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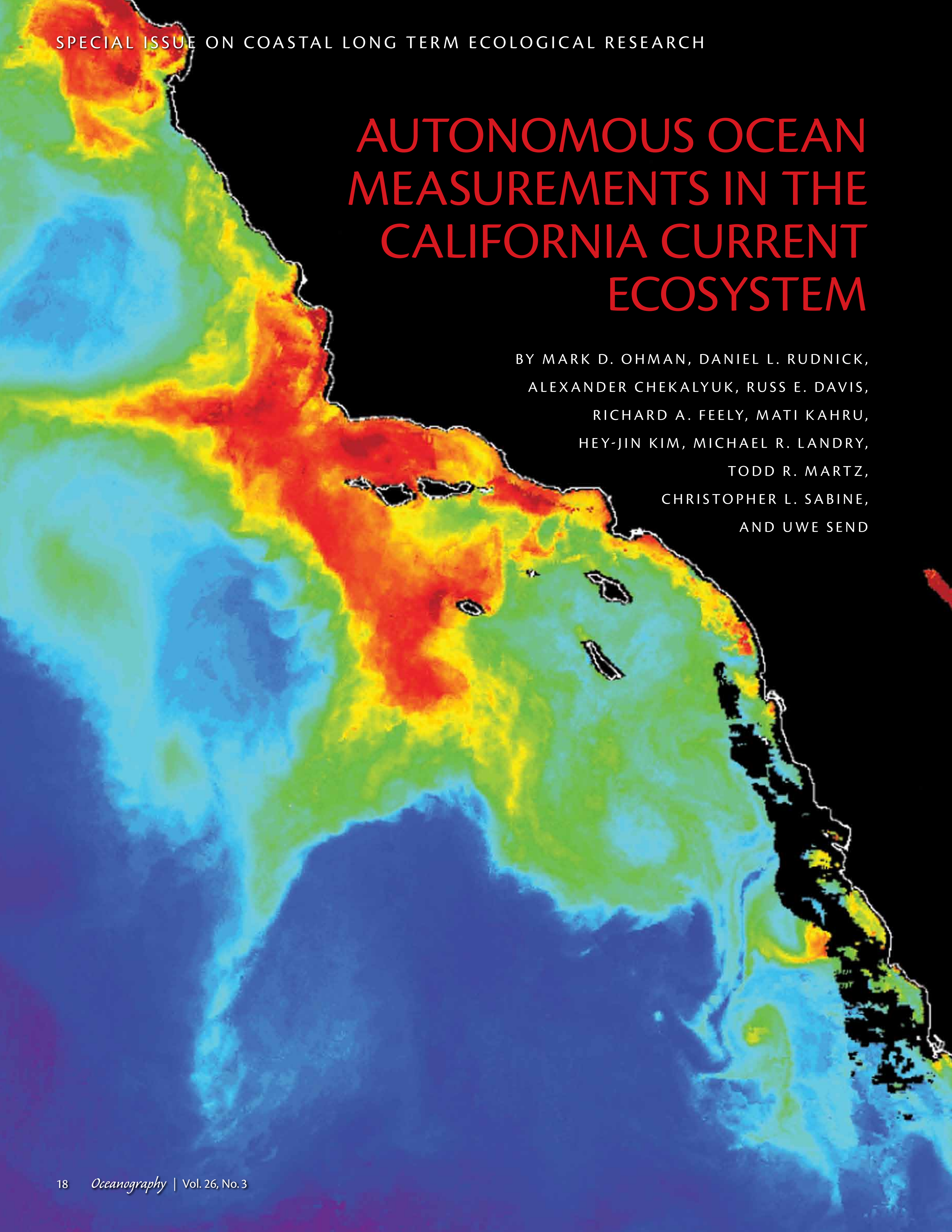

AUTONOMOUS OCEAN MEASUREMENTS IN THE CALIFORNIA CURRENT ECOSYSTEM

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ABSTRACT. Event-scale phenomena, of limited temporal duration or restricted spatial extent, often play a disproportionately large role in ecological processes occurring in the ocean water column. Nutrient and gas fluxes, upwelling and downwelling, transport of biogeochemically important elements, predator-prey interactions, and other processes may be markedly influenced by such events, which are inadequately resolved from infrequent ship surveys. The advent of autonomous instrumentation, including underwater gliders, profiling floats, surface drifters, enhanced moorings, coastal high-frequency radars, and satellite remote sensing, now provides the capability to resolve such phenomena and assess their role in structuring pelagic ecosystems. These methods are especially valuable when integrated together, and with shipboard calibration measurements and experimental programs.

