Autonomous Tracking and Sampling of the Deep Chlorophyll Maximum Layer in an Open-Ocean Eddy by a Long-Range Autonomous Underwater Vehicle

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Abstract—Phytoplankton communities residing in the open ocean, the largest habitat on Earth, play a key role in global primary production. Through their influence on nutrient supply to the euphotic zone, open-ocean eddies impact the magnitude of primary production and its spatial and temporal distributions. It is important to gain a deeper understanding of the microbial ecology of marine ecosystems under the influence of eddy physics with the aid of advanced technologies. In March and April 2018, we deployed autonomous underwater and surface vehicles in a cyclonic eddy in the North Pacific Subtropical Gyre to investigate the variability of the microbial community in the deep chlorophyll maximum (DCM) layer. One long-range autonomous underwater vehicle (LRAUV) carrying a third-generation Environmental Sample Processor (3G-ESP) autonomously tracked and sampled the DCM layer for four days without surfacing. The sampling LRAUV’s vertical position in the DCM layer was maintained by locking onto the isotherm corresponding to the chlorophyll peak. The vehicle ran on tight circles while drifting with the eddy current. This mode of operation enabled a quasi-Lagrangian time series focused on sampling the temporal variation of the DCM population. A companion LRAUV surveyed a cylindrical volume around the sampling LRAUV to monitor spatial and temporal variation in contextual water column properties. The simultaneous sampling and mapping enabled observation of DCM microbial community in its natural frame of reference.

Index Terms—Autonomous underwater vehicle (AUV), eddy, Environmental Sample Processor (ESP), phytoplankton, sampling, tracking.

I. INTRODUCTION

OCEANIC life depends upon photosynthetic production of organic matter by microscopic organisms. Photosynthesis requires light and nutrients, and in the open ocean it is limited by low concentrations of nutrients in shallow water that receives the most sunlight. At the base of the nutrient impoverished surface layer (∼100-m depth), nutrient concentrations increase across the strong density gradient of the pycnocline. This creates a vertically limited layer in which photosynthetic microbes can access both nutrients from below and light energy from above. With its locally enhanced concentration of the photosynthetic pigment chlorophyll, this layer is referred to as the deep chlorophyll maximum (DCM) [1], [2]. The DCM is a ubiquitous feature of open-ocean stratified ecosystems. Physical processes that alter the vertical distributions of nutrients and DCM microbes shape the functioning of open-ocean ecosystems and global biogeochemical cycles [3].

Among the physical processes influencing the DCM are eddies, vortical circulations that affect vertical transport. Global analyses of eddies using satellite altimeter data [4], [5] show that eddies in our study region, north of the Hawaiian Islands (see Fig. 1), are responsible for approximately half of the variance in sea level anomaly (SLA). These eddies have a mean radius scale of ∼100 km and a mean westward zonal propagation speed of ∼5 cm/s. Eddy circulation can be cyclonic or anticyclonic (counterclockwise and clockwise in the northern hemisphere, respectively). In the context of this study, cyclonic eddies are of particular importance because of the consequences of their circulation, including upward transport of nutrients and DCM populations, which enhances both nutrient and light resources for photosynthesis and thus productivity and biomass, and changes in species composition and export of organic matter to the deep sea [6], [7]. Furthermore, the interacting eddy field
Fig. 1. SLA and geostrophic current velocity around the Hawaiian Islands on March 28, 2018. SLA is negative in cyclonic (counterclockwise) eddies, and positive in anticyclonic (clockwise) eddies. Range of current speeds: 0 ∼ 0.72 m/s. On the day represented by this map, a four-day quasi-Lagrangian study was initiated within the cyclonic eddy (marked by the box) located immediately north of the central islands. Data source: Copernicus Marine Environment Monitoring Service (CMEMS).

