

OCEAN TURBULENCE AND MIXING COURSE

STUDENT-LED INSTRUCTION AND AT-SEA EXPERIMENTATION

SUPPLEMENTARY SCIENCE REPORT

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This Supplementary Science Report aims to (1) outline the main scientific concepts covered in Combined Ocean Mixing Course, Experiments, and Practices for Turbulence Science (COMCEPTS), and (2) provide a detailed summary of the course's field experiment. It offers a background overview of ocean turbulence; describes the rationale behind the three science projects participants carried out, including the instrumentation used to collect measurements during the field component of the course; and gives an overview of the typical activities carried out while at sea. The final sections present observations made, figures participants assembled using the data they collected, and suggestions future work.

SCIENTIFIC BACKGROUND

KEY CONCEPTS

- **Turbulence:** Irregular, three-dimensional fluid motions characterized by fluctuations over a range of spatial and temporal scales.
- **Molecular Diffusion:** The transport of a substance due to random molecular motion, acting to reduce concentration gradients.
- **Eddy Diffusivity κ :** A parameter describing the turbulent transport down their mean gradients of scalar properties such as heat, salt, or other tracers.
- **Molecular Viscosity:** A fluid's internal resistance to flow, caused by random molecular motions and momentum exchanges.
- **Eddy viscosity, K :** A parameter describing the turbulent transport of momentum down its mean velocity gradient, analogous to molecular viscosity but caused by unresolved turbulent motions.
- **Dissipation Rate of Turbulent Kinetic Energy ε :** The rate at which turbulent kinetic energy is converted irreversibly into heat by molecular viscosity.
- **Dissipation Rate of Scalar Variance χ :** The rate at which temperature, salinity, or other scalar gradients are mixed away by molecular diffusion.
- **Mixing:** The irreversible homogenization of water properties by molecular diffusion, often accelerated by turbulence through the creation of fine spatial structures.
- **Flux Richardson number R_f :** The fraction of turbulent kinetic energy production by shear that is converted into buoyancy flux $R_f = B/P$.
- **Mixing Coefficient Γ :** The ratio of turbulent buoyancy flux to kinetic energy dissipation, in other words the effectiveness of the conversion of kinetic energy to potential energy through irreversible mixing.

TURBULENCE, MIXING, AND DIAPYCNAL FLUXES IN THE OCEAN

Ocean turbulence comprises the chaotic, three-dimensional fluid motions that transfer momentum and create fine structure in temperature, salinity, and other tracers. At sufficiently small scales, molecular diffusion acts across this fine structure to irreversibly mix water properties. Thus, turbulence can strongly enhance

mixing, even though it is molecular diffusion that ultimately makes mixing irreversible (Thorpe, 2007; Meredith and Naveira Garabato, 2021).

In the density-stratified ocean, turbulence enables the exchange of heat, salt, nutrients, carbon, and other tracers across density surfaces or isopycnals. This process, known as diapycnal mixing, influences large-scale ocean circulation, air-sea exchange, and marine ecosystems. Turbulent diapycnal fluxes quantify the associated cross-density transport and have been proposed as a pilot Essential Ocean Variable within the Global Ocean Observing System (Le Boyer et al., 2023).

Much of the ocean's interior is stably stratified, which inhibits vertical motions and suppresses turbulence. Internal waves can displace density surfaces and generate strong vertical shear. If that shear is sufficiently strong relative to the background stratification, the flow can become unstable and generate turbulent overturns. These overturns transfer energy to smaller scales, where it is dissipated by molecular viscosity and contributes to diapycnal mixing (MacKinnon et al., 2017).

Energy supplied to turbulent motions at relatively large spatial scales is transferred through a cascade to smaller scales. At sufficiently small scales, the turbulent kinetic energy is converted irreversibly to heat by molecular viscosity. For locally isotropic turbulence, the distribution of kinetic energy across wavenumbers follows the Kolmogorov spectrum, which provides the basis for estimating dissipation from microstructure shear spectra (Pope, 2000; Thorpe, 2007).

OBSERVING AND INFERRING MIXING IN THE OCEAN

Directly sampling and resolving the irreversible molecular diffusion that constitutes mixing is difficult, as the relevant gradients occur at millimeter and submillimeter scales. Thus, oceanographic measurements of turbulence and mixing instead quantify turbulence through the rate at which turbulent kinetic energy is dissipated (lost as viscous heat), ε , and the rate at which temperature variance is dissipated, χ . These quantities can be combined with local stratification and mean tracer gradients to estimate turbulent diffusivities and fluxes.

Microstructure profilers used in observational oceanography measure centimeter- and smaller-scale velocity shear and temperature fluctuations using shear probes and fast-response thermistors. Under assumptions about locally isotropic turbulence, the observed shear and temperature spectra can be integrated and used to estimate ε and χ , respectively. The Osborn relation uses ε , stratification, and an assumed mixing coefficient to estimate diapycnal diffusivity, whereas the Osborn-Cox method uses χ and the mean temperature gradient to estimate thermal diffusivity (Osborn and Cox, 1972; Osborn, 1980).

If microstructure observations are not available, one can also infer dissipation from lower resolution measurements of density

and velocity through fine-scale parameterizations or Thorpe-scale methods (Gregg, 1989; Thorpe, 2007). Fine-scale parameterizations use observed shear and strain to estimate dissipation associated with an internal wave field, and Thorpe-scale methods use measurements of temperature and salinity to estimate density overturns and from that estimation to infer turbulent length scales. Each method relies on assumptions that may not hold in all environments, particularly if turbulent processes are influenced by boundary layers, fronts, strong stratification, or submesoscale dynamics.

During COMCEPTS, participants used microstructure observations to estimate turbulence and learned how stratification, shear, and the gradient Richardson number (as well as other dimensionless parameters) can be used to characterize the flow's susceptibility to shear instabilities. The gradient Richardson number compares the stabilizing effect of stratification with destabilizing vertical shear; values below approximately 0.25 indicate conditions favorable for shear instability (Thorpe, 2007).

SCIENTIFIC QUESTIONS ADDRESSED BY COMCEPTS

The COMCEPTS field experiment examined processes that can generate or modulate mixing on the San Diego continental shelf. Vertical mixing on continental shelves is driven by both surface and internal waves (Woodson, 2018), as well as atmospheric processes like wind and solar heating (Lentz and Fewings, 2012). The three projects addressed (1) internal wave transformation and mixing across the shelf (Internal Tide Project), (2) upper-ocean mixing forced by atmospheric and surface-wave processes (Air-Sea Project), and (3) the influence of mixing on the dispersal of the Point Loma wastewater plume (Plume Dynamics Project). Sampling for all three projects was concentrated near the Point Loma Ocean Outfall (PLOO) mooring (main manuscript [Figure 3a](#)), which continuously monitors discharge from the Point Loma Wastewater Treatment Plant.