INTRODUCTION

The California Current System, like other eastern boundary current upwelling ecosystems, is a dynamic environment forced by atmospheric and ocean changes across a spectrum of different temporal and spatial scales. Particularly challenging to measure are processes that occur on the "event" scale (i.e., of limited temporal duration or restricted spatial extent), for example, individual upwelling or downwelling events, patch feeding by transient schools of fishes or migratory pods of cetaceans, ocean mixing events, and passage of submesoscale eddies. Such events can play a disproportionately large role in regulating fluxes of nutrients or gases, aggregation of zooplankton or fishes, and export fluxes of phytoplankton, carbon, nitrogen, and other ecologically important elements. Although these phenomena potentially play a key role in the structuring of planktonic ecosystems and ocean biogeochemistry, they are difficult to resolve with infrequent shipboard sampling. The important events often happen when we are not there.

AUTONOMOUS INSTRUMENTATION

Developments in autonomous vehicles (Perry and Rudnick, 2003; Rudnick et al., 2004), interdisciplinary moorings (Dickey et al., 2009; Nam et al., 2011), and satellite telemetry now make it possible to resolve temporally transient or spatially abrupt phenomena in situ, below the sea surface, in near-real time. Figure 1 illustrates the subsurface expression of both temperature and chlorophyll *a* (Chl-*a*) frontal features off Pt. Conception in the southern California Current System, as detected by *Spray* ocean gliders, together with the areal extent of the fronts and associated coastal filaments and mesoscale eddies, as resolved by satellite sensors. More than six years of extensive *Spray* glider surveys at the California Current Ecosystem (CCE) Long Term Ecological Research (LTER) site have revealed surprising changes in the plankton biota associated with such frontal features, including a pronounced change in the diel vertical migration (DVM) behavior of mesozooplankton detected with

