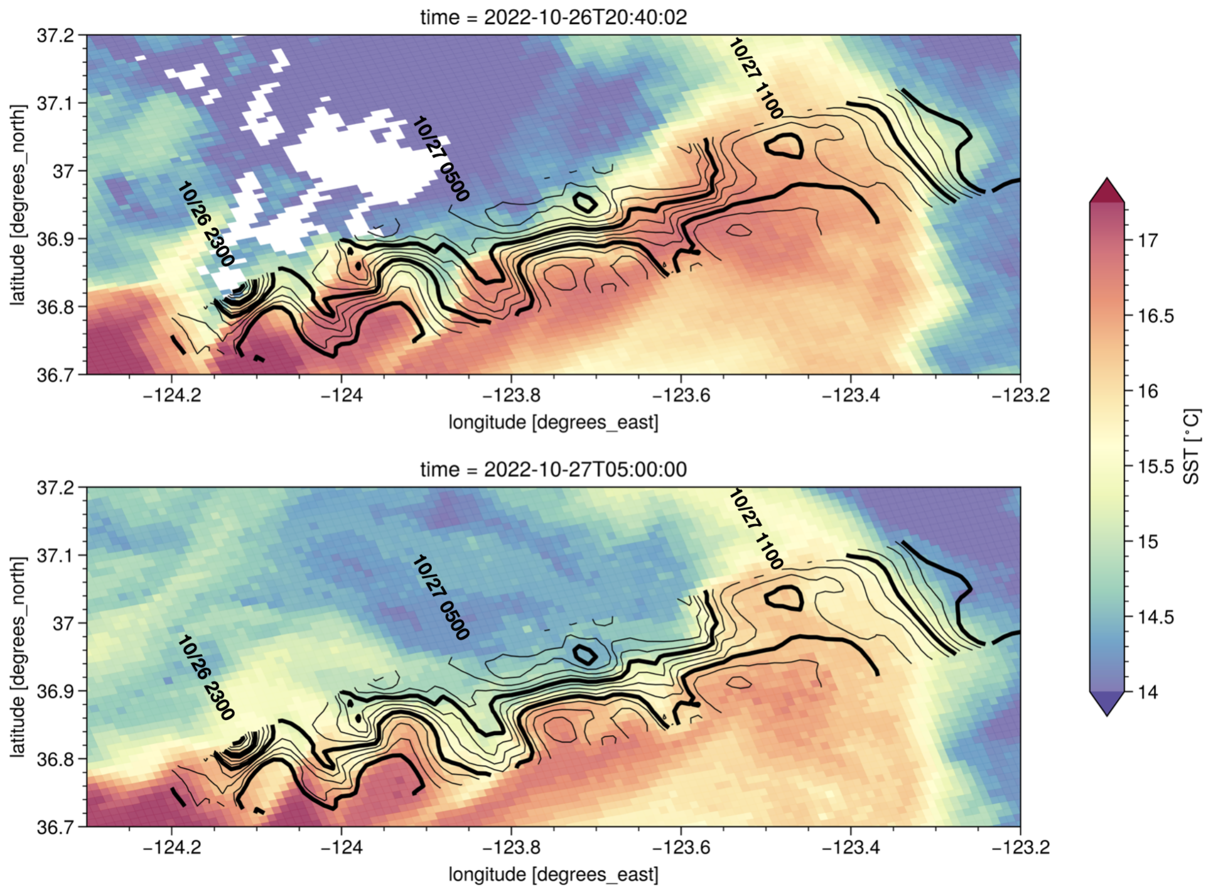

Fig. 9: A comparison between near-surface Saildrone temperature (contours) two SST images (colors) during the Saildrone survey across mature mixed-layer instabilities. The instabilities propagated east at about 0.3 m/s, while the Saildrones traveled east at 1-2 m/s. The subplot title is the time for the respective SST image. The annotations indicate the time the Saildrones crossed the respective longitude.

Seagliders (PI: Luc Rainville, UW)

All five Seagliders continued to sample as part of the S-MODE array, crossing the targeted front several times before being recovered by the *M/V Bold Horizon* on 28 October 2022. Prior to the recoveries, gliders participated in calibration dives, where the ship collected CTD profiles while several gliders were diving nearby. In total, the six S-MODE Seagliders collected 3326 profiles (1663 dives), covering 4311 km in total distance.