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Glider and remote sensing observations of the upper ocean response to an extended shallow coastal diversion of wastewater effluent

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ABSTRACT

The Orange County Sanitation District (OCSD) diverted wastewater discharge (5.3×10^8 l d^{-1}) from its primary deep (56 m) outfall 8 km offshore, to a secondary shallower (16 m) outfall 1.6 km offshore for a period of three weeks. It was anticipated that the low salinity and density of the effluent would cause it to rise to the surface with limited dilution, elevating nutrient concentrations in near-surface waters and stimulating phytoplankton blooms in the region. Three Teledyne Webb Slocum gliders and a Liquid Robotics surface wave glider were deployed on transects near the outfalls to acquire high spatial and temporal coverage of physical and chemical parameters before, during, and after the wastewater diversion. Combined autonomous underwater vehicle (AUV) and MODIS-Aqua satellite ocean color data indicated that phytoplankton biomass increased in the upper water column in response to the diversion, but that the magnitude of the response was spatially patchy and significantly less than expected. Little evidence of the plume or its effects was detectable 72 h following the diversion. The effluent plume exhibited high rates of dilution and mixed throughout the upper 20 m and occasionally throughout the upper 40 m during the diversion. Rapid plume advection and dilution appeared to contribute to the muted impact of the nutrient-rich effluent on the phytoplankton community in this coastal ecosystem.

1. Introduction

The coastline of the Southern California Bight extends ~700 km along the west coast of North America from Point Conception, California, to just south of San Diego, California. Some parts of the Bight are highly impacted by human activities, with nearly 20 million people situated centrally along the coast in the greater Los Angeles region. This region contributes significantly to nutrient availability in near-shore waters, in part due to large ocean discharges of treated sewage effluent from several subsurface and offshore outfalls. A recent study indicated that inorganic nitrogen (N) in effluent discharged into the central Southern California Bight was a substantial contributor to the region's N budget (Howard et al., 2014).

These large outfalls have been designed to minimize the impact of effluent on local nutrient budgets by discharging into relatively deep water (>50 m) at significant distances from shore (≈5–8 km), and sufficiently mixing the wastewater such that diluted discharge plume remains below the pycnocline. However, maintenance or repairs occasionally require that effluent must be redirected to older outfalls that are shallower and closer to shore. Positive buoyancy of the effluent plume, due to low salinity and density, enhances the potential for transport of nutrient-rich effluent into surface waters, especially during effluent diversion events. Such diversions have the potential to stimulate the standing stock of phytoplankton in the area of effluent discharge due to increased nutrient inputs. Hyperion Treatment Plant of the City of Los Angeles carried out such a diversion in November 2006 through its near-shore outfall located 1.6 km from shore in Santa Monica Bay. Although the Hyperion diversion lasted only 50 h, a significant, albeit patchy phytoplankton bloom ensued. The bloom was

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dominated by *Cochlodinium* sp., a toxic dinoflagellate, reaching chlorophyll-*a* concentrations of 100 mg m^{-3} within 4–7 days of the diversion (Reifel et al., 2013). The Hyperion treatment plant diversion took place only 65 km north of the study site in San Pedro Bay described here.

The Orange County Sanitation District (OCSD) conducted repairs of its primary offshore outfall in September 2012. Effluent was diverted to a secondary, shallow outfall located at 16 m depth and only 1.6 km from shore for a period of 3 weeks. It was expected that the OCSD diversion might elicit a major phytoplankton bloom in the near-shore coastal ecosystem, based on observations following the 2006 Hyperion diversion. The timing of the OCSD diversion during late summer is a period when local waters are highly stratified due to warm surface waters and are generally nutrient depleted. Predictions of the impact of effluent discharge on the phytoplankton community during the 3-week OCSD diversion were presented in an Environmental Impact Report. The report indicated that advective mixing and tidal modulation of the plume could yield parcels of coastal water containing up to 42 μM ammonium, resulting in an algal bloom with 40–50 mg m^{-3} chlorophyll-*a* (OCSD, 2011; Jones and Caron, 2011). These values are equivalent to the largest phytoplankton blooms observed in this region (Kim et al., 2009; Seubert et al., 2013). Concern over the potential for harmful algal blooms and coastal water quality led to an intense monitoring and research effort during the OCSD diversion.