Studies of how eddies influence open-ocean microbial populations have largely relied on ship-based sampling strategies. While this approach permits synoptic descriptions of eddies and microbial populations, it cannot provide effective sampling of DCM microbial populations in their natural frame of reference, which is moving with ocean currents. Previously developed Lagrangian platforms were used to measure volume transport in the Gulf Stream [9] and Drake Passage [10], track water parcel motion in the convecting layer of the Labrador Sea [11]–[13], and reveal mesoscale dynamics that influence the North Atlantic spring bloom [14]. These passive Lagrangian platforms were not designed to possess mobility for finding an oceanographic feature. There is a growing effort toward enabling AUVs to autonomously detect and track a variety of ocean features, such as the thermocline [15]–[18], internal waves [19], [20], various plumes [21]–[25], intermediate nepheloid layers [26], phytoplankton patches [27], [28], and coastal upwelling fronts [29], [30]. In [31], an AUV demonstrated the ability to perform a Lagrangian-box survey around a drifter. Some AUVs are now equipped with water samplers to take advantage of the vehicle’s mobility to collect material while underway [26], [32]–[36].

This study integrates multiple autonomous systems, including surface and underwater vehicles, and a robotic molecular analytical instrument installed in one underwater vehicle, to study DCM microbial ecology in its natural frame of reference on time scales from hours to days, thereby permitting resolution of time-dependent evolution of the microbial population in response to environmental variations. The design of the March-April 2018 SCOPE (Simons Collaboration on Ocean Processes and Ecology) Hawaiian Eddy Experiment is illustrated in Fig. 2, and details are given in Section III.

A drifting second-generation Environmental Sample Processor (2G-ESP, a robotic sample acquisition and analysis system [36], [37]) has been deployed to study microbial ecology off the northern California coast [38] and in the North Pacific Subtropical Gyre [39], [40]. The 2G-ESP was suspended at a fixed depth (23 m) beneath a free-drifting surface float, and took water samples every 2 or 4 h. This drifting ESP was intended for quasi-Lagrangian sampling, but windage from the large surface buoy, and the fixed depth of all samples made it difficult to stay in the areas of greatest biological activity within the water column. In the study presented in this paper, our goal was to accurately follow and observe a plankton community over multiple diel cycles in the DCM layer in a cyclonic eddy. The DCM layer is not only deep, but also undulates in depth due to internal tides and inertial oscillations. Hence, a 2G-ESP suspended at a fixed depth from a surface float cannot accomplish the task. A Tethys-class LRAUV equipped with a 3G-ESP and targeted sampling intelligence enables precise and persistent occupancy of the DCM layer.

LRAUV Aku containing a 3G-ESP (deployed in the 2018 Hawaiian Eddy Experiment) is shown in Fig. 3. The vehicle is 3.2 m long and 0.3 m in diameter at the midsection. A Tethys-class LRAUV can run from 0.5 to 1 m/s using a propeller. Using a primary battery, the vehicle has demonstrated a range of 1800 km (three-week duration) at 1-m/s speed [41]. Long range is realized by minimizing propulsion power consumption through an innovative design of a low-drag body and a high-efficiency propulsion system [42]. In addition, by using a
Fig. 2. Illustration of collaborative operation of LRAUVs Aku, Opah, and Wave Glider Mola in the experiment. Opah and Mola both acoustically tracked Aku. Aku tracked and sampled the DCM layer (marked by the orange curve). Opah spiraled around Aku to collect contextual data.

Fig. 3. LRAUV Aku deployed in the March–April 2018 Hawaiian Eddy Experiment. The 3G-ESP was installed in the vehicle’s fore-mid section. (The photos were taken by Elisha Wood-Charlson during the experiment.)