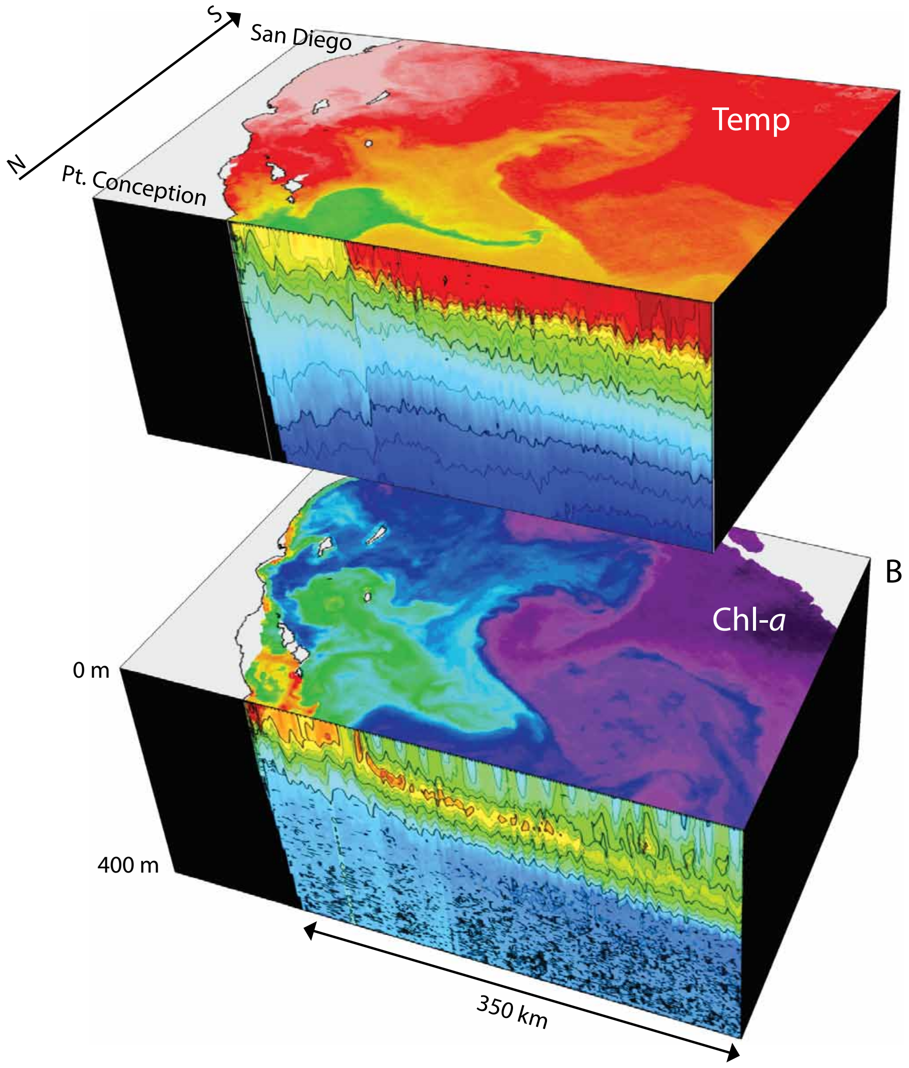

Figure 1. Mesoscale and submesoscale features in the southern California Current System. Satellite images of (A) sea surface temperature (merged from MODIS-Aqua and MODIS-Terra) and (B) phytoplankton Chl-*a* (merged from SeaWiFS and MODIS-Aqua), integrated with *Spray* glider vertical sections (0–400 m depth). The viewing angle is from north to south, from Pt. Conception to San Diego, along the California coast. Note the well-defined frontal features off Pt. Conception that have pronounced subsurface expressions. Glider and satellite images are on different color scales. *Figure composition courtesy of Peter J.S. Franks, Scripps Institution of Oceanography*

a glider-mounted sonar (Figure 2A; Powell, 2013). The deeper daytime depths and larger amplitude DVM behavior associated with the offshore waters at frontal transitions are attributable to a faunistic change across the front and associated spatial changes in light-mediated predation risk (Powell, 2013). There are nearly coincident changes in horizontal shear and in phytoplankton Chl-*a* associated with this feature (Figure 2B,D). Satellite-derived time series from our region show that the frequency of such frontal systems has been increasing over the past 30 years (Kahru et al., 2012), suggesting a growing role for these ocean features in the future.

Spray gliders patrol continuously across the main axis of the California Current along CalCOFI (California Cooperative Oceanic Fisheries Investigations) lines 66.7, 80, and 90 (http://www.sccoos.org/data/spray/?r=0), extending 350–600 km offshore. The gliders are deployed ~ 1–2 km from shore from a small boat, then navigated remotely via the Internet using Iridium satellite telemetry for ~ 100-day missions at sea. Continuous coverage by the gliders makes it possible to resolve the timing of events that are

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impractical to measure from research vessels. For example, continuous glider coverage showed that the onset of the October 2009 El Niño event in southern California was nearly synchronous with the appearance of El Niño along the equator, suggesting that this event propagated to mid-latitudes initially via atmospheric teleconnections, not by oceanic advection (Todd et al., 2011a).

Gliders permit continuous interrogation of relatively large ocean areas, but they move rather slowly (~ 25 cm s^{-1}) and thus revisit the same location relative to the seafloor infrequently (unless directed to remain in a specific location). Fixed-location moorings, on the other hand, sample at high temporal frequency and for extended time periods. Moorings can also draw on substantial battery (or solar) power, considerably increasing the instrument payload. Inductive telemetry can be used to telemeter subsurface data in real time, and vertically profiling moorings are now being deployed (Send et al., 2012). Integration of mooring with glider data provides the advantages of both spatial and temporal resolution.

Figure 3A illustrates a glider-derived horizontal section of aragonite saturation state (Ω_{arag}), based on a robust proxy relationship for Ω_{arag} from dissolved oxygen and temperature (Alin et al., 2012). Ω_{arag} is a useful geochemical index of potential dissolution of aragonitic calcium carbonate shells of marine organisms due to ocean acidification (Bednaršek et al., 2012). The section shows the shoaling of the saturation horizon where $\Omega_{arag} = 1.0$ from a depth of 180–200 m in the offshore region to 35–50 m inshore, near the upwelling zone off Pt. Conception. These data, collected during 182 glider dives, provide a larger-scale spatial picture of the horizontal and depth distribution of waters potentially corrosive to aragonite-secreting organisms. Mooring-based measurements also permit Ω_{arag} to be estimated from the proxy relationship. For example, our offshore mooring location (CCE-1, ~ 220 km offshore) reveals relatively stable Ω_{arag} that is always oversaturated, while the inshore mooring (CCE-2, ~ 35 km off Pt. Conception) shows several episodes of undersaturation at 76 m that are associated with the upwelling of dense, high $p\text{CO}_2$, low pH, low O_2, and high nitrate waters (Figure 3B). The moorings permit real-time measurement of the magnitude, frequency, and duration of undersaturation events, key variables that influence the responses of calcifying organisms to the stress of