A combination of glider and satellite remote sensing was used to determine spatial and temporal responses of the phytoplankton community to the OCSD wastewater diversion. Observations began two weeks before the diversion to establish pre-diversion conditions and continued during and after the diversion to capture responses to the expected shallow effluent plume. The glider sensors allowed tracking of both the effluent plume and surface and subsurface phytoplankton responses.

2. Methods

2.1. Location and effluent composition

OCSD discharges treated wastewater into the San Pedro Bay, California, off the coast of Orange County in the central Southern California Bight (Fig. 1). The facility typically discharges approximately 5.3×10^8 l d^{-1} through a primary outfall diffuser located 8 km offshore at a depth of 56 m. OCSD conducted a three-week repair to the primary outfall from 11 September to 3 October 2012, and diverted effluent to a shallower (16 m) outfall located 1.6 km from shore. The secondary effluent pipe included a 295 m long diffuser section, outfitted with 120 circular effluent ports of 15.9 cm diameter designed to increase initial dilution rates (OCSD, 2009). The effluent is especially N-enriched relative to phosphorus (P) with N:P ~100:1, ammonium (NH_4^+) ≈2.1 mM and phosphate (PO_4^{3-}) ≈8.5 μM (Lyon and Sutula, 2011). Although not reported for OCSD effluent, silicate (SiO_4) is often present in sewage effluent at concentrations >550 μM (Petrenko et al., 1997). Responses of the phytoplankton community to such large nutrient additions were monitored using a variety of *in-situ* and remote sensing instrumentation.

2.2. Slocum gliders

Teledyne Webb Slocum gliders (North Falmouth, Massachusetts) and a Liquid Robotics (Sunnyvale, California) surface Wave Glider were deployed during the diversion along transect lines near the outfall pipes to obtain spatial and temporal coverage of biological and physical properties before, during, and after the

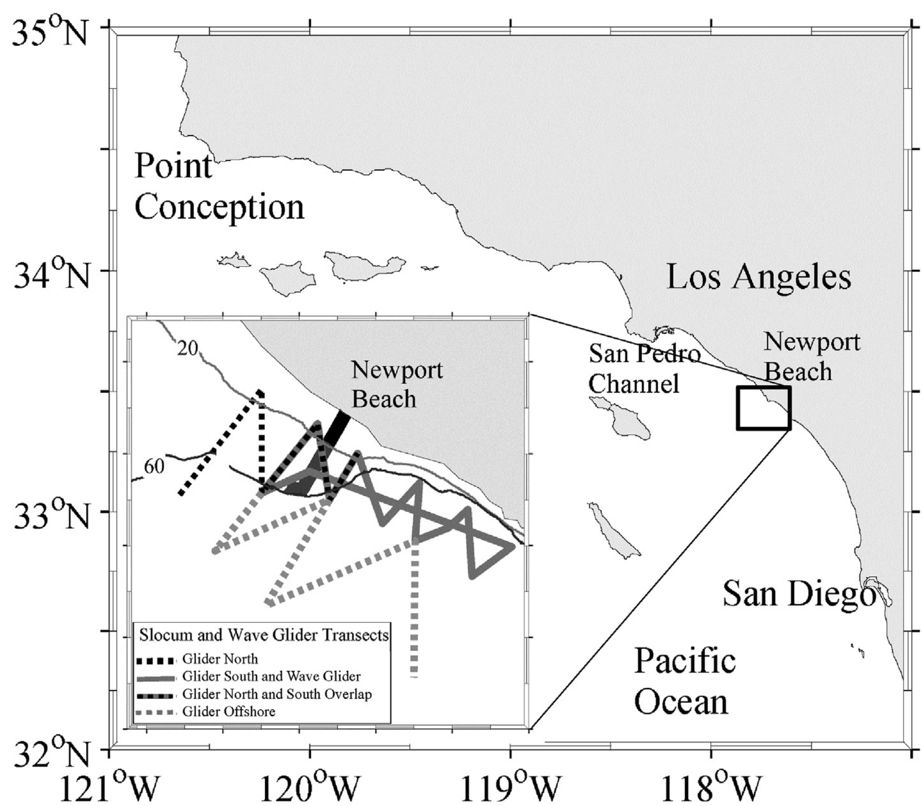

Fig. 1. Southern California Bight with inset indicating the study area for the Orange County Sanitation District diversion. Transect lines are indicated for the Slocum glider and Wave Glider in San Pedro Bay near Newport Beach. Primary outfall pipe (bold dark grey), diversion outfall (bold black), and 20 and 60 m isobaths are also shown.

diversion. Gliders are superior to shipboard measurements for tracking effluent plumes, given the high spatial and temporal variability of water-quality responses (Rogowski et al., 2013).