buoyancy engine, the vehicle is capable of ballasting to neutral buoyancy and drifting in a lower power mode. The LRAUV thus combines the mobility and speed of propeller-driven vehicles and energy savings of buoyancy-driven vehicles. Aku’s science sensors suite (all in the nose section) includes Sea-Bird Scientific (SBE) Glider Payload Conductivity-Temperature-Depth (GPCTD) sensors, a WET Labs BB2FL fluorescence/backscatter sensor (chlorophyll fluorescence excitation wavelength 470 nm and emission wavelength 695 nm), an Aanderaa 4831F dissolved oxygen sensor, and a LI-COR LI-192SA PAR (photosynthetically active radiation) sensor. The WET Labs fluorescence sensor’s raw count output is converted to chlorophyll concentration using a formula provided by the manufacturer, and the sensor is periodically sent back to the manufacturer for routine calibration. The PAR sensor points to 20° from the vertical (when the vehicle lies horizontal). In this configuration, when the vehicle runs on a yo-yo trajectory of ±20° pitch angles, the PAR sensor will point upward on ascent profiles for accurate light irradiance measurement.

1The SBE GPCTD sensors are installed on the vehicle’s horizontal center plane and just outside the hull. The temperature measurement range is –5 to +42 °C with a resolution of 0.001 °C. The conductivity measurement range is 0 to 9 S/m, with a resolution of 0.00001 S/m. The depth measurement range is 0 to 350 m, with a resolution of 0.007 m.
The LRAUV software architecture uses state configured layered control [43], which divides the vehicle’s operations into a group of behaviors assigned with hierarchical levels of priority. For each AUV mission, the vehicle runs a mission script that invokes appropriate AUV behaviors to achieve a specified goal [41], [44].

The 3G-ESP instrument [35], [36] is installed in the forward pressure housing of the LRAUV. It uses cartridges to collect and process ocean microbial samples. Up to 60 cartridges are installed on a circular wheel, and each cartridge contains the filters and reagents necessary for collecting and processing one sample. The cartridges connect to a central ring of valves that are part of a pumped seawater loop. When the LRAUV mission program triggers a sampling event, the 3G-ESP rotates the motor-driven cartridge wheel to align a designated cartridge with the processing station, where power and actuators can be applied to the cartridge. The pumped seawater loop is flushed clear, and actuators open valves to direct the seawater through the cartridge, concentrating particles and small organisms onto the filters. After a specified volume of water has been filtered, the seawater valves are closed and a valve in the cartridge is moved so the particulate material can be processed with reagents. When processing a cartridge, either a preservative reagent in the cartridge can be added to the sample to preserve the cellular material for later analysis in the laboratory, or the cartridge can prepare the sample for in situ detection and quantification of environmental targets. In this study, all particulate samples were preserved onboard for subsequent analyses in a shore side laboratory [45].

We previously designed and field tested an algorithm for an LRAUV to autonomously detect and track the depth of the chlorophyll peak, and sample at that depth [46]. However, the chlorophyll peak’s depth varies over time because of the phytoplankton’s vertical migration and internal waves [47], which was also seen in our experiment [46].

Based on the underlying physics of the chlorophyll maximum layer in an eddy, we developed a new method for an LRAUV to accurately track and sample the DCM layer. In the 2018 Hawaiian Eddy Experiment, a 3G-ESP LRAUV Aku ran the algorithm to track the DCM layer in a cyclonic eddy for four days and acquired 38 ESP samples. The algorithm is presented in Section II. The experiment is described in Section III. We conclude and outline future work in Section IV.

II. AUTONOMOUS DETECTION, TRACKING, AND SAMPLING OF THE DCM LAYER

A. Design Principle

Horizontal and temporal variations of the DCM layer depth tend to follow those of an isopycnal layer [47], [48]. When density variation is dominated by temperature variation, an isopycnal can be effectively tracked by tracking an isotherm. Hence, we developed an algorithm to enable an LRAUV to autonomously track and sample the DCM layer by locking onto the isotherm corresponding to the chlorophyll peak. The algorithm comprises the following key components.