As they travel across the continental shelf, internal waves steepen and break, becoming an important source of vertical mixing (e.g., MacKinnon and Gregg, 2003; Whitwell et al., 2024; Papoutsellis et al., 2026). Preliminary results from the Internal Tide Project found that high vertical dissipation rates occurred with the steepening of isopycnals (main manuscript [Figure 3d](#)), showing internal waves developing into internal bores and mixing as they travel across the shelf.

The Air-Sea Project investigated the role of surface forcing in setting the upper ocean mixing in the region. The turbulent surface boundary layer is the main medium for the transfer of momentum, heat, and salt between the atmosphere and the ocean (D'Asaro, 2014). Under conditions of relatively weak winds (main manuscript [Figure 3c](#)), atmospheric cooling, and waves ([Figure 8a–c](#)), we found that the deepening of the boundary layer (main manuscript [Figure 3c](#)) along the continental shelf occurs with the strengthening of the onshore wind, highlighting the potentially

important influence of land-sea breezes on upper ocean mixing in coastal systems when other surface drivers are weaker.

The Plume Dynamics Project investigated the turbulent processes driving the dispersal of a treated wastewater plume. Treated wastewater is discharged offshore through a pipe located near the seafloor and close to the PLOO mooring. Wastewater effluent impacts coastal ecosystems by introducing an additional nutrient load (Kessouri et al., 2021) and water that is warmer and saltier than surrounding waters. During the study, the plume was traced using fluorescent dissolved organic matter, a proxy for colored dissolved organic matter (CDOM; Washburn et al., 1992; main manuscript [Figure 3a](#)). The observed CDOM-rich water mass spread offshore over the course of the day sampled (main manuscript [Figure 3e](#)). The dispersal of this plume is likely tied to turbulent mixing.

STUDY REGION AND FIELD EXPERIMENT INTERNAL TIDE DYNAMICS

Internal waves (IW) and internal tides (ITs) can transport energy across continental shelves and generate mixing as they interact with topography and stratification. Topographic criticality compares the local seafloor slope with the characteristic propagation slope of an internal wave at a specified frequency and stratification. Slopes gentler than the wave characteristic are termed subcritical; slopes steeper than the wave characteristic are supercritical; and the two are equal at criticality. Near-critical topography can modify wave propagation and enhance shear, wave breaking, and turbulent mixing (Legg and Adcroft, 2003).

Across the central California inner shelf near Point Sal, McSweeney et al. (2020) observed strong internal bores every ~6 hrs that contributed to changes in stratification in the cross- and along-shelf directions. Further south, Lucas and Pinkel (2022) observed shoaling IWs in less than 100 m depths off La Jolla, California. These papers focus on the dynamics of IWs over the gently sloping, relatively shallow (less than 100 m depth) shelf off California. There have also been experiments observing IW dynamics over steeper, deeper parts of an energetic shelf. Whitwell et al. (2024) studied IW-driven mixing over the offshore side of a pelagic ridge on the Australian North West Shelf. They observed IWs interacting with topography, intermittent mixing, and the relationship between IW modes and mixing strength. Davis et al. (2020) used numerical simulations and a distributed temperature sensing (DTS) array in the South China Sea to examine the evolution of internal waves from the shelf break to the surf zone as well as the influence of wave origin.

One of the aims of this experiment was to observe IWs crossing a steep slope onto a narrow shelf, giving us the opportunity to track the evolution of IWs on a small scale in order to connect steep slope and shallow shelf dynamics. Criticality was estimated relative to the local M_2 internal-tide characteristics using an observed stratification profile.

AIR-SEA INTERACTIONS

The ocean surface boundary layer (OSBL) is the region through which momentum, heat, and fresh water are exchanged between the atmosphere and the ocean interior primarily through vertical mixing. Mixing within this layer is governed by surface forcing in the form of wind, wave, and buoyancy effects (D'Asaro, 2014) as well as processes in the transition layer below that entrain water into the boundary layer (Johnston and Rudnick, 2009). Horizontal gradients in density at the submesoscale (10 km or less) can also drive vertical turbulent transport in the OSBL through instabilities like mixed layer eddies (Fox-Kemper et al., 2008).

The shallow coastal environment adds a layer of complexity to characterization of processes that drive mixing in the upper ocean. The sea state is more variable near the coast. Hence, the influence of swell in the misalignment of wind and waves in coastal seas can bias estimates of momentum transfer between wind and waves (Sauvage et al., 2023; Chang et al., 2025), which then affect predictions of turbulent mixing by wave breaking and Langmuir turbulence. The surface and bottom boundary layers may also interact at these shallow depths. Previous studies have found that wave generated Langmuir turbulence can extend across the water column in shallow coastal seas, particularly during strong wind events (Gargett and Wells, 2007). There is also evidence that tidally driven bottom boundary mixing and near-inertial oscillations can influence exchange across the upper ocean in shelf seas (Rippeth, 2005). Alternatively, thermal restratification from strong solar heating favors the formation of upper ocean diurnal warm layers that can act as barriers to mixing and exchange between the surface and deeper ocean. Recent observations along the California continental shelf show that deepening of diurnal warm layers may be associated with breaking of high frequency internal waves in the transition layer (Zeiden et al., 2024) and Langmuir turbulence (Andriatis et al., 2024).

Given the variability in surface atmospheric and ocean conditions at our study site during the summer, we expected to observe vertical mixing in the upper ocean either under a variable sea state driven by local summer storm events or under thermal restratification from strong solar heating. During our field experiment, winds and waves were generally weak, and daytime atmospheric heating favored the formation of shallow diurnal warm layers. These conditions provided an opportunity to examine the evolution of near-surface stratification, shear, and turbulent fluxes across the upper ocean over a daily heating cycle. The Air-Sea Project used repeat near-surface profiling aligned with the wind to investigate the relationship between atmospheric forcing, upper-ocean structure, and mixing along the continental shelf.

WASTEWATER-PLUME DYNAMICS

Turbulent mixing plays a key role in the diffusion and dispersal of pollutants, a key public health concern for the densely populated beaches of the Southern California Bight. A major source of

water pollution comes from wastewater effluent that is discharged offshore through submerged diffuser systems. Treated wastewater effluent can alter the coastal nutrient, oxygen, and carbon conditions, creating a potential concern for eutrophication and ecosystem health (Kessouri et al., 2021).

The Point Loma Wastewater Treatment Plant, the largest wastewater facility in the San Diego region, treats (and discharges) 175 million gallons of wastewater per day (City of San Diego, 2026). The treated wastewater is carried offshore 7.2 km from the coast and discharged at the Point Loma Ocean Outfall (PLOO) at a depth of approximately 100 m. As the wastewater effluent is fresher and warmer than the ambient ocean conditions above the seafloor, this initial plume just after discharge is less dense relative to the cold and salty surrounding seawater. The plume's buoyancy is the primary driver of mixing in the near field (within 200 m of the source) until it reaches an equilibrium depth of about 40–50 m above the seafloor (Rogowski et al., 2012). Further away from the source, mixing is primarily driven by submesoscale oceanic variability (Uchiyama et al., 2014). Far from the outfall, the vertical and temporal distribution of wastewater plumes can be strongly influenced by diurnal and higher-frequency variability in local vertical shear (Lucas and Kudela, 2017).