Slocum gliders were equipped with a flow-through Seabird CTD, WET Labs ECO Puck fluorometers for sensing chlorophyll-*a* (excitation 470 nm/emission 695 nm), colored dissolved organic matter (CDOM) (excitation 370/emission 460 nm), and phycoerythrin (excitation 540/emission 570 nm), and WET Labs ECO Puck Backscattering Sensors at 532, 660, and 880 nm. Estimated vertical resolution was 30 cm for glider fluorescence and backscattering ECO Pucks, and 60 cm for the CTD. Horizontal surface resolution of a Slocum glider is approximately three times the dive depth with an estimated horizontal speed of 0.3 m s^{-1}. Data were binned to 1 m for profile analysis. Slocum gliders were removed every 22–26 d for a battery change, cleaning, and CDOM and chlorophyll-*a* calibrations following protocols described in Cetinić et al. (2009). The gliders were not used to estimate effluent dilution rates because calibration curves for this purpose were not developed for the gliders.

We deployed Slocum gliders two weeks prior to the diversion until two weeks after (29 August – 16 October), covering three along-coast zigzag transects, designed to maximize spatial coverage on and off the shelf, and temporal resolution around the outfall. The glider paths were based on the assumption that the primary direction of transport of the plume would be along-coast away from the outfall, and that the cross-section of the plumes (major gradients) would be oriented cross-shelf (Hamilton et al., 2006). The zigzag pattern minimized the number of waypoints necessary to move the glider along and across the shelf, which can increase glider efficiency. Slocum gliders profiled from 3 to 90 m depth, or 5 m above the bottom when on the shelf. Two glider transects covered the near-shore from ~20 m isobath to beyond the shelf break. The northern transect covered an along-shore distance 12 km north/northwest of the outfalls, while the southern transect covered a distance 17 km down-coast from the outfalls. Along-shore coverage was greater to the south, based on the expectation that near-surface currents tend to be southward during late summer (Dong et al., 2009; Hamilton et al., 2006; Noble et al., 2009). Northern and southern transects overlapped near the outfalls to maximize coverage in their vicinities (Fig. 1). An offshore glider transect covered the region out to 20 km offshore from the near-shore outfall to detect offshore transport and subsequent phytoplankton blooms (Fig. 1).

2.3. Effluent characterization used for tracking the plume

The ability of gliders to track both the effluent plume and its influence on the coastal ecosystem required reliable identification of the plume. A variety of approaches have been used previously to map these plumes. Early efforts relied on NH_4^+ and coliform bacteria as unambiguous tracers of the plume as concentrations and abundances of these constituents in effluent exceed ambient values (e.g. Jones et al., 1987). Later work identified the plumes on the basis of temperature, salinity, turbidity, and chlorophyll-*a* fluorescence anomalies (Washburn et al., 1992; Wu et al., 1994). Previous studies in San Pedro Bay used a combination of salinity and fecal indicators to track the plume (Jones et al., 2002). Todd et al. (2009) combined glider measurements of temperature, salinity, and density to detect effluent in water column profiles.

Advances of optical instruments and autonomous underwater vehicles (AUV) have expanded the tools available to track effluent plumes. Recent work showed CDOM is a robust and reliable tracer (Petrenko et al., 1997; Rogowski et al., 2012, 2013). Rogowski et al. (2012) used salinity, temperature, and CDOM measurements from a REMUS (Remote Environmental Monitoring UnitS) to successfully track an effluent plume off the southern California coast near San Diego. Their results demonstrated that tracking the plume using CDOM as a tracer was superior to salinity gradients.