B. Lowpass Filtering of Chlorophyll Measurement

To remove spurious peaks due to sensor noise, the raw chlorophyll measurement is lowpass filtered by a moving-average window of duration $\tau_{LP}$. Given the chlorophyll sensor’s sampling interval $\tau_{s,chl}$, the length of the lowpass filter window is $L = \lceil \tau_{LP}/\tau_{s,chl} \rceil + 1$ samples, where $\lceil \cdot \rceil$ rounds up to the nearest integer. The real-time lowpass filtering of chlorophyll runs as follows:

$$Chl_{LP}(l) = \frac{1}{L} \sum_{i=0}^{L-1} Chl(l - i)$$

where $l$ is the current sample index, $Chl(l)$ is the raw chlorophyll measurement, and $Chl_{LP}(l)$ is the lowpass filtered signal.

The raw temperature measurement is lowpass filtered by the same moving-average window of duration $\tau_{LP}$. Given the temperature sensor’s sampling interval $\tau_{s,temp}$, the length of the lowpass filter window is $M = \lceil \tau_{LP}/\tau_{s,temp} \rceil + 1$ samples. The real-time lowpass filtering of temperature runs as follows:

$$T_{LP}(m) = \frac{1}{M} \sum_{i=0}^{M-1} T(m - i)$$

where $m$ is the current sample index, $T(m)$ is the raw temperature measurement, and $T_{LP}(m)$ is the lowpass filtered signal.

The raw depth measurement is also lowpass filtered by the same moving-average window of duration $\tau_{LP}$. Given the depth sensor’s sampling interval $\tau_{s,depth}$, the length of the lowpass filter window is $N = \lceil \tau_{LP}/\tau_{s,depth} \rceil + 1$ samples. The real-time lowpass filtering of depth runs as follows:

$$z_{LP}(n) = \frac{1}{N} \sum_{i=0}^{N-1} z(n - i)$$

where $n$ is the current sample index, $z(n)$ is the raw depth measurement, and $z_{LP}(n)$ is the lowpass filtered signal.

Note that the lowpass filter introduces a delay of $\tau_{LP}/2$ in $Chl_{LP}$, $T_{LP}$, and $z_{LP}$. Compared with chlorophyll, the temperature and depth measurements are much less noisy. Despite their lower noise levels, we apply the same lowpass filter to temperature and depth as to chlorophyll to synchronize $T_{LP}$ and $z_{LP}$ with $Chl_{LP}$, as will be elaborated in Section III-B.

C. Autonomous Detection of the DCM Layer

The AUV performs the following steps to autonomously find the peak chlorophyll layer and the corresponding isotherm, and then stay on that isotherm. These steps are illustrated in Fig. 4, labeled with the corresponding step number.

1) The AUV descends from the surface to $DeepBound$ (a deep bound that is sufficiently deeper than the anticipated DCM layer depth). On the descent, the AUV seeks $Chl_{LP, max}$ (the peak of the $Chl_{LP}$ signal) and the corresponding temperature $T_{LP, ChlPeak}$. Because $Chl_{LP}$ and $T_{LP}$ carry the same delay of $\tau_{LP}/2$ (due to the same lowpass filter), $T_{LP, ChlPeak}$ truly marks the temperature of the chlorophyll peak, as will be seen in Fig. 7 in Section III-B.
The vehicle can descend in spiral mode (propeller turned ON with a nonzero rudder angle) or drift mode (propeller turned OFF; adjusting buoyancy).

2) When reaching depth $D_{\text{Deep Bound}}$, the vehicle turns to an ascent (in spiral mode or drift mode). To confirm the turn from descent to ascent, the AUV checks the following two conditions [18]: first, the depth has decreased four times in a row. Second, the depth has decreased from the maximum depth by more than 1 m. Once the turn is confirmed, the vehicle reports the peak signal value $\text{Chl}_{\text{LP max}}$ of the entire descent leg and the corresponding temperature $T_{\text{LP ChlPeak}}$.

3) On the ascent, when the AUV reaches temperature $T_{\text{LP ChlPeak}}$, it stops ascending and follows the targeted water mass by temperature. The isotherm tracking algorithm is given in Section II-D.

