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In Box

Coherent Pathways for Vertical Transport from the Surface Ocean to Interior

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A long-standing challenge in oceanography is the observing, modeling, and prediction of vertical transport, which links the sunlit and atmospherically mediated surface boundary layer with the deeper ocean. Vertical motions play a critical role in the exchange of heat, freshwater, and biogeochemical tracers between the surface and the ocean interior. The most intense vertical velocities occur at horizontal scales less than 10 km, making them difficult to observe in the ocean and to resolve in models. Understanding how finescale turbulent motions and 0.1–10 km submesoscale processes contribute to the large-scale budgets of nutrients, oxygen, carbon, and heat and affect sea surface temperature, the air–sea exchange of gases, and the carbon cycle is one of the key challenges in oceanography.

The ocean, as the atmosphere, is largely in geostrophic balance at mesoscales (10–100 km) or larger scales. Since the horizontal pressure gradientforce (per unit mass) is balanced by Coriolis acceleration and the ocean is density stratified, vertical velocities are typically 1,000 to 10,000 times smaller than horizontal velocities at these scales. Interest in submesoscale dynamics has grown in recent years because its deviation from geostrophic balance enables the intensification of the vertical component of velocity, which results in the transport of biogeochemical tracers and heat (Klein and Lapeyre 2009; McWilliams 2016; Mahadevan 2016; McWilliams et al. 2019). The strong theoretical and modeling evidence for the existence of unbalanced vertical velocities that account for vertical transport has not been effectively accompanied by direct observation, although indirect estimates have shown the relevance of these vertical exchanges (Omand et al. 2015).

In recent modeling studies that resolve submesoscale dynamics, the vertical velocity has a wide range of space and time scales (Freilich and Mahadevan 2019). Vertical advective transport, attributed to water parcel trajectories originating in the surface mixed layer and ending up in the pycnocline (region of strong vertical density gradient beneath the mixed layer), is not randomly distributed, but occurs at specific sites (Ruiz et al. 2019). Models and oceanic observations show anomalous signatures of water mass and biogeochemical properties in the stratified pycnocline that have their origins in the surface mixed layer (Omand et al. 2015). These anomalies have horizontal length scales of a few kilometers and vertical length scales of a few (up to 10) meters. A hypothesis that emerges is that there are dynamically controlled, advective, coherent pathways for subduction from the mixed layer to pycnocline. The sites for active subduction occupy a relatively small fraction of the surface area. Observing this process by targeting sites of active subduction and measuring vertical transport in the field is notoriously difficult. First, it entails Lagrangian measurement of relatively small vertical displacements (tens of meters) on horizontal trajectories spanning tens of kilometers. Second, the majority of vertical motion in the surface mixed layer changes direction before water parcels cross the base of the mixed layer and only a small fraction of trajectories cross the base of the mixed layer along outcropping isopycnals. Further, in the field, we are confounded by the lack of clear separation between advection along isopycnals and the upward and downward motion of isopycnals by eddy dynamics and waves on near-inertial and shorter time scales. Even models have not clearly isolated the dynamical mechanisms by which water parcels are irreversibly subducted. Frontogenesis, which intensifies fronts, and restratification of the unstratified mixed layer by the slumping of isopycnals are two proposed mechanisms (Fox-Kemper et al. 2008), but isolating such mechanisms in the field is challenging when the space and time scales, as well as sites for subduction, are not known a priori. Furthermore, turbulence induced by surface cooling and winds is heterogeneous in space. It can be selectively intensified at fronts to generate vertical velocities, as large as centimeters per second, that contribute to the irreversible vertical transport of tracers (Smith et al. 2016).

Observing, understanding and predicting the three-dimensional pathways by which water from the surface ocean makes its way into the interior is the goal of an Office of Naval Research Departmental Research Initiative, "CALYPSO" (Coherent Lagrangian Pathways from the Surface Ocean to Interior). In CALYPSO, scientists from several institutions in the United States, Spain, Italy, and France are collaborating to use innovative observational techniques along with process study models, predictive models, and data synthesis to identify pathways for vertical transport and to diagnose and predict the physical processes that underlie subduction and transport across the base of the surface mixed layer.