We used low salinity and elevated CDOM to identify the effluent plume with glider data. The inherent variability of vertical profiles made it difficult to identify the plume based on a specific salinity or CDOM value. Instead, we used salinity and CDOM anomalies for individual profiles as evidence of the effluent plume. Our approach was similar to Todd et al. (2009) who used salinity anomalies to identify the effluent plume. Representative profiles of mean salinity and CDOM were created using profiles unaffected by effluent. All glider profiles >12 km from the offshore ocean outfall were used to establish the mean profile free from the effects of effluent. Mean profiles were then used to sort individual profiles. Profiles with salinity anomalies < −0.04 (i.e., value used by Todd et al., 2009), and a corresponding CDOM anomaly >1.25 ppb quinine sulfate equivalents (QSE), were considered plume profiles. This characterization of plume and non-plume profiles was used to track the effluent plume throughout the diversion. Unpaired, two-sample *t*-tests using Matlab were used to determine significant differences of plume and non-plume values at each depth. In addition, large sample sizes supported the use of effect size using Cohen's d, a value that expresses the mean difference between two groups in standard deviation units. Cohen (1988) suggested that d from 0.2 to 0.5 correspond to a small effect size, d from 0.5 to 0.8 to a moderate effect size, and $d > 0.8$ a large effect size.

2.4. Wave glider

Wave Glider SV2 (Liquid Robotics, Sunnyvale, California) is an autonomous surface vehicle that uses ocean-wave energy for propulsion. We equipped the Wave Glider with an above-surface Airmar PB200WX weather station, a SeaBird GPCTD, and a Turner Designs model C3 fluorometer to measure CDOM, chlorophyll-*a*, and crude oil at a depth of 20–30 cm. CDOM and chlorophyll-*a* fluorescence were reported in relative fluorescence units (RFUs) to identify patterns and trends. The Wave Glider was deployed 4 days prior to the diversion on 7 September and was removed on 19 September. It completed six traverses of the near-shore southern glider transect, providing overlapping coverage with the Slocum glider (Fig. 1). CTD data collection ended on 15 September as the CTD was sheared off the Wave Glider.

2.5. MODIS

Ocean color images from the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua satellite at 250 m resolution provided expanded regional coverage of near-surface chlorophyll-*a* and CDOM during the diversion. Previous studies have successfully used MODIS data in the near-shore and shelf region of the Southern California Bight to track surface plumes and phytoplankton responses (e.g., Nezlin et al., 2008; Lahet and Stramski, 2010). We acquired MODIS Aqua data for this study as Level 0 files from the NASA Ocean Biology Processing Group, and processed them to Level 2 using SeaDAS 7.0 software with the NIR/SWIR atmospheric correction. Chlorophyll-*a* concentrations were calculated using the OC2 algorithm, and CDOM absorption (a_g) was determined using the Quasi Analytical Algorithm (QAA) (Lee et al., 2002, 2007). Ocean color images from MODIS-Aqua are described in more detail by Gierach et al. (2017).

3. Results

3.1. Pre-diversion conditions

Slocum gliders were deployed nearly two weeks before the near-shore diversion (29 August to 11 September), providing baseline data for pre-diversion conditions. Pre-diversion conditions showed strong summer stratification with sea-surface temperatures from 18 to 22 °C (Fig. 2A). Monthly sea-surface temperatures (2003–2013) from MODIS Aqua revealed that September temperatures were above average with an anomaly of 1.37 °C (Kudela et al., 2017). The distribution of phytoplankton was characterized by a subsurface chlorophyll-*a* maximum centered at 38.6 ± 6.8 m. Maximum chlorophyll-*a* averaged from all profiles offshore of the shelf break was 6.0 ± 2.2 mg m^{-3} ($n = 870$; Fig. 2B). The subsurface chlorophyll maximum was shallower over the shelf (27.6 ± 5.9 m), with maximum chlorophyll-*a* averaging 5.3 ± 1.8 mg m^{-3} ($n = 923$).

The effluent plume identified by high CDOM and reduced salinity was evident in the section nearest the primary outfall during the pre-diversion period (Fig. 2D–E), but was also observed in both directions along the coast from the outfall. The effluent plume disrupted the subsurface chlorophyll layer as effluent with low chlorophyll-*a* shoaled in the water column. Both the center section and the section to the northwest (left) showed reduced chlorophyll-*a* fluorescence (Fig. 2B), coinciding with the plume identified by elevated CDOM (Fig. 2D).