D. Isotherm Tracking Algorithm

We previously designed an AUV autonomous isotherm tracking algorithm [49]. In an initial vertical search, the vehicle records the depth corresponding to the target temperature $T_{\text{target}}$ and holds that depth. During depth holding, if the measured temperature $T_{\text{measured}}$ goes beyond a tolerance range (e.g., $T_{\text{target}} \pm 0.2 \, ^{\circ}\text{C}$), the vehicle ascends or descends to reacquire the target temperature. In each reacquisition maneuver, a lock-out time (several minutes) is allowed for any depth overshoot to damp down. In an experiment in Monterey Bay in June 2015, an LRAUV ran the algorithm to track a targeted temperature for 13 h. The standard deviation of temperature was $0.11 \, ^{\circ}\text{C}$; 95% of the temperature points fell within $T_{\text{target}} \pm 0.25 \, ^{\circ}\text{C}$. In this method, the AUV holds depth until the temperature error is larger than the tolerance range. This introduces a latency in responding to temperature discrepancy.

Therefore, we improved the approach so that the temperature error is continuously fed back to the controller for achieving a more responsive and accurate isotherm tracking, as illustrated in Fig. 5. In each control cycle of duration $\Delta t$, a projected temperature $T_{\text{proj}}$ is calculated based on the discrepancy between the target temperature $T_{\text{target}}$ and the measured temperature $T_{\text{measured}}$, as well as the rate of temperature change on the vehicle’s vertical maneuver $\dot{T}$. The difference between $T_{\text{proj}}$ and $T_{\text{measured}}$ produces a depth adjustment $z_{\text{adj}}$, which is subtracted from the measured depth $z_{\text{measured}}$ to give the commanded depth $z_{\text{commanded}}$. The AUV maneuvers (by adjusting attitude when in flight mode) to attain $z_{\text{commanded}}$.

III. EXPERIMENT

A. Experimental Design

During March and April 2018, two LRAUVs along with one Liquid Robotics Wave Glider were deployed to the north of Hawaiian Islands to investigate the diel variability of the microbial community in the DCM layer residing in a cyclonic eddy [50], as shown in Fig. 2. LRAUV Aku carried a 3G-ESP. Aku ran the presented algorithm to autonomously find and track the DCM layer, and trigger 3G-ESP water sampling. During Aku’s submerged tracking, Wave Glider Mola acoustically tracked it to provide safety assurance and the functionality of terminating Aku’s mission. LRAUV Opah also acoustically tracked Aku and spiraled around it to measure the contextual water properties.

Prior to the experiment, the University of Hawaii scientists studied satellite SLA maps to identify eddies and plan ship tracks to transect the targeted eddy. A cyclonic eddy to the northeast of Molokai was selected for study, as shown in Fig. 6. The sea surface sloped downward toward the eddy center (hence the most negative SLA at the center) to balance the Coriolis force exerted on the eddy current by the Earth’s rotation. While R/V Falkor transected through the eddy, the onboard scientists identified the eddy center by observing in real time the
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Fig. 5. Diagram of LRAUV’s control mechanism for isotherm tracking.

Fig. 6. Trajectories of Aku, Opah, and Mola during the four-day mission, overlaid on the CMEMS SLA and geostrophic current velocity map. The triangle and the square mark the start and the end of the mission, respectively. Time is in Hawaii Standard Time (HST). HST = Coordinated Universal Time (UTC) – 10:00.

diminishing current velocity measured by the shipboard Acoustic Doppler Current Profiler (ADCP) and by tracking the depth of isopycnal surfaces measured with the underway Conductivity-Temperature-Depth (CTD) sensors deployed from the ship’s stern. At the eddy center, we deployed Aku, Opah, and Mola to kick off the experiment which comprised two legs. In leg 1 from March 17 to 21, Aku took 36 ESP samples from the DCM layer in three segments (the vehicle surfaced between segments). At the end of this leg, we recovered the vehicles, and retrieved the ESP samples. On March 28, we redeployed the vehicles at the eddy center for leg 2 through April 2, in which Aku took 46 ESP samples from the DCM layer in three segments. In the longest segment from March 28 13:57 to April 1 14:34 (all times in HST), Aku tracked the DCM layer to the north of the eddy
center for four days without surfacing, and took 38 ESP samples. This longest nonstop segment is reported below.