Approach

Region of study. Our study is focused on the Alborán Sea in the western Mediterranean, where fresher water from the Atlantic ocean flowing through the Strait of Gibraltar meets the saltier Mediterranean water to form an unstable front. Mesoscale meanders, $O(100)$ km in extent, fill the basin (Renault et al. 2012), often forming two anticyclonic gyres that are clearly outlined in sea surface height elevation (Fig. 1). The front, with its strong density contrast and powerful currents, provides an ideal setting for studying the interaction of mesoscale and submesoscale motions and the resulting vertical exchanges. Vertical motion is known to be enhanced at ocean fronts and has been previously diagnosed in this region with the quasigeostrophic omega equation (Tintoré et al. 1988, 1991; Ruiz et al. 2009), a diagnostic equation for the vertical velocity that depends on the geostrophic velocity gradients and density gradients. The region is largely nutrient-depleted at the surface and the growth and distribution of phytoplankton responds to the upwelling of nutrients at the boundaries of the basin and along the front, as well as to horizontal advection by the mesoscale and submesoscale currents (Fig. 1). Serving as a tracer for advection, phytoplankton, which grows in the presence of sunlight, is helpful in identifying subducted water that has made its way into the density stratified region beneath the mixed layer known as the pycnocline.

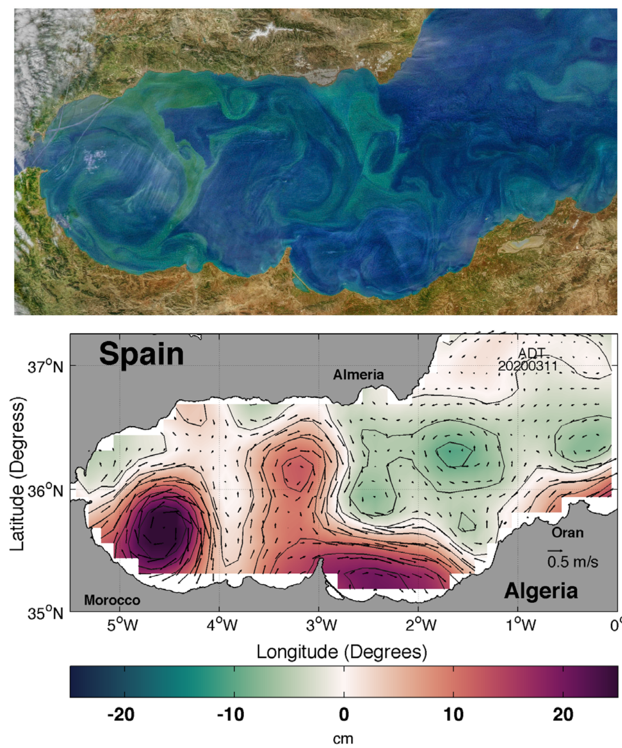

Fig. 1. (top) Phytoplankton in the western Mediterranean Sea captured by MODIS on the NASA *Aqua* satellite on 11 Mar 2020. Image is from the NASA Oceancolor website, courtesy of Norman Kuring. The edge of the western and eastern Alborán Gyres are strong fronts and show an accumulation of phytoplankton. The phytoplankton chlorophyll is observed subsurface from gliders and underwater ship-based measurements as it is subducted at the front. (bottom) Absolute dynamic topography (ADT in cm) estimated from satellite altimetry at approximately the same time as the image above. The mesoscale circulation in the Alborán Sea shows the western and eastern Alborán Gyres, which shape the patterns of chlorophyll. The strong fronts at the edges of the gyres show elevated chlorophyll, which is associated with horizontal advection, and likely also vertical advection as suggested by modeling (Fig. 2).