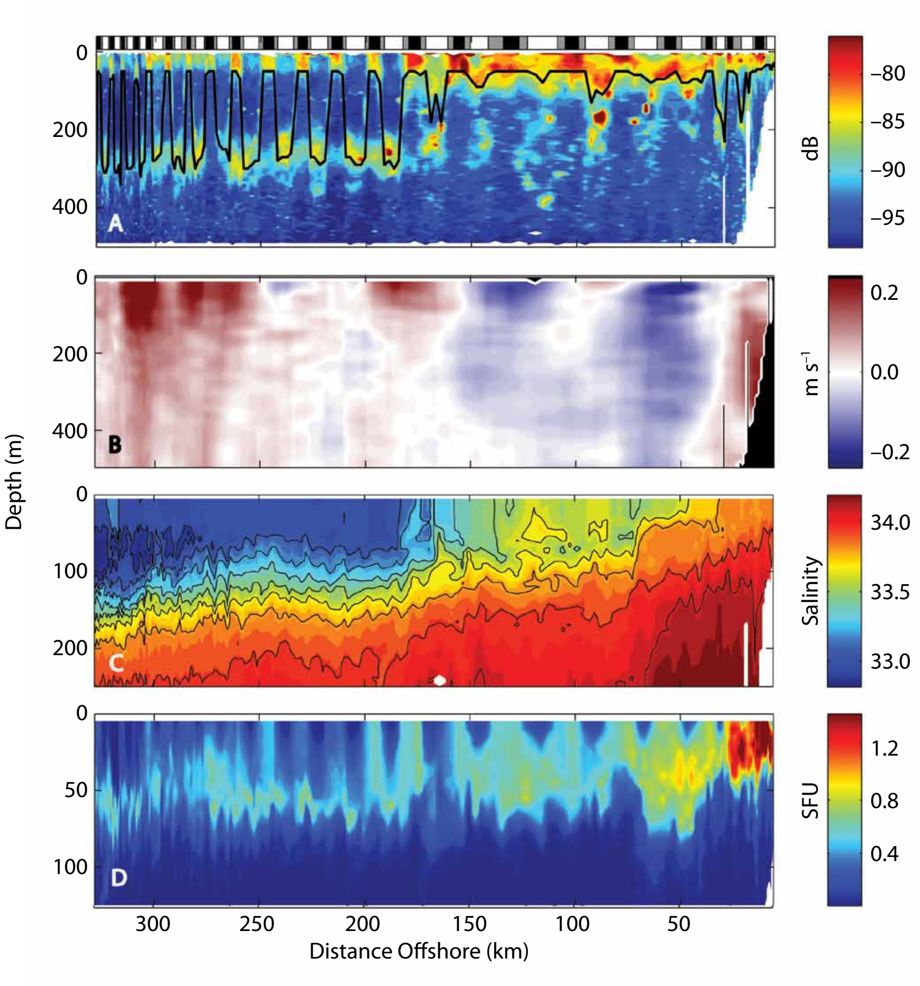

Figure 2. Cross-frontal changes in amplitude of zooplankton diel vertical migration, cross-track currents, and Chl-*a*, largely coincident with two salinity fronts. *Spray* glider sections from offshore (left) to onshore (right), along CalCOFI (California Cooperative Oceanic Fisheries Investigations) line 80 off Pt. Conception. (A) Acoustic backscatter (dB) from a 750 kHz acoustic Doppler profiler (ADP); black line indicates median depth of samples with mean volume backscatter values above the 85th percentile for a given dive. (B) Cross-track current velocity (m s^{-1}) from the ADP. (C) Salinity. (D) Phytoplankton Chl-*a* (Standardized Fluorescence Units, SFU). Depth scale varies by panel. Alternating white-gray-black-gray bars in uppermost panel indicate day-dusk-night-twilight, respectively. *Figure courtesy of Jesse R. Powell, Scripps Institution of Oceanography*

ocean acidification, while gliders provide a broader spatial context. Autonomous gliders with different instrumentation are also being utilized in the Santa Barbara Coastal LTER site (David Siegel, University of California, Santa Barbara, 2013, *pers. comm.*), the Palmer Station LTER site (Oliver et al., 2012), and in research programs located elsewhere.