While the City of San Diego conducts quarterly environmental water sampling using a semi-permanent mooring in the vicinity of the outfall, its monitoring methods lack the combined temporal resolution and horizontal spatial coverage that is possible with a ship-based experiment designed to measure the effects of turbulence. Thus, the effects of turbulent processes induced by IWs on the PLOO effluent plume had not been directly measured. Our study site focused on the region around the plume's y-shaped diffuser port, providing a unique opportunity to directly measure the effects of turbulent mixing on the wastewater effluent.

To detect the plume, we measured fluorescent dissolved organic matter (fDOM), which has previously been shown to be a good tracer for the PLOO effluent plume (Rogowski et al., 2013). As there is ambiguity in the absolute definition of a plume due to variable instrument calibration, as well as the presence of unrelated sources of fluorescent CDOM from river input and biological processes near the surface, we define the plume to be where the measured CDOM exceeds the 95th percentile value of all values measured below 50 m depth within the same cruise module (at similar times) (Nezlin et al., 2020).

INSTRUMENTATION AND SAMPLING

Two types of profiling instruments were used for the cruise: an epilometer microstructure profiler and a small CTD + Optics package. Both were deployed using a Lindgren Pitman 2400 Electric Fishing Reel mounted in the port corner of the back deck, facing aft (Figure 1). Deployments and recoveries were accomplished by lowering the instruments over the side (hand over hand) while the ship was traveling at approximately 1–2 knots. Profiler use during

the cruise is plotted in Figure 2. Photos of the winch and each profiler are shown in Figure 3. Shipboard instrumentation (vessel mounted acoustic Doppler current profilers, ADCPs) measured ocean currents and meteorological data.

EPSILOMETER

The epsilometer is a microstructure profiler, developed by the Multiscale Ocean Dynamics (MOD) group at Scripps Institution of Oceanography, that carries a CTD, airfoil shear microstructure

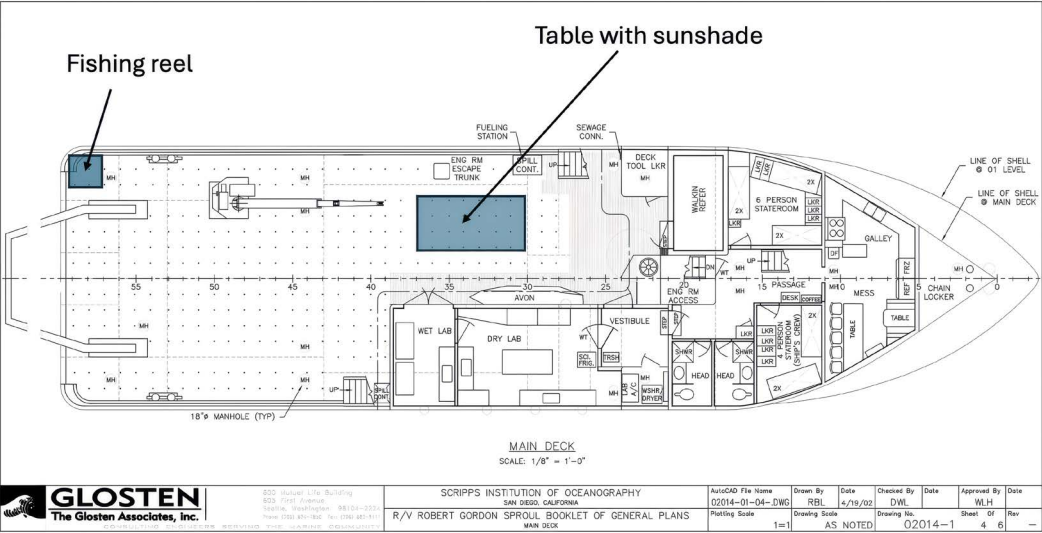


FIGURE 1. Layout of main deck of R/V Robert Gordon Sproul.

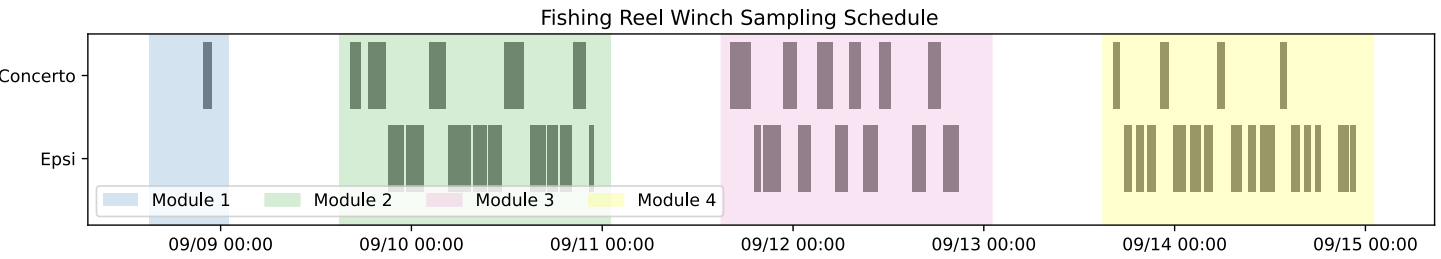


FIGURE 2. Alternating sampling schedules for the Epsilon and the CTD from the fishing reel winch through the whole cruise. Times are in UTC.

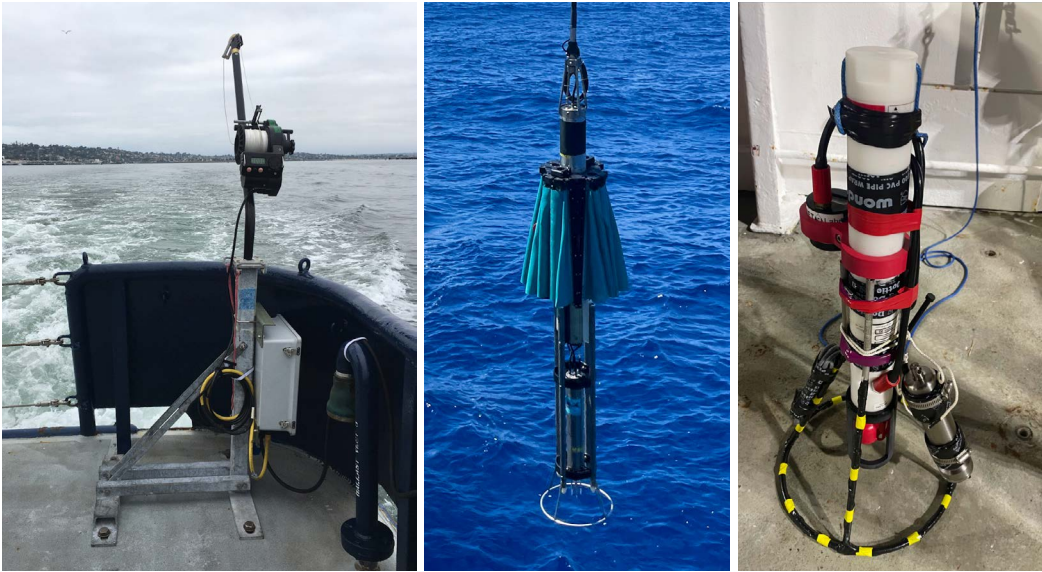


FIGURE 3. From left to right, photos show the winch, the epsilometer, and the CTD + Optics package.