Strategy. Guided by more recent observational, theoretical, and modeling work (Pascual et al. 2017; Ruiz et al. 2019), we expect downward transport from the surface to occur in kilometer-wide filaments, which are more prevalent on the dense side of fronts with strong cyclonic vorticity. The lateral strain of the mesoscale meandering flow is intensified at the strongest front, which is sharpened by frontogenesis, and acts to generate filaments of intensified positive vorticity that are tens of kilometers in the alongfront direction (Fig. 2a). In models, the intensity and width of such downwelling regions are sensitive to the numerical resolution, which determines the strength of the lateral density gradients. Tracers capture the advective downward motion of mixed layer water along sloping isopycnals that outcrop in the mixed layer. Subsurface maxima in tracers that originated at the surface reveal the importance of three-dimensional pathways in transporting the tracer into the pycnocline (as seen beneath the gyre of less dense water in Fig. 2b). Understanding the dynamics and Lagrangian pathways for such vertical transport are major goals of the proposed work and is more complicated than the vertical velocity field shown in Fig. 2c. This emphasizes the need for measurements of the lateral density gradient, vorticity, strain, and convergence, with sufficient spatial and temporal resolution to allow meaningful comparison with theory and models (Shcherbina et al. 2015).

Measurements. Two field campaigns have been conducted so far: in May–June 2018, one week of measurements were made from the NRV Alliance and R/V SOCIB, and in March–April 2019, a two-week field campaign was conducted from the research vessels Pourquoi Pas? and SOCIB. These campaigns sampled very different regimes—a thermally stratified upper ocean in May–June, and a relatively deeper mixed layer, with extremely strong surface wind forcing in March–April. The measurements consisted of two components: Eulerian and Lagrangian. In 2018, an array of three gliders repeatedly crossed the Almeria–Oran Front for 2.5 months, measuring temperature, salinity, velocity, chlorophyll, and acoustic backscatter. The array resolved the three-dimensional, time-evolving mesoscale structure with the goal of diagnosing vertical velocity with the quasigeostrophic Omega equation, which uses the gradients of density and horizontal geostrophic velocity to calculate the frontal intensification, and thereby the overturning secondary circulation that acts to slump the front. On the submesoscale, gliders observed the associated frontal convergence and vorticity of the secondary circulation, and plumes of chlorophyll descending along the sloping isopycnals of the front (Fig. 3). In 2019, an array of eight gliders was deployed for 2 months. One of these gliders was programmed to follow a temperature surface, producing a series of 24-h Lagrangian drifts with the goal of tracking the downward motion of water parcels in the frontal region.

The ships made intensive, adaptive measurements using a variety of tools (Fig. 4). Satellite imagery (altimetry, SST, and ocean color) and real-time model output helped to target regions for more detailed study. Arrays of surface drifters, totaling more than 200 drifters, were deployed across target regions to measure the surface currents, strain, vorticity, and convergence across the front. This was done at more than one depth by using different drogue depths for the drifters. The free-falling UCTD and EcoCTD (Dever et al. 2020) were deployed and reeled back to the ship while underway, to profile the water column at 1 m resolution in the vertical, and $O(1)$ km spacing in the horizontal. A freely drifting, vertical profiling platform, the Wire-Walker, provided repeated profiling to approximately 150 m depth at 10–20 min intervals. Using the ship, we surveyed through an evolving and translating array of drifting instruments (Fig. 4) measuring velocity, temperature, salinity, chlorophyll, optical backscatter, and oxygen in the upper 200 m. These measurements characterized the frontal structure and identified signatures of downwelling water parcels from their temperature and salinity anomalies, and their bio-optical and oxygen signatures. Rates of mixing were measured from microstructure profiles. Water samples taken at multiple depths along- and across-front provided information on the biogeochemistry, phytoplankton types, and genomic characteristics to examine the effects of subduction on the phytoplankton community. A towed chain with temperature and salinity sensors and an ADCP was used to measure the finescale horizontal structure.