We used the combination of elevated CDOM and reduced

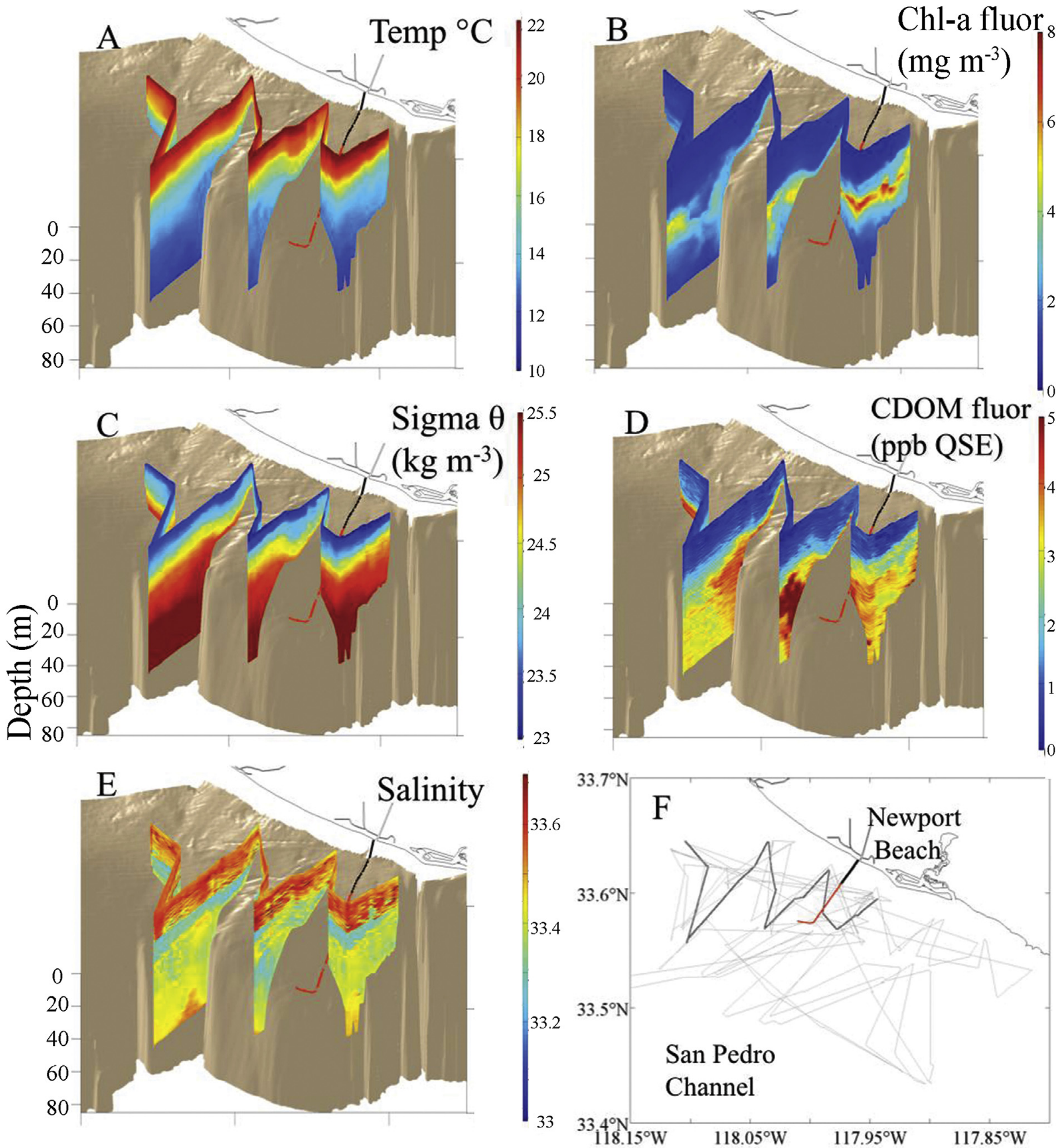

Fig. 2. Example of pre-diversion Slocum glider curtain plots (29 August to 3 September) showing temperature (A), chlorophyll–*a* fluorescence (B), Sigma θ (C), CDOM fluorescence (D), salinity (E), and the path of the transect in dark grey with the transects covered throughout the entire pre-diversion sampling in light grey (F). Coastline depicted on the top, right of each image, and bathymetry in brown beneath the glider curtain plots. Offshore outfall (red) and the near-shore diversion outfall (bold black) are shown offshore from Newport Beach. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

salinity anomalies in glider data to detect plume profiles, enabling us to map the effluent plume during the pre-diversion period (Fig. 3, top panel). Of 1793 pre-diversion profiles, 534 (30%) were considered plume profiles and 1259 (70%) non-plume profiles. Most of the plume profiles were located on the shelf to the west/northwest of the outfall (Fig. 3).