Other autonomous measurements in the CCE LTER region include diverse satellite-based sensors (Kahru et al., 2012). In addition, an array of shore-based high-frequency radars maps surface currents to a distance of up to 150 km from shore off the California coast (Kim et al., 2011). A growing family of autonomous drifting instruments has been deployed in recent years. The original Argo Lagrangian float program included only conductivity-temperature-depth sensors (Roemmich et al., 2009), but there are now autonomous floats with instrumentation more relevant to ocean ecology, including a Laser Optical Particle Counter (Checkley et al., 2008), nitrate and dissolved oxygen sensors (Johnson et al., 2010), and optically based particulate carbon and particle flux sensors (Bishop, 2009), with others in development. A major distinction between gliders and floats is the user's ability to control the horizontal position of gliders.

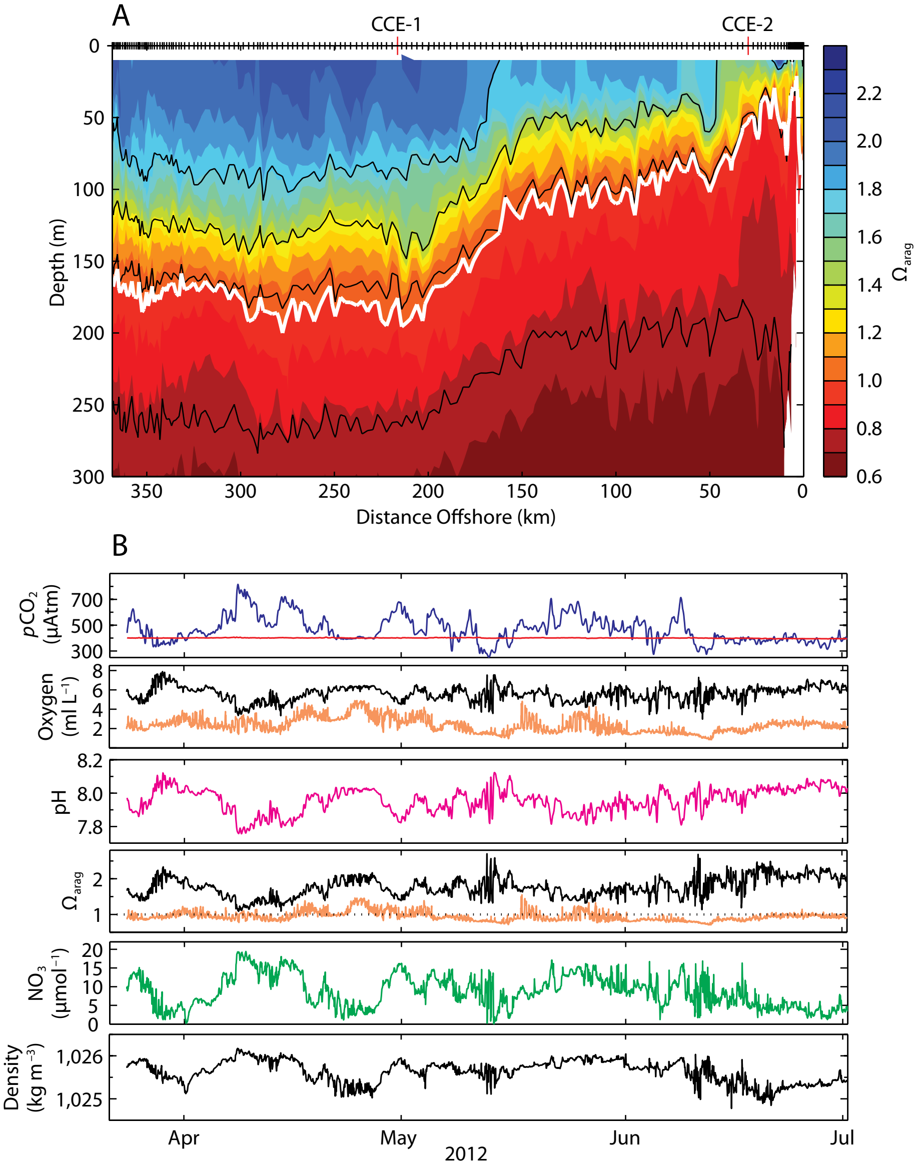

Figure 3. Spatial and temporal variations in aragonite saturation state (Ω_{arag}) along CalCOFI line 80, off Pt. Conception. (A) Cross-shore variations in Ω_{arag} from *Spray* glider section (April 17–May 9, 2012). California Current Ecosystem (CCE)-1 and CCE-2 indicate the locations of two interdisciplinary moorings. White contour: Ω_{arag} = 1.0. (B) Temporal variations in water column properties measured at the CCE-2 mooring (March 23–July 1, 2012). Top to bottom: pCO$_2$ (blue = in water, red = in air), dissolved O_2 (black = 16 m, orange = 76 m), pH (16 m), Ω_{arag} (black = 16 m, orange = 76 m), NO_3 (16 m), density (16 m). For both (A) and (B), Ω_{arag} was derived from the proxy relationship in Alin et al. (2012).

Autonomously deployed sensors require careful calibration before and after deployment and, preferably, independent verification during a deployment. Sensor drift, degradation, and biofouling can alter instrumental responses. In the CCE LTER program, we benefit from shipboard measurements made quarterly by the CalCOFI program (http://www.calcofi.org). The high-quality CalCOFI data, co-located with our mooring and glider sampling, make it possible to verify instrumental responses independently with in situ samples multiple times per year.

Integration of diverse types of sampling in the CCE LTER region has many benefits, including the complementarity of different temporal and spatial scales resolved by different devices, redundancy of measurements when cloud cover or technical issues restrict availability of one type of sensor, and the ability to calibrate and verify sensor performance through intercomparisons. Figure 4 reflects the present integration of our gliders, moorings, satellite remote sensing, and shipboard measurements. Satellite coverage provides larger-scale