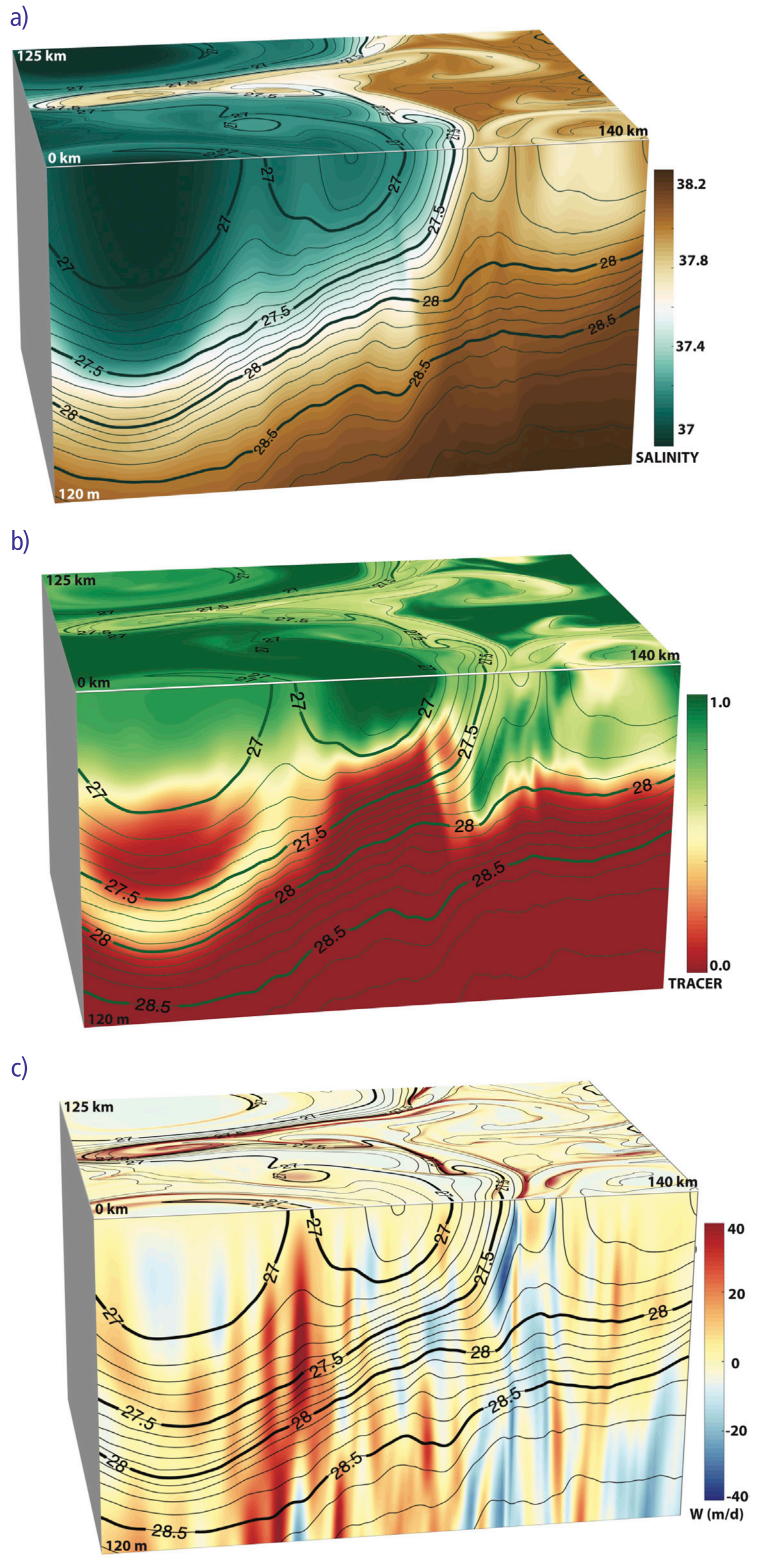

Fig. 2. Fields from a three-dimensional process study ocean model (PSOM) showing (a) the salinity (colors) and density structure (contours) of a frontal meander in the Alborán Sea. (b) The model was initialized with a tracer within the mixed layer. After a few days, the tracer is seen to have subducted beneath the mixed layer along a three-dimensional advective pathway. (c) Vertical component of the relative vorticity (normalized by *f*) (top surface) and vertical velocity (vertical sectional view) show the submesoscale character of the flow. Positive relative vorticity dominates, with values larger than *f* in frontal regions. Downwelling occurs in narrow, well-defined regions along the front and transports the tracer along isopycnals. This model was run by Mariona Claret and is described in Ruiz et al. (2019).

In addition, an array of three moorings resolved the high-frequency time-variability of the flow closer to shore during the period of ship-based observations.