The Wave Glider was deployed on 7 September for four days to obtain pre-diversion surface observations at 20–30 cm depth. Pre-diversion sea-surface temperatures ranged from 20 to 22 °C along the Wave Glider transect (Fig. 4). On-shelf sea-surface temperatures and salinities were lower than off-shelf measurements.

Pre-diversion ocean color imagery from MODIS Aqua for 2 September provided a regional overview of near-surface conditions (Fig. 5, top). The nearshore area within 3 km of shore had elevated chlorophyll-*a* and CDOM signals. However, there were no chlorophyll-*a* or CDOM patterns associated with the outfall pipes during the pre-diversion period. Chlorophyll-*a* was generally <1 mg m^{-3} near the outfall pipes, and CDOM absorption was also low with values less than 0.1 m^{-1}, corresponding to low CDOM concentrations.

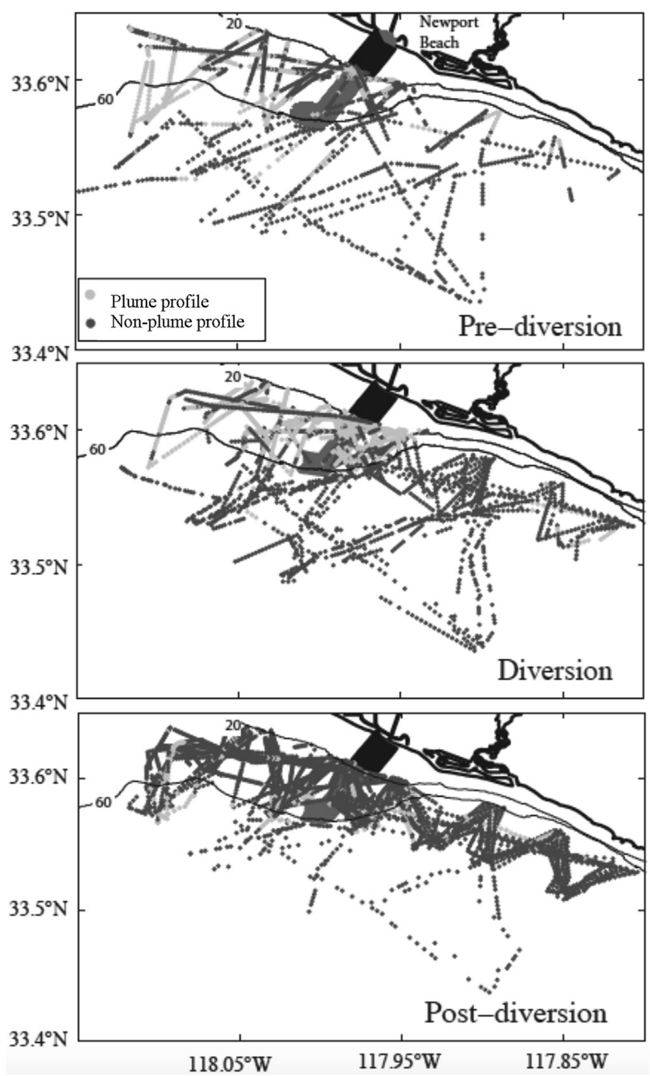

Fig. 3. Locations of plume profiles and non-plume profiles from pre-diversion (top), during the diversion (middle), and post-diversion (bottom). Also, shown is the OCSD offshore outfall (bold dark grey), the nearshore diversion outfall (bold black), and the 20 m and 60 m isobaths.