probes, and fast-response microstructure thermistors (FP07) (Le Boyer et al., 2021). The free-falling probe is equipped with a chute that unfolds to stabilize it during descent. The fall rate was about $0.5\text{--}0.6\text{ m s}^{-1}$, and we used this and the known bottom depth to time the fall to reach the desired depth before turning around conservatively about 40 m above the bottom. We used two complete epsilon packages that each consisted of a frame called a “fish,” which contained a CTD and a sensor package called a “minnow,” and swapped them about every six to eight hours. Although the MOD epsilon package can be set up to display real-time data using a special cable and winch, the setup we used was a closed loop, so after each deployment the instrument was opened to download the data.

CTD + OPTICS PACKAGE

The second profiling instrument comprised a fluorometer (RBRtridente) and an oxygen sensor (RBRcoda T.ODO) mounted on a CTD (RBRconcerto). The RBRtridente is a three-channel optical sensor that measures chlorophyll *a*, fDOM, and optical backscatter. This package had a fall rate of about 1 m s^{-1} , and it was also deployed by timing each profile, but it was allowed to reach 10 m above the bottom.

SHIPBOARD INSTRUMENTS

R/V *Robert Gordon Sproul* is equipped with a Teledyne Marine Ocean Surveyor 150 kHz ADCP that ran continuously throughout the cruise. The ADCP data were processed using the University of Hawai‘i Data Acquisition System (UHDAS; Hummon et al., 2023). We also used the shipboard CTD rosette for collecting water samples.

CRUISE MODULES AND SAMPLING STRATEGY

The fieldwork was divided into four cruise modules. These modules were operational sampling legs that provided observations for one or more of the three science projects described above.

- **Plume Module (Module 1).** A day cruise to map the wastewater plume near the outfall, collect water samples from the outfall, and establish the hydrographic context for later modules.
- **Internal Tide (IT) Module (Module 2).** An overnight cross-isobath survey targeting a supercritical slope to examine internal wave structure, shear, and dissipation across a full tidal cycle.
- **Plume and Tide Interactions (PluTide) Module (Module 3).** An overnight cross-isobath survey centered on the outfall and crossing a transition from subcritical to supercritical bathymetry to investigate the potential interaction of internal waves, turbulence, and plume dispersal.
- **Air-Sea Interactions Module (Module 4).** An overnight survey focused on the upper ocean, with the ship’s heading dictated by the wind direction to examine the evolution of near-surface stratification and mixing.

Across all four modules, the participants practiced planning adaptive sampling at sea, operating profiling instruments, and interpreting preliminary data in real time. Through the course of the cruises, each student was involved in all of the data collection methods under the supervision of the instructors. Sampling took place continuously for at least 24 hr for each of the overnight modules, and students were divided into 12 hr shifts, either staying up late or waking up early. See [Figure 4](#) for the module locations. The overall cruise timeline is detailed in [Table 1](#) where dates/times are local (UTC−07:00).

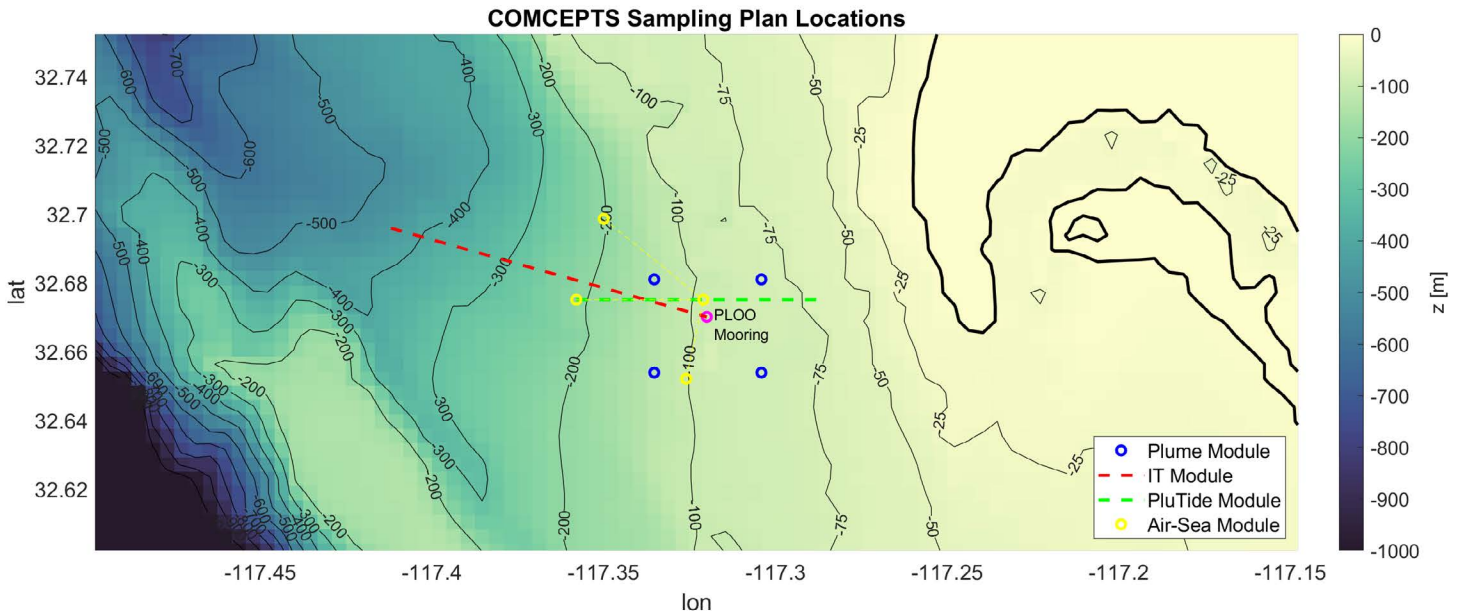


FIGURE 4. Waypoints and transects for each of the four modules over bathymetry.

TABLE 1. Timeline of cruise in local time (UTC–07:00).