To directly trace the three-dimensional trajectories of subducting water originating at these fronts, Lagrangian floats were deployed in convergence regions defined by these measurements. These float deployments traced the pathways of water for over 24 h before being recovered. In future measurements, an array of 3–5 Lagrangian floats will be embedded within the drifter array and detailed surveys will be conducted with an autonomous underwater vehicle [Remote Environmental Monitoring Units (REMUS)] near the Lagrangian float and in the front.

Modeling and analysis. A hierarchy of numerical models is beingemployed to span the range of scales from 300 km to tens of meters. Operational models run by the Copernicus Marine Service, Balearic Islands Coastal Observing and Forecasting System (SOCIB), and the Massachusetts Institute of Technology predict the evolution of the front and circulation in response to changing conditions. Other regional research models with subkilometer resolution simulate submesoscale instabilities and features not resolved in the operational model. These occur both at strong fronts and near topography where bottom friction can greatly modify the flow. Process study models of frontal instability and subduction are used to track water parcel trajectories and understand the mechanisms underlying their downward motion. Large-eddy simulations are being used to investigate the interaction of submesoscale fronts with boundary layer turbulence, which is hypothesized to play a critical role in frontal secondary circulations. Model simulations help identify targets for the field measurements. In particular, Lagrangian analysis methods including finite-time Lyapunov exponents (FTLEs) and coherent structure identification show how surface structures that are well sampled by dense drifter arrays can be used to predict the locations of downwelling and Lagrangian pathways from the surface into the interior. Model trajectories are being compared to observed transport pathways derived both indirectly, from biological tracers, physical properties, and surface drifters, and directly, by Lagrangian floats and gliders.

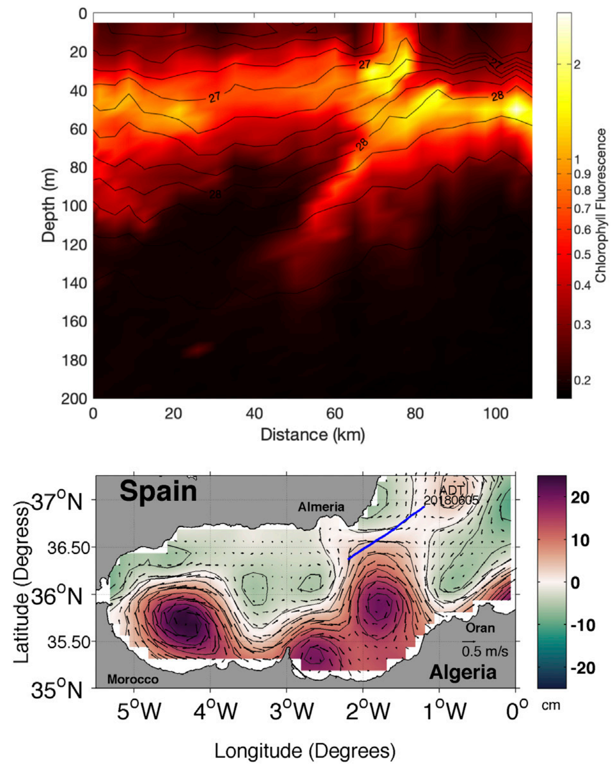

Fig. 3.(top) Chlorophyll fluorescence (color, log scale) and density (contours) measured by a glider crossing the front on the eastern flank of the eastern Alborán Gyre in June 2018. The subduction at the front (along sloping isopycnals) is evidenced by the downward advection of phytoplankton from about 50 to 120 m depth. (bottom) Absolute dynamic topography (ADT in cm) constructed from five satellite altimeters shows the mesoscale circulation on 5 Jun 2018. The strongest ADT gradient is at the front, which differentiates Atlantic waters (roughly marked by positive ADT) from Mediterranean waters (negative ADT). The location of the glider transect is shown as a blue line.

Highlights from 2018 and 2019 observations and modeling

The early summer (May–June 2018) and spring (March–April 2019) campaigns revealed very different conditions. In summer, thermal stratification isolates the surface layers so that deeper subsurface isopycnals are unable to outcrop at the ocean surface. Hence, Lagrangian pathways from the surface did not penetrate deeper than the mixed layer depth in May–June. Subduction to depths of 100–150 m occurred mostly from about 50–70 m, as revealed by chlorophyll signatures drawn from the deep chlorophyll maximum (Fig. 3). In the late winter, we found frontal isopycnals outcropping at the surface through 20–50 m deep mixed layers. Subduction occurred through the combination of boundary layer turbulence, which carried water across the mixed layer, and frontal slumping, which isolated the bottom portion of the mixed layer (D'Asaro et al. 2018).