3.2. Diversion conditions

Mean profiles for each variable were compiled from glider surveys for the 22 d diversion to characterize conditions. The diversion profiles were separated into plume and non-plume profiles to examine the influence of effluent on the coastal ecosystem. The majority of plume profiles during the diversion were located on the shelf west/northwest of the outfall, a distribution similar to the pre-diversion period (Fig. 3, top and middle panels). Warm water persisted at the surface for most of the region throughout the diversion, as during the pre-diversion period (Fig. 6A). However, plume profiles had slightly cooler temperatures in the upper 30 m than non-plume profiles (6A). A subsurface chlorophyll-*a* maximum was a common feature of non-plume profiles throughout the diversion (Fig. 6B). In comparison, plume profiles had increased surface chlorophyll-*a*, with significantly higher concentrations in the upper 33 m than non-plume profiles (*t*-test, $p < 0.05$). We observed a 2–3 fold increase of mean chlorophyll-*a* at depths shallower than 14 m compared to the mean non-plume profile (Fig. 6B). During the diversion, 733 of the 2943 (25%) glider profiles had maximum chlorophyll-*a* in the top 20 m, with a maximum surface chlorophyll-*a* averaging 5.09 ± 2.75 mg m^{-3}. Cohen's effect-size values ($d > 0.8$) for chlorophyll-*a* throughout the upper 12 m confirmed a significant effect of the plume (Fig. 6E). The effect-size values ($0.5 < d < 0.8$) corresponded to a moderate impact from 13 m to 33 m, with little effect size deeper than 33 m ($d < 0.5$). In addition to elevated surface chlorophyll-*a*, plume profiles ($n = 1305$) had significantly lower salinity and higher CDOM than non-plume profiles in the upper 42 m ($n = 1649$), with the largest differences in the upper 20 m (Fig 6C,D,E).

Phytoplankton responses during the diversion were of modest magnitude and patchy spatially, with increased chlorophyll-*a* in close proximity to the effluent plume (Fig. 7B). A notable chlorophyll-*a* feature in the upper water column extended down-coast from the outfall from 29 September to 3 October (diversion days 17–22). Chlorophyll-*a* in this patch exceeded 8 mg m^{-3}, while chlorophyll-*a* fluorescence indicated concentrations <2 mg m^{-3} in near-surface waters for most of the surrounding region, and <5 mg m^{-3} in the subsurface chlorophyll-*a* maximum (Fig. 7B). Increased chlorophyll-*a* directly coincided with increased CDOM (Fig. 7D) and reduced salinity (Fig. 7E) in the effluent plume. The effluent plume of reduced salinity had slightly lower temperatures than surrounding surface waters, reducing the density difference between the effluent plume and the ambient ocean, and perhaps enhancing mixing (Fig. 7A).

We surveyed surface waters using a Wave Glider throughout the diversion area until 19 September. Apparent in Wave Glider data were the patchy distribution of near-surface water affected by the plume and the patchiness of the phytoplankton response (Fig. 4). The distribution of surface effluent, indicated by elevated CDOM and reduced salinity, was patchy throughout the area surveyed (Fig. 4). Chlorophyll-*a* fluorescence as RFU showed a limited increase of chlorophyll-*a* from 11 to 13 and 15–17 September.

Ocean color imagery from MODIS Aqua revealed effects of the diversion on surface chlorophyll-*a* and CDOM (Fig. 5; 20 September and 1 October). Responses were very localized with limited offshore and along-shore signals. Chlorophyll-*a* and CDOM had similar distributions in the region near the outfall pipe. Imagery from 20 September and 1 October showed highest chlorophyll-*a* on the shelf to the west/southwest and a narrow band of elevated chlorophyll-*a* along the coast to the southeast. CDOM values indicative of diluted effluent plume at the surface overlapped with the elevated chlorophyll-*a*. There was good agreement between locations of elevated CDOM derived from MODIS-Aqua imagery and many of the glider plume profiles (Fig. 3; middle panel).