**B. LRAUV Aku’s Detection, Tracking, and Sampling of the DCM Layer**

From March 28 13:57 to April 1 14:34, Aku autonomously found the DCM and continuously tracked the DCM layer without surfacing, as shown in Fig. 7. During the four-day tracking, Aku took 38 ESP samples: 24 samples in the layer at 3-h intervals, followed by 14 samples in, below, and above the layer for comparison. In the first panel, the raw chlorophyll is shown by the blue dots, and the lowpass filtered chlorophyll (on the initial dive and the succeeding ascent) is shown by the red line. The red circle marks the peak of the lowpass filtered chlorophyll found on the initial dive. The green dots mark the ESP sampling duration of each sample. In the second panel, the raw temperature is shown by the blue dots, and the lowpass filtered temperature is shown by the red line. The red circle marks the lowpass filtered temperature corresponding to the chlorophyll peak. In the third panel, temperature is zoomed in for examining Aku’s isotherm tracking accuracy. The fourth panel shows Aku’s depth trajectory. We see that the tracked isotherm undulated in depth. In the fifth panel, Aku’s PAR measurement clearly shows four daily cycles. Note that the very high PAR peak on 1 April was due to Aku ascending to a much shallower depth (50 m) in daylight. Details of DCM detection, tracking, and sampling are given below.

1) **Autonomous Detection of the DCM Layer:** A close-up view of the initial dive and the succeeding ascent is shown in Fig. 8. Aku spiraled from the surface down to $D_{P, \text{DeepBound}} = 260$ m to seek the DCM layer. The vehicle’s rudder angle was set to $13^\circ$ and the vehicle speed was 1 m/s (with the vertical component of 0.14 m/s). At 102.36-m depth, the vehicle found the peak chlorophyll $\text{Chl}_{P, \text{max}} = 0.72 \mu g/L$ and the corresponding temperature $T_{LP, \text{ChlPeak}} = 21.04 ^\circ C$. All values were lowpass filtered output from an 8-s moving-average window.

The WET Labs BB2FL fluorescence/backscatter sensor’s sampling frequency was 2 Hz. Hence, the 8-s sliding window averaged 16 chlorophyll measurements to produce the lowpass filtered output at each time instant. This was sufficient to smooth out the noise, as shown in the upper left panel of Fig. 8. At the
vehicle’s 0.14 m/s vertical speed, the 8-s time window was equivalent to a 1.1 m depth window. The DCM thickness on Aku’s initial dive was 8 m (when chlorophyll dropped to 90% of the peak level). The 8-s lowpass sliding window’s thickness was small compared with the DCM layer thickness, thus well preserving the chlorophyll signal. The SBE GPCTD temperature sensor and Keller depth sensor’s sampling frequencies were 1 and 2.5 Hz, respectively. Hence, the 8-s sliding window averaged 8 temperature measurements or 20 depth measurements.

The purpose of applying the same lowpass filter to temperature and depth as to chlorophyll was to synchronize $T_{LP}$ and $z_{LP}$ with Chl$_{LP}$. Because they carried the same delay of $8s/2 = 4s$, $T_{LP,Chl_{Peak}}$ truly marked the temperature of the chlorophyll peak, as shown in the right panels of Fig. 8. In the upper right panel, Chl$_{LP}$ (red line) has a 4-s delay relative to the raw chlorophyll (blue dots). The red circle marks Chl$_{LP,max}$. With a 4-s displacement (to correct the delay), the red circle falls back onto the raw chlorophyll and is recolored blue. In the middle right panel, $T_{LP}$ (red line) has a 4-s delay relative to the raw temperature (blue dots). The red circle marks $T_{LP,Chl_{Peak}}$ that corresponds to Chl$_{LP,max}$. The 4-s delay-corrected $T_{LP,Chl_{Peak}}$ (blue circle) falls back on the raw temperature. Delay-corrected Chl$_{LP,max}$ and $T_{LP,Chl_{Peak}}$ are vertically aligned in the two panels, both lying on the raw chlorophyll’s peak. This verifies that $T_{LP,Chl_{Peak}}$ corresponded to the chlorophyll peak.