The Almeria–Oran Front, with distinctly contrasting water masses on the eastern flank of the eastern Alborán Gyre, was the strongest front measured during the pilot study in May–June 2018. In March–April 2019, the eastern Alborán Gyre was absent, but the flanks of the western gyre included a strong front that revealed signatures of subduction downstream of the meander crest. The Almeria–Oran Front made its appearance in mid-April as the eastern gyre developed and persisted through the end of the glider missions in late May 2019.

Surface drifter arrays were useful in mapping out the mesoscale structure of the flow and in identifying fronts in real time. Analyses of trajectories of drifter clusters on scales smaller than 10 km revealed alternating regions of convergence and divergence along the front, similar to what is seen in submesoscale-resolving models.

Our techniques successfully surveyed the mesoscale structure and measured strong submesoscale surface convergence, vorticity, and subduction. Two realizations of three-dimensional trajectories captured with a Lagrangian float returned to the surface within hours. In March–April 2019, a Lagrangian float trajectory went from the surface mixed layer to the stratified region just below the mixed layer. Water mass analysis showed coherent features in anomalous subducted water masses at the periphery of an eddy and along a front. Our numerical

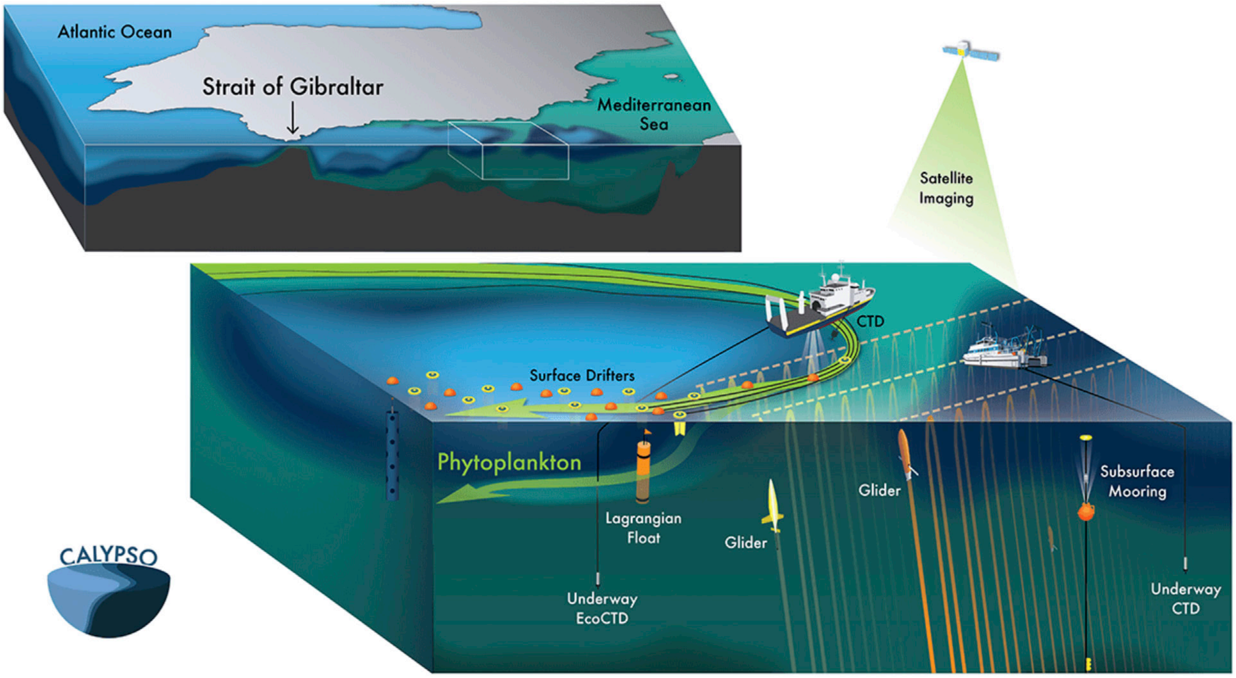

Fig. 4. Schematic showing (top) our region of study (white box) in the western Mediterranean, a meeting ground for fresher Atlantic and saltier Mediterranean waters. Satellites, underwater gliders, two ships with towed instruments, moorings, and an array of drifting instruments are used to measure the flow and property contrasts at the front. The mesoscale (≈100 km) meander harbors a current with strong (max 1 m s^{-1}) horizontal velocities. Vertical motion occurs within select regions along the front and subducts surface water along with its phytoplankton, oxygen, and other properties beneath the mixed layer.

models show that most three-dimensional trajectories of water parcels reverse their vertical direction on time scales of less than a day, and only a small fraction of water parcels that are subducted remain sequestered below the mixed layer. Understanding the dynamics that leads to deeper, more permanent vertical transport is an outstanding problem.

Numerical models are revealing the interaction between submesoscale structures and the mesoscale flow field. Modeled vertical velocities in the wintertime mixed layer are larger than in the shallow summertime mixed layer, but in both cases, the mesoscale strain and frontogenesis are important for subduction. Vertical excursions of water parcels in models are correlated with the FTLEs and other Lagrangian measures of coherent structures at the surface, suggesting that it may be plausible to detect subsurface vertical motion from surface data.

Future experimental priorities and plans

Based on modeling and preliminary measurements, we hypothesize that in our experimental region, a significant component of vertical transport from the surface to below the mixed layer results from submesoscale motions. This transport is concentrated near kilometer-wide fronts with the downward component tending to be on the dense side of the fronts, thus transporting dense water downward. The location and intensity of these regions are modulated by the properties of the mesoscale and mean fields in which they are embedded and the air–sea forcing; in this sense, the mesoscale and submesoscale work together to make coherent pathways for subduction.