synoptic views of near-surface phenomena. In our application, *Spray* gliders provide continuous coverage to a depth of 500 m, extending 350 to 600 km offshore. Moorings record higher temporal frequency phenomena, with more diverse instrumentation. In addition to our surface-expressed moorings, a parallel mooring effort by the Scripps Whale Acoustic Lab (http://cetus.ucsd.edu) deploys passive acoustic hydrophones, typically at a depth of 20 m off the bottom, to record vocalizations by whales, dolphins, and porpoises at some of the same locations as our moorings. Regular shipboard sampling by CalCOFI at specific stations is important, both for calibration measurements and for the more diverse array of sampling, multifrequency acoustic surveys, and experimentation that is possible aboard ship. In addition, our integrated water column measurements can be related directly to processes at the deep-sea benthic study site at Station M (located due north of the CCE-1 mooring), where autonomous sediment traps and a deep-sea benthic rover record fluxes and corresponding changes in benthic communities and sediment community oxygen demand (see http://www.mbari.org/pelagic-benthic/deepsea.htm).

Glider, satellite, mooring, and CalCOFI shipboard observations help identify features of interest for experimental process studies. We customarily use such measurements for initial broad-scale surveys that are followed by additional fine-scale shipboard surveys to localize specific features for intensive experimentation. For example, Figure 5A illustrates an eddy dipole that was detectable in AVISO (Archiving, Validation and Interpretation of Satellite Oceanographic Data) sea-surface height anomaly imagery, with an associated frontal region between the anticyclonic and cyclonic features. This frontal region was then more precisely mapped using two shipboard instruments (Figure 5B,C): a free-fall Moving Vessel Profiler (MVP; Herman et al., 1998; Ohman et al., 2012) and a continuous underway Advanced Laser Fluorometer (ALF; Chekalyuk and Hafez, 2008; Chekalyuk et al., 2012), an imaging device that permits resolution of different phycobiliproteins, Chl-*a*, other pigments, CDOM (chromophoric dissolved organic matter), and assessment of phytoplankton physiology (F_v/F_m). Once deployed, the MVP profiles repeatedly from the surface to 200 m depth, making it well suited to resolving subsurface frontal gradients, while ALF continuously measures near-surface features from the ship's continuous flow intake. Having identified a feature such as shown in Figure 5, it then becomes possible to conduct targeted experimental studies of plankton growth, grazing, and particle export (e.g., the A-Front special issue of the *Journal of Plankton Research*, September 2012; Landry, Ohman et al.,