2) Autonomous Tracking and Sampling of the DCM Layer: Aku locked onto the 21.04 $^\circ$C peak-chlorophyll isotherm for three days to track and sample the DCM layer, as shown in the second and third panels of Fig. 7. The standard deviation of temperature was 0.06 $^\circ$C; 98% of the temperature points fell within 21.04 $^\circ$C ± 0.15 $^\circ$C. The isotherm tracking accuracy improved by a factor of two over the previous algorithm (in Section II-D). The depth of the peak-chlorophyll isotherm undulated between 83 and 124 m depths. The large depth undulation of the DCM layer manifests the importance of enabling the LRAUV to track the peak-chlorophyll isotherm rather than a certain depth.

Aku triggered the 3G-ESP sampling every 3 h. For each sample, filtration took 65 min and processing took 12 min. A 100-min wait was inserted before the next sampling to make the inter-sample spacing 3 h. Thus, 24 samples were acquired inside the DCM layer in three days. On the fourth day, Aku switched to a different sampling sequence to acquire 14 ESP samples from inside, below and above the DCM layer for comparison: 2 in DCM; 2 at 250-m depth; 2 at 50-m depth; 2 in DCM; 2 at 250-m depth; 2 at 50-m depth; 2 in DCM. In total, 38 samples were acquired in four days. All particulate samples were preserved to support transcriptomic analysis after vehicle recovery.

The chlorophyll fluorescence and PAR levels in the DCM layer measured by Aku are shown in the first and fifth panels of Fig. 7, respectively. The DCM chlorophyll fluorescence level
exhibited diel variation, and the daily highest level was reached around 15:00 (local time), following the daily peak in PAR. The daily chlorophyll fluorescence peak level also showed day-to-day variation co-varying with the PAR level. These variations in chlorophyll fluorescence may have been associated with population growth, variation of cell pigmentation levels [48], and nonphotochemical quenching, which can occur at low PAR levels [51]. The diel pattern of the DCM chlorophyll level is similar to that observed in a separate experiment in the North Pacific Ocean (27.7° N, 139.5° W) measured by an autonomous profiler [52].

On the 21.04°C isotherm of the DCM, Aku ran on tight circles (circle radius ∼10 m) at 13° rudder angle and 1 m/s speed while drifting with the eddy current. The trajectories of Aku, Opah, and Mola during Aku’s four-day mission are shown in Fig. 6. Mola’s trajectory is given by its continuous GPS tracking on the sea surface. Opah’s trajectory is estimated by underwater dead-reckoned navigation that is corrected by periodic GPS fixes on the surface. Aku’s trajectory is estimated by combining Mola’s own location and Aku’s acoustic range and bearing from Mola (with a horizontal positioning error of about 50 m).

In 74-h continuous tracking of the DCM layer, Aku drifted 72 km in the eddy current at an average drift speed of 0.27 m/s. Concurrently, a GPS-tracked drifter comprising a surface float and a drogue at 120-m depth was deployed near Aku. In the same 74-h duration, the drifter drifted 71 km at an average drift speed of 0.27 m/s. Another reference was Falkor’s shipboard ADCP measurement near Aku’s route. The ADCP-measured Earth-referenced current velocity at the 103-m depth bin (nearest DCM’s mean depth of 105 m) in this duration was 0.25 m/s. The closeness between Aku’s drift speed and that of the drifter as well as the ship ADCP-measured eddy current velocity shows that Aku largely followed the DCM water mass in a quasi-Lagrangian mode.