An intensive field campaign is being planned for spring 2022 from the research vessels L'Atalante, Pelagia, and SOCIB. A priority will be to conduct several Lagrangian experiments with surface drifters, Lagrangian floats, profiling floats, and isopycnal-tracking gliders, all within a larger scale Eulerian survey. The Lagrangian platforms will be tracked in real time using new technologies. Furthermore, an autonomous underwater vehicle (AUV) will be used to conduct high-resolution measurements at the sharpest front. Direct measurement of vertical velocity will be attempted from drifting platforms. Bio-optical and physical properties will be measured with underway profiling equipment so as to resolve spatial variability at submesoscales. Models will be used to simulate and test the sampling strategies ahead of time.

Implications and challenges

Though there has been progress in diagnosing and modeling submesoscale vertical velocities, our understanding of advective transport from the surface mixed layer to pycnocline is still rudimentary. We find that that vertical motion occurs on a vast range of space and time scales, but much of it is reversible and does not lead to net transport on time scales beyond a few days. From the Lagrangian perspective, only a small fraction of water parcel trajectories that originate in the mixed layer end up in the stratified region below the mixed layer and remain there for days (or until the mixed layer deepens and re-entrains the water). The advective transport of water from the mixed layer into the stratified region beneath, for which we have observational evidence, occurs along sloping isopycnal surfaces at fronts. But, we are yet to understand how it is controlled through the interaction of mesoscale and submesoscale dynamics and quantify the volumetric exchange. Furthermore, the role of three-dimensional turbulence on this exchange needs to be better understood.

While Earth system models are able to capture the horizontal circulation of the ocean, the rates of vertical exchange are highly sensitive to model resolution and surface forcing and are difficult to corroborate with existing observations. Better measurements, quantification, and dynamical understanding of such transport will enable us to make progress in predicting where (and how much) vertical transport occurs, and possibly infer it from satellite observations in the future. Parameterizing such vertical exchange in large-scale circulation and climate models with biogeochemistry will impact not only heat uptake, but also the transport of nutrients, carbon, oxygen, and other properties across the mixed layer base and stratified pycnocline, affecting estimates of the ocean's biological productivity, export of carbon, and ventilation of oxygen.

Further information and the list of participants for CALYPSO can be found at https://calypsodri.whoi.edu/.

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For further reading

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