MODULE	DATE - TIME	NOTES
September 8 MODULE 1 Plume Module	08 - 08:00	Departure
	08 - 09:00	Arrival at NE module site
		CTD plume tracking NE of PLOO mooring
	08 - 10:30	CTD water sampling
		CTD plume tracking E of PLOO mooring
	08 - 14:00	CTD water sampling
		Transects west of PLOO mooring with fishing reel
	08 - 15:00	Concerto
	08 - 17:00	Return
September 9–10 MODULE 2 Internal Tide (IT) Module	09 - 08:00	Departure
	09 - 09:00	Begin internal tide module transects
		Alternate concerto and epsilon meter on fishing reel
	10 - 16:00	Return
September 11–12 MODULE 3 Plume and Tide Interactions (PluTide) Module	11 - 08:00	Departure
	11 - 09:00	Begin plume-internal tide module transects
		Alternate concerto and epsilon meter on fishing reel
	12 - 06:30	CTD water sampling
		Alternate concerto and epsilon meter on fishing reel
	12 - 14:30	CTD water sampling
		Alternate concerto and epsilon meter on fishing reel
	12 - 16:00	Return
September 13–14 MODULE 4 Air-Sea Interactions Module	13 - 08:00	Departure
	13 - 09:00	E-W transects, against the wind (one-way)
		Alternate concerto and epsilon meter on fishing reel
	14 - 00:00	SE-NW transects due to wind-direction change
	14 - 06:00	NE-SW transects due to wind-direction change
	14 - 13:00	E-W transects, against the wind (one-way)
		Return

PRELIMINARY OBSERVATIONS

INTERNAL WAVES AND TIDES

Figure 5 shows the evolution of depth-dependent cross-shore velocity relative to the barotropic tidal phase during the PluTide module. The cross-shore velocity structure generally exhibited two layers, though there were brief periods that were more barotropic. Vertical shear appeared weakest right before the peak (nadir) of high (low) tide, and strongest during the transition between high and low tides, though the signs flipped depending on the phase.

Intervals of weaker shear also coincided with greater isopycnal variability, possibly suggesting strengthened internal waves during these tidal phases. Because each ADCP section represents several hours of sampling, Figure 5 should be interpreted as a sequence

of temporally averaged snapshots rather than instantaneous fields. The sampling resolution is nevertheless sufficient to resolve the barotropic tidal cycle.

Figure 6 is an example of a transect from sampling module 3. It shows the shoaling of isopycnals, in panel (a) aligned with high turbulent dissipation rates (ϵ), and in panel (b) with strong shear. Together these features are consistent with a nonlinear internal wave or bore undergoing transformation across the slope. The apparent onset of upper-water-column isopycnal oscillations near the criticality transition (from supercritical to subcritical) motivates further analysis of the role of topographic criticality in wave evolution and mixing.

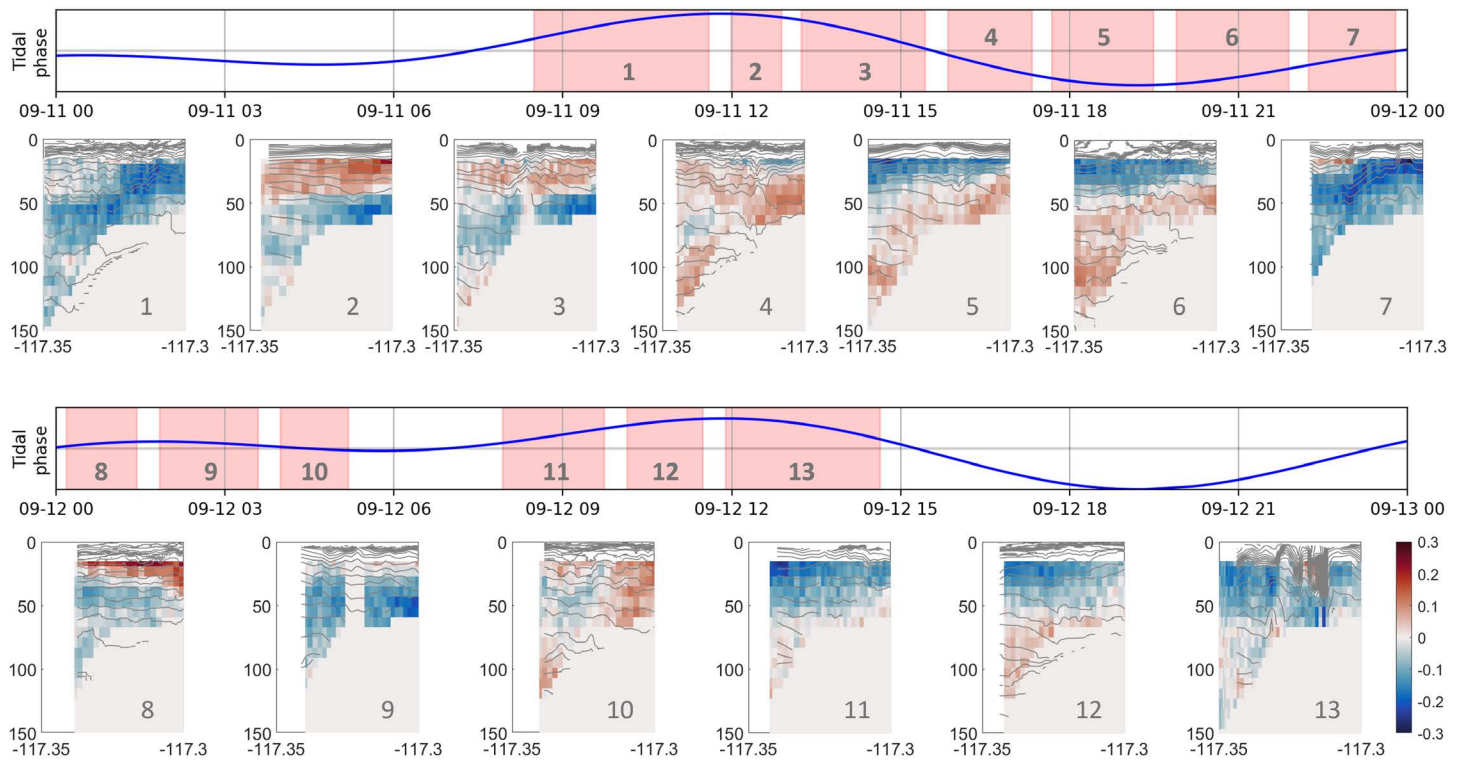


FIGURE 5. Evolution of cross-shore currents and isopycnals across the criticality transition mapped to tidal phases for module 3 (PluTide). Each number in the tidal phases shown is associated with a depth section. The gray lines represent isopycnals, and the colormap represents cross-shore velocity (where red is onshore and blue is offshore).