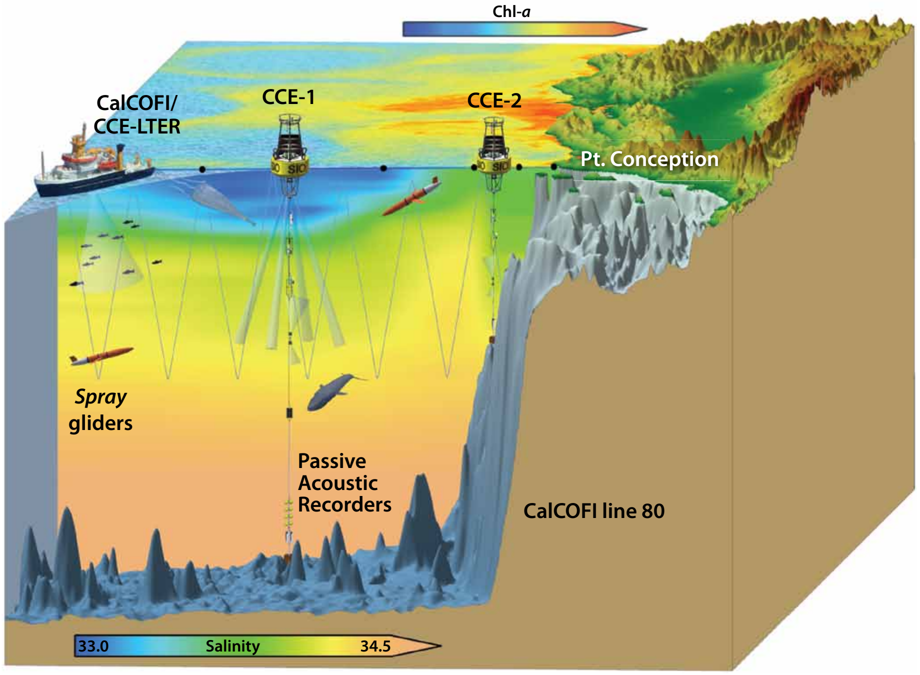

Figure 4. Schematic illustration of the integrated autonomous and shipboard measurement systems in place in the California Current Ecosystem (CCE) Long Term Ecological Research region, including satellite remote sensing, *Spray* ocean gliders, CCE-1 and CCE-2 moorings, HARP (High-frequency Acoustic Recording Package) passive acoustic moorings, and CalCOFI shipboard sampling and multifrequency sonar surveys. Due north of the CCE-1 mooring is Ken Smith's (Monterey Bay Aquarium Research Institute) Station M deep-sea benthic study site (not shown). Surface color contours are Chl-*a* from SeaWifs; vertical section contours are salinity, indicating the low-salinity core of the California Current (blue).

2012). Gliders have also been deployed in a quasi-Lagrangian mode in connection with such studies to measure along-flow and cross-flow property gradients of a water parcel and to guide adaptive sampling (Davis et al., 2008).

Our growing network of autonomous platforms not only resolves key event-scale ecosystem processes but also permits concurrent measurement of linked biophysical phenomena on comparable spatial and temporal scales, thus helping to resolve cause-and-effect relationships. This observational network also provides key data needed to constrain models (Todd et al., 2011b; Franks et al., 2013, in this issue; Ariane Verdy, Scripps Institution of Oceanography, 2013, *pers. comm.*) and thus improve our basis for forecasting future changes in the southern California Current Ecosystem.