C. LRAUV Opah’s Contextual Mapping Around Aku

Mola, Opah, and Aku were each equipped with a Teledyne Benthos directional acoustic transponder that integrates an acoustic modem and an ultra-short baseline acoustic positioning system. Opah acoustically tracked Aku, while spiraling up and down between 50 and 200 m depths around Aku to measure the contextual water properties. During the four-day mission, the distance between the two vehicles varied from 30 m to 3 km, averaging 840 m. It is useful to know how representative the water column structure mapped by Opah was in relation to Aku, considering the distance between them and the DCM structure. This requires synoptic mapping data of the eddy, as acquired by Opah and Aku on two 100-km cross-eddy yo-yo transects (north-south and east-west, respectively) prior to Aku sampling mission. The average DCM thickness (when chlorophyll dropped to 90% of the peak level) was 13 m. At 3-km distance, the average difference of DCM depths was 7 m, smaller than the DCM thickness. This indicates that Opah water column data accurately represented the vertical structure around Aku during the sampling mission.

In the upper panel of Fig. 9, Aku’s depth trajectory is overlaid on Opah-measured contextual chlorophyll. The overlap of Aku’s depth and Opah-measured chlorophyll-maximum depth confirms that Aku precisely tracked the DCM layer. In the lower
panel, Aku’s depth trajectory is overlaid on Opah-measured contextual temperature, which shows that Aku stayed on the targeted isotherm corresponding to the DCM.

IV. CONCLUSION AND FUTURE WORK

In the 2018 SCOPE Hawaiian Eddy Experiment, a 3G-ESP LRAUV ran our targeted sampling algorithm to autonomously detect, track, and sample the DCM layer in a cyclonic eddy for four days and acquired 38 water samples from inside, below, and above the DCM layer. Molecular analysis of the samples is underway, aimed at understanding the function, activity, and environmental sensitivities of microbial populations over four consecutive diel cycles. The result is expected to shed light on how eddy physics affects biological processes and ocean productivity over time.

In the Hawaiian Eddy Experiment, all cartridges were of “archival” type, i.e., the samples were preserved for lab analysis after the LRAUV was recovered. We are currently working on another type of cartridge that will allow on-board processing of filtered material, creating a homogenate for downstream in situ analysis [36]. To perform the in situ analysis, reactive reagents are added to the filtered material, which is then heated to release the genetic material and proteins. Additional reagents are added to the sample, and the mixture is pushed from the cartridge to a detection instrument embedded within the 3G-ESP. The detection instruments (under development) will target environmental toxins or nucleic acids. Real-time molecular detection and reporting opens exciting possibilities for 3G-ESP LRAUVs to react to genomic findings and accordingly modify missions to maximize scientific gains.

Multivehicle collaboration allowed continuous sampling and contextual mapping in a moving eddy field, enabling quasi-Lagrangian observation of DCM microbial ecology [53]. The Wave Glider and the contextual-mapping LRAUV acoustically tracked the sampling LRAUV, but there was no data exchange between them. We are in the process of testing intervehicle acoustic messaging. Exchange of key information (e.g., chlorophyll level and ESP status) will greatly improve efficiency, flexibility, and persistence of autonomous targeted sampling missions.

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cycles, microbial metabolism, and air–sea exchange. Our understanding of pathways and controls on microbially mediated matter and energy flow in the ocean has been enhanced by the Simons Collaboration on Ocean Processes and Ecology to help prepare the next generation of microbial oceanographers.

Dr. DeLong received the B.S. degree in bacteriology from the University of California at Davis, CA, USA, in 1982, and the Ph.D. degree in marine biology from Scripps Institute of Oceanography, University of California at San Diego, San Diego, CA, USA, in 1986. He is currently a Microbial Oceanographer focusing on marine microbial genomics, geochemistry, and evolution. A large part of his efforts have been devoted to the study of microbes and microbial processes in the ocean, combining laboratory, and field-based approaches. Development and application of genomic, biochemical, and metabolic approaches to study and explore microbial communities and processes is primary area of interest. He is also interested in using autonomous robotic sensors and samplers with genomic technologies, to derive highly resolved spatial and temporal maps of microbial community gene distributions and gene expression datasets in four dimensions in the oceans water column.

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