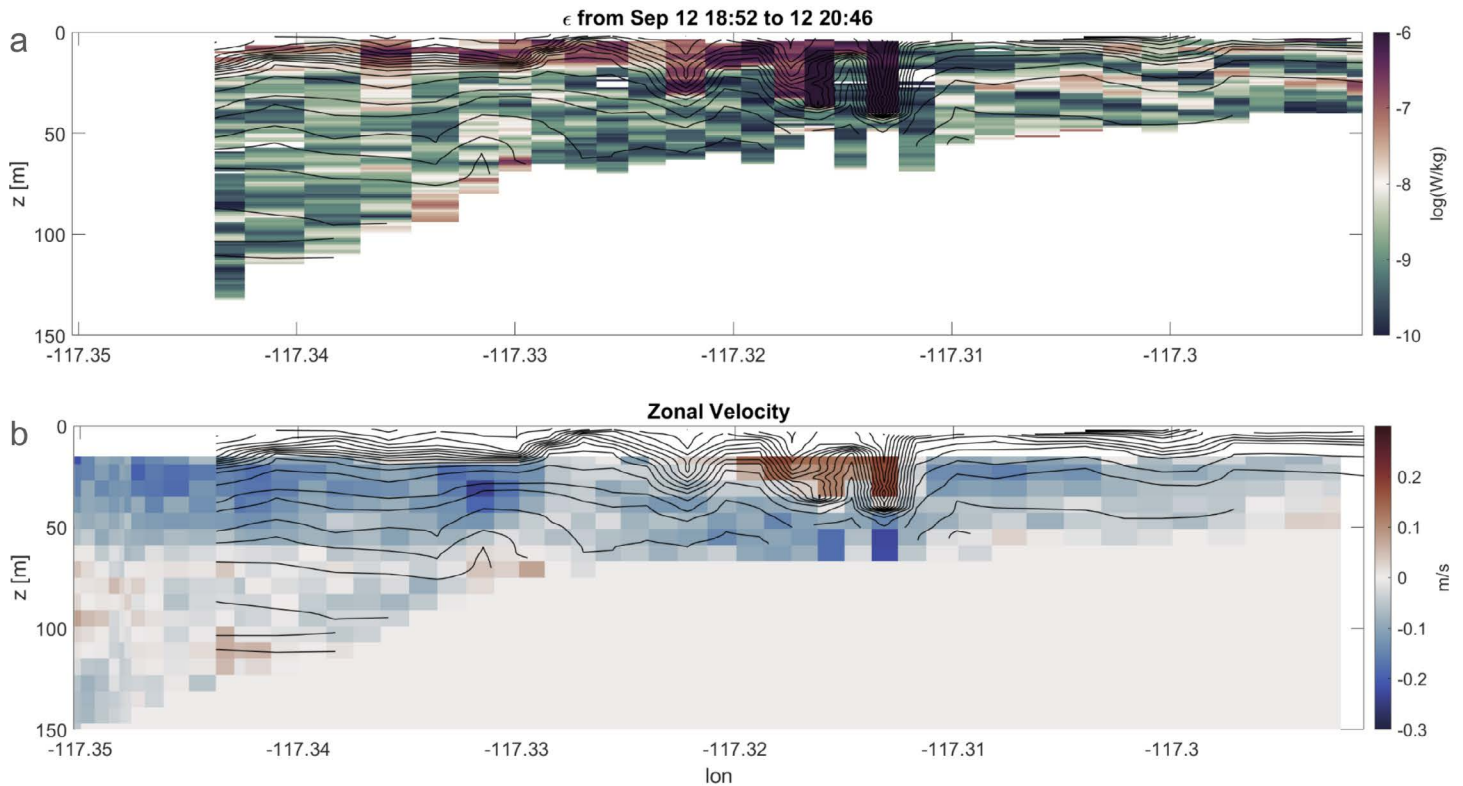


FIGURE 6. A transect from module 3 (PluTide) shows (a) dissipation of turbulent kinetic energy, and (b) the zonal velocity. Isopycnals are overlaid in black. This is the same section as number 13 in Figure 5.

WASTEWATER PLUME EVOLUTION

Figure 7 shows the position and evolution of the wastewater effluent plume across different deployments over the course of the PluTide module. The plume has a clear signature in the fluorescent CDOM concentration, with higher values near the bottom close to the PLOO mooring and the outfall plume location. We define the position of the plume based on a fluorescent CDOM threshold of 2.28 ppb, which is the 95-percentile value of CDOM below 50 m. Throughout the module, we found that the majority of the plume signature remained at densities between 25.3 and 25.4 kg m^{-3} and did not reach the surface.

The plume signature was associated with a negative signal in spice, a dimensionless quantity that describes the variation in ocean salinity and temperature along an isopycnal. As density is governed by a nonlinear combination of these quantities, the spice may vary along the same isopycnal. It is often used as a passive tracer in the

interior of the ocean for water parcels that have a common point of origin at the surface (Cole and Rudnick, 2012). A negative spice value indicates water that is fresher and colder (minty) than other water along the same isopycnal, while a positive spice value indicates that waters are saltier and warmer (spicy). Our results show that the outfall effluent is comparatively minty relative to the surrounding background field. However, the negative spice value appears to persist even when the concentration of CDOM is below background, such as during Deployment (Dep) 11. We also see that there is a lowered spice value at the location of the plume.

Figure 7 shows the horizontal transects of the plume and isopycnals imposed upon the CDOM concentration, spice, and background horizontal currents for all RBRConcerto deployments during the PluTide module. Initially, we observed that the plume was located inshore of the PLOO mooring, near the center of the outfall and close to the site of the initial discharge. As the tidal