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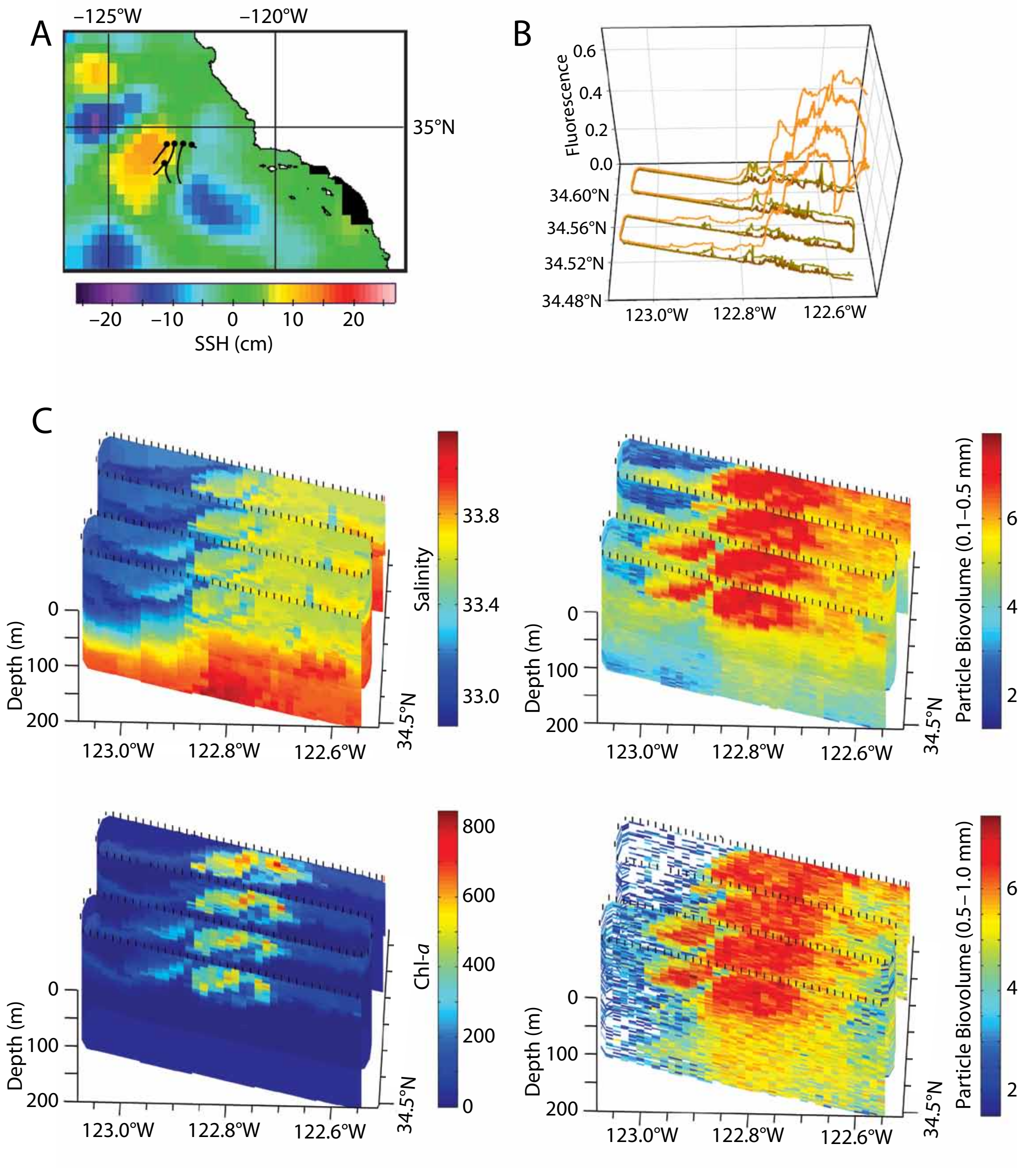

Figure 5. Localization of the E-Front, an eddy-associated front sampled in July 2012, using autonomous and shipboard measurements. (A) Sea surface height anomaly (in cm, AVISO), overlain by mixed layer drifter tracks spanning the frontal region. (B) Advanced Laser Fluorometer (Chekalyuk and Hafez, 2008) underway measurements at 3 m depth of two types of *Synechococcus* with fluorescence peaks at different wavelengths (orange line = 565 nm, brown line = 578 nm) and cryptophytes (green line; fluorescence in relative units). (C) Moving Vessel Profiler (Ohman et al., 2012) vertical profiles from 0–200 m of salinity, Chl-*a* (counts, relative units) and Laser Optical Particle Counter particle biovolume ($\log_{10}$ mm^3 m^{-3}) in two size categories: 0.1–0.5 mm and 0.5–1.0 mm equivalent spherical diameter.

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