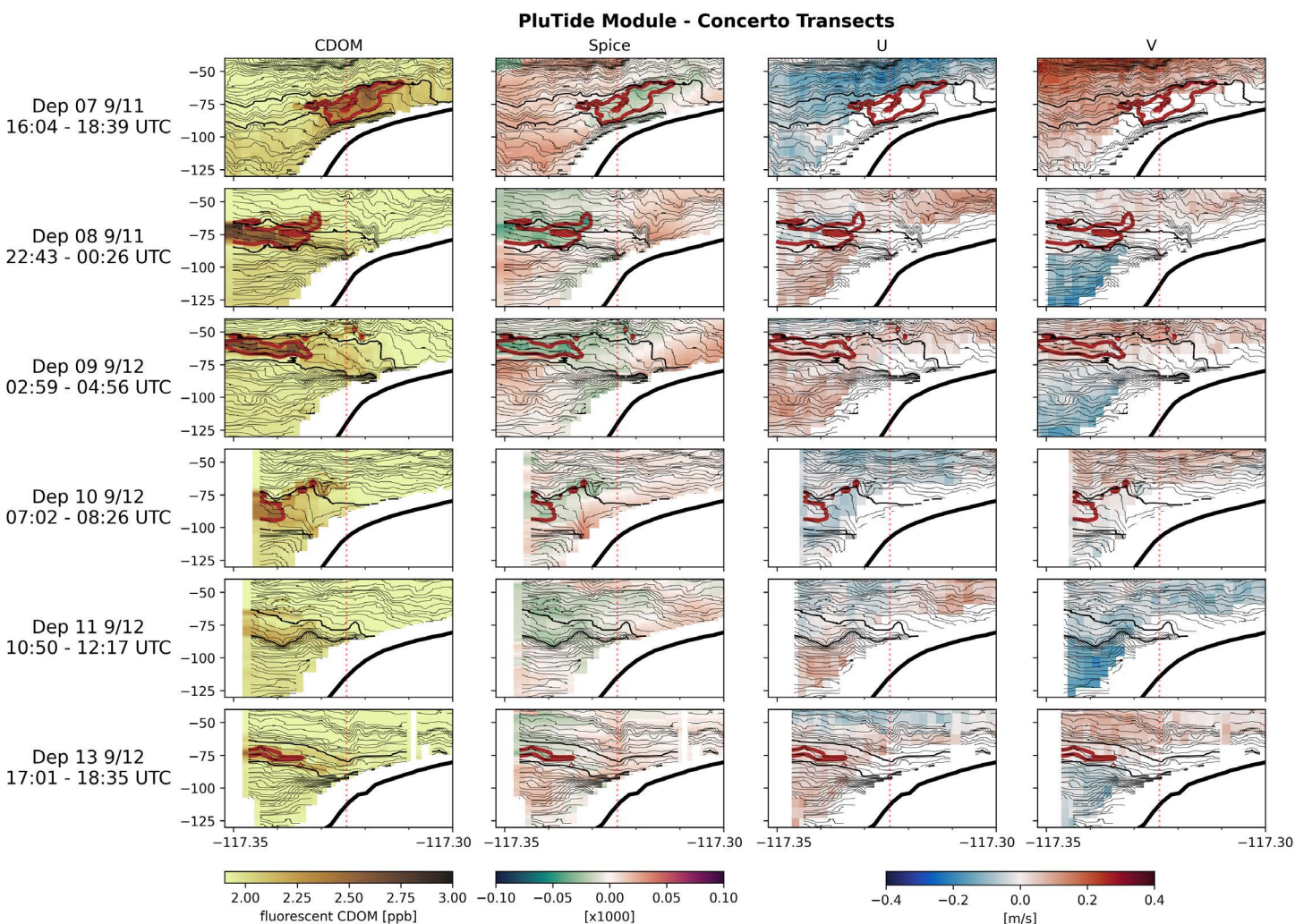


FIGURE 7. The evolution of the Point Loma wastewater plume over the course of the PluTide module compared to transects of (from left to right) fluorescent CDOM, spice, cross shelf velocity, and along-shelf velocity. The location and extent of the plume is indicated across all panels by the burgundy outline while the position of the stationary Point Loma Ocean Outfall (PLOO) mooring is shown by the red dotted line. Density contours appear in black for every 0.02 kg m^{-3} , with the 25.3 kg m^{-3} and 25.4 kg m^{-3} isopycnals bolded for reference.

current shifted, the plume moved further offshore. Between Dep 8 and Dep 10, there are some signatures of the plume at isopycnals shallower than 25.28 kg m^{-3} . In Dep 9 and 10, these lighter plume signatures are displaced inshore compared to the main bulk of the plume and co-located with strong horizontal density gradients that could suggest potential IW shoaling, which could also indicate wave-driven onshore transport. The following deployment (Dep 11) did not see a plume, although there remained an elevated CDOM concentration just below the plume concentration threshold that could be due to dilution as a result of mixing during the previous two deployments. However, this change in concentration may also be due to offshore advection from the tidal flow, because a plume was detected during the last deployment once the tidal currents shifted onshore. These results suggest that IWs could be responsible for the mixing and onshore transport of the PLOO plume. However, more analysis is needed to detangle the effects of horizontal advection, aliasing, and even a changing plume discharge rate, as municipal water usage varies through the day.

UPPER-OCEAN EVOLUTION

Upper-ocean mixing during the field experiment was characterized by a diurnal cycle in the boundary layer as well as instabilities in the pycnocline, the layer below the boundary layer with a sharp density gradient. Here, the pycnocline is qualitatively described as a region of elevated stratification ($>10^{-4} \text{ s}^{-2}$) below the boundary layer.

During our experiment, boundary layer deepening (Figure 8d) corresponded to a peak in wind speed and a westerly alignment of the winds (Figure 8b), consistent with an onshore sea breeze during the daytime. Following this period of stronger atmospheric forcing, dissipation rates of both turbulent kinetic energy and temperature variance in the upper ocean were enhanced (Figure 9c–d). The boundary layer shoals over the course of the night as the winds weaken (Figure 8d). These findings suggest that diurnal variation in the wind field may drive boundary layer deepening of order 5 m when other surface forcing (heat fluxes and waves—Figure 8a,c), is relatively weak.

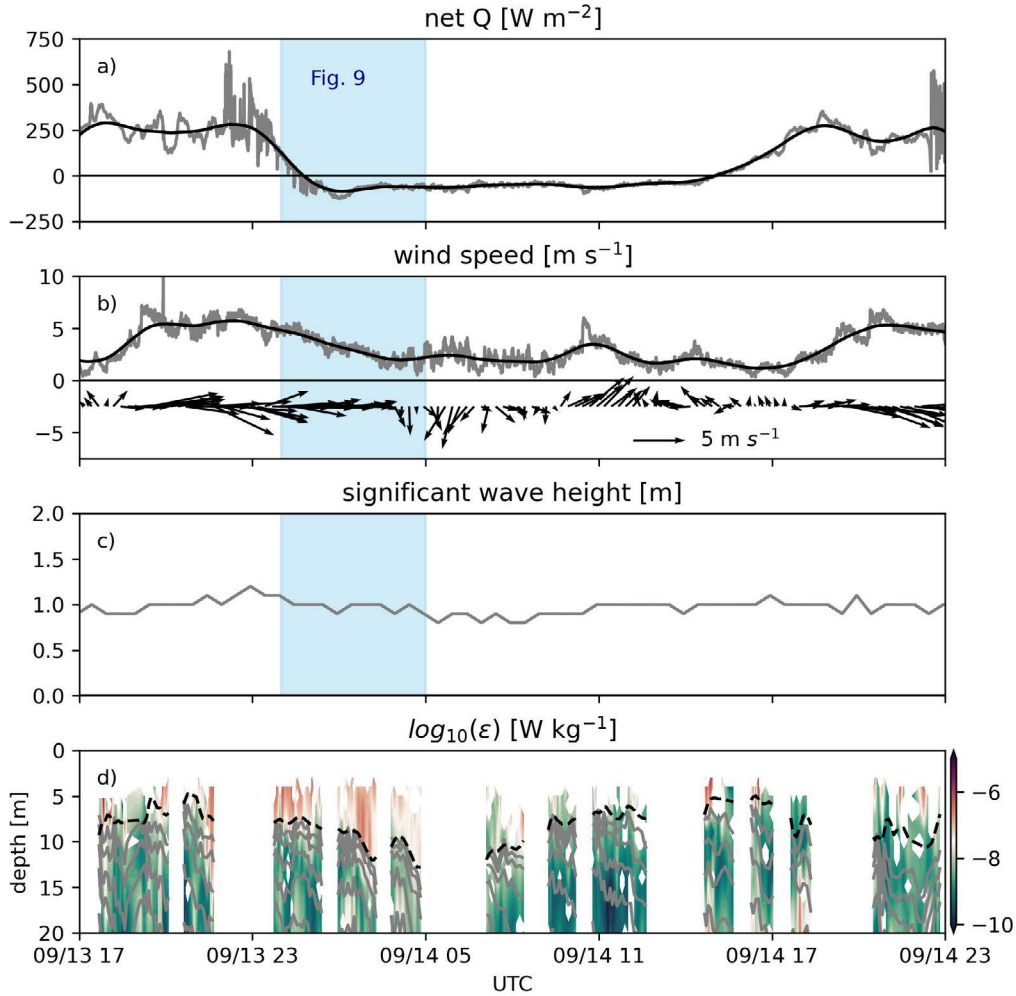


FIGURE 8. Surface boundary layer evolution over the Air-Sea Project. Time series of (a) net surface heat flux (W m^{-2}), (b) wind speed (m s^{-1} from the shipboard MET system), (c) significant wave height (m) from the nearest wave buoy, NDBC 46258, and (d) dissipation rate of turbulent kinetic energy or ϵ (W kg^{-1}) from shipboard epilometer profiling. The surface boundary layer (dotted, black) and contours of density referenced to the surface (solid, gray) are shown in panel d.

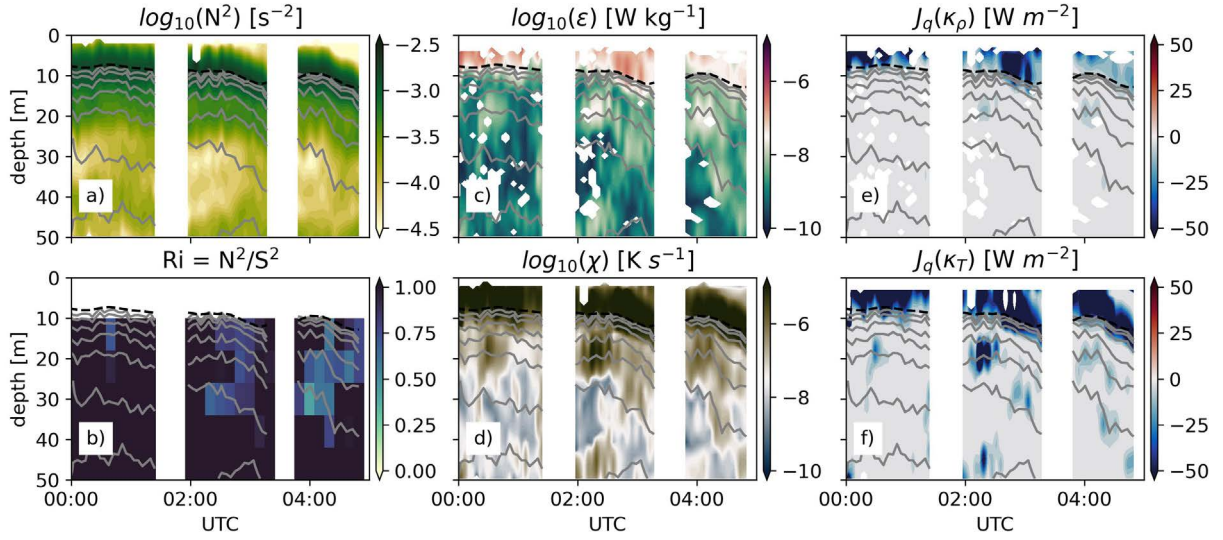


FIGURE 9. Pycnocline evolution over the Air-Sea Project for a subset of the measurements that are highlighted in blue in Figure 8: time series plots show (a) stratification (s^{-2}), (b) Richardson number, (c) dissipation rate of turbulent kinetic energy or ϵ ($W\ kg^{-1}$), (d) dissipation rate of temperature variance or χ ($K\ s^{-1}$), (e) vertical turbulent heat flux computed with ϵ , and (f) vertical turbulent heat flux computed with χ from shipboard profiling with the epilometer. The Richardson number additionally uses shear from the ship's acoustic Doppler current profiler. The surface boundary layer (black dotted lines) and contours of density referenced to the surface (solid gray lines) are shown in all panels.

Below the boundary layer, vertical turbulent heat fluxes calculated from ϵ and χ , respectively, indicate enhanced mixing in the pycnocline (Figure 9e–f). Osborn (1980) parametrizes vertical turbulent eddy diffusivity of buoyancy as

$$\kappa_\rho = \frac{R_f}{1 - R_f} \frac{\epsilon}{N^2} = \Gamma \frac{\epsilon}{N^2} = 0.2 \frac{\epsilon}{N^2}$$

where R_f is the mixing efficiency, Γ is an associated mixing coefficient usually taken to be 0.2, and

$$N^2 = -\frac{g}{\rho_0} \frac{\partial \bar{\rho}}{\partial z}$$

is the buoyancy frequency. Similarly, Osborn and Cox (1972) derive an effective turbulent diffusivity of temperature as

$$\kappa_T = \frac{\chi_T}{2 \left(\frac{\partial \bar{T}}{\partial z} \right)^2}$$

where $\frac{\partial \bar{T}}{\partial z}$ is the mean vertical temperature gradient. Fluxes for heat, salt, and buoyancy can be computed using these diffusivities by assuming Fickian diffusion.

Right below the boundary layer, regions of elevated dissipation rates (Figure 9c–d) and elevated turbulent heat fluxes (Figure 9e–f) are observed in the pycnocline, indicating a generally downward transfer of heat. Elevated turbulent fluxes tended to follow isopycnal layers and were near areas of isopycnal tilting. Moreover, these regions were associated with Ri numbers between 0.25 and 1 (Figure 9b). Note that the vertical resolution of the ADCP used to compute Richardson number was approximately 8 m. Hence, this quantity can only identify shear instabilities at these length scales. Although these values themselves do not diagnose a particular instability mechanism, their co-occurrence with

enhanced turbulent fluxes and isopycnal deformation is consistent with potentially elevated shear-driven mixing. Further analysis is required to distinguish the relative roles of shear instability, internal-wave processes, and submesoscale processes.

DISCUSSION AND FUTURE WORK

This fieldwork was conducted as part of COMCEPTS to serve both scientific and educational purposes. Participants practiced instrument deployment, overnight sampling, and preliminary data analysis, and they were exposed to the use of shore-based and shipboard observations to inform the sampling plan in real time. These activities taken together gave students, many of them participating in at-sea fieldwork for the first time, direct experience with the more practical aspects of collecting microstructure data and conducting fieldwork in general. All the data collected during the cruise—microstructure, hydrographic, velocity, and optical along with discrete water sample observations—were organized and shared among all participants, and some of it will be used in individual students' research.

Preliminary analyses of the cruise data document internal-wave transformations occurring across the shelf, the temporal evolution of the Point Loma wastewater plume, and near-surface stratification and mixing associated with the daily heating cycle. These observations motivate further examination of the relationships between tides, internal waves, topographic criticality, turbulence, and plume dispersal.

There are still many open questions and more work to be done. Much of the analysis shown in this report is based on data collected from only a couple of the cruise modules—many of our observations have yet to be examined. This expedition has resulted

in a dataset that combines direct turbulence measurements with the more standard ocean variables, which we hope will allow us to better understand this very dynamic region.

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