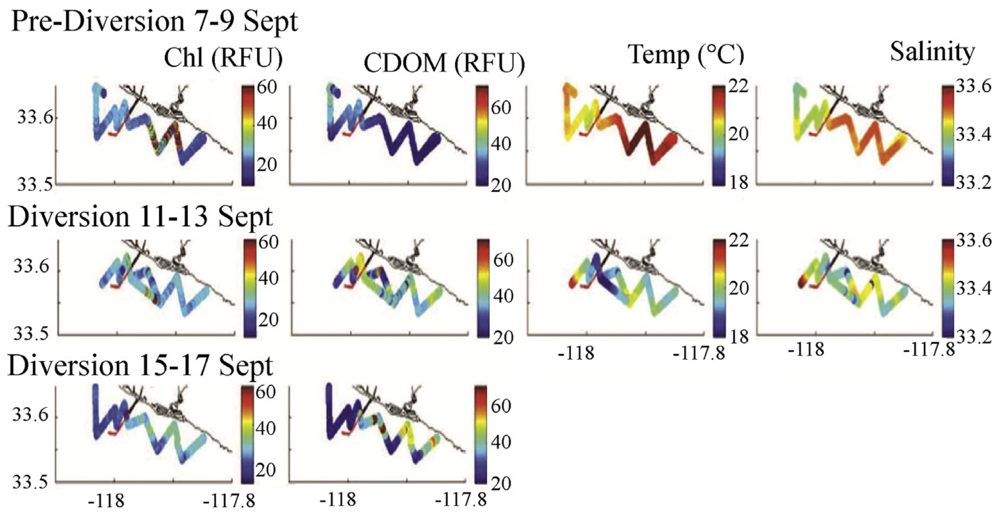

Fig. 4. Maps of chlorophyll-*a*, CDOM, temperature, and salinity at 20 cm depth from Wave Glider for pre-diversion (top panels) and diversion periods (middle and bottom panels). Offshore outfall (red) and near-shore diversion outfall (bold black) are shown. Wave Glider CTD was sheared off 15 Sept and no temperature or salinity data are available after that date. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

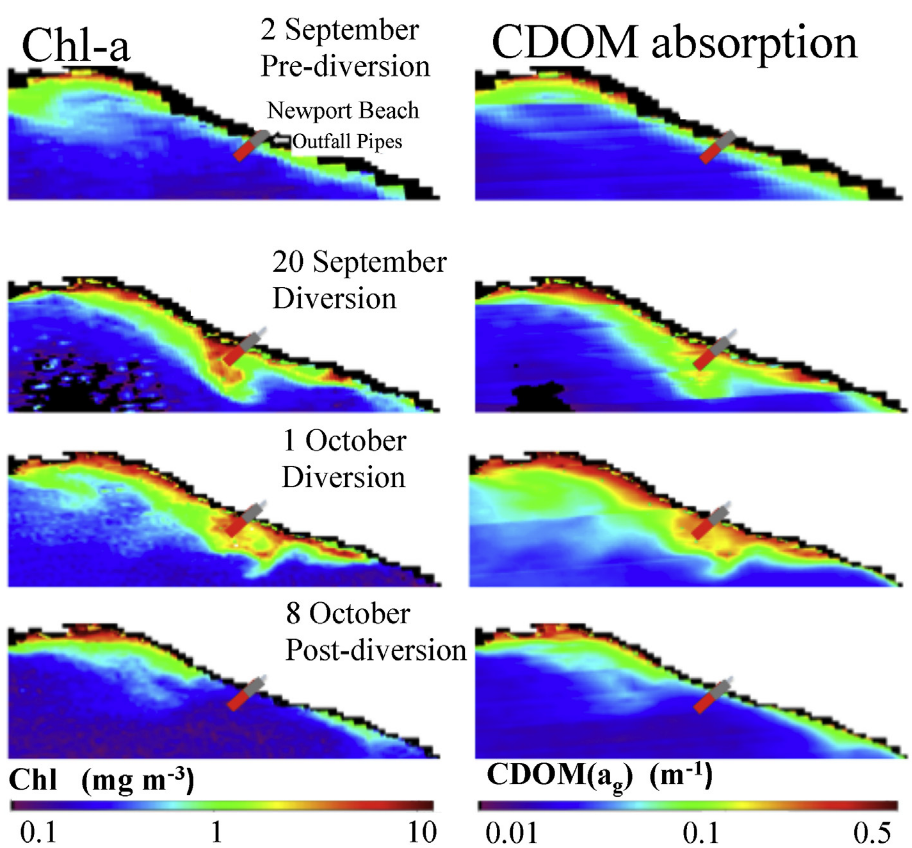

Fig. 5. Pre-diversion, diversion, and post-diversion estimates of chlorophyll-*a* (left panels) and CDOM (a_g) absorption at 443 nm (right panels) from MODIS Aqua. Locations of primary and near-shore outfall pipes are shown in red and grey, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.3. Post-diversion

Water-quality properties measured within 72 h of the end of the diversion retained little evidence of its occurrence. Glider profiles conducted on 5–8 October, 3–6 days after the diversion, showed low surface chlorophyll-*a* accompanied by low CDOM in much of the region (Fig. 8). Ocean color imagery from MODIS-Aqua for 8 October showed no increase of chlorophyll-*a* or CDOM near the outfall pipes (Fig. 5, bottom panel), suggesting the diversion had minimal lasting influence on regional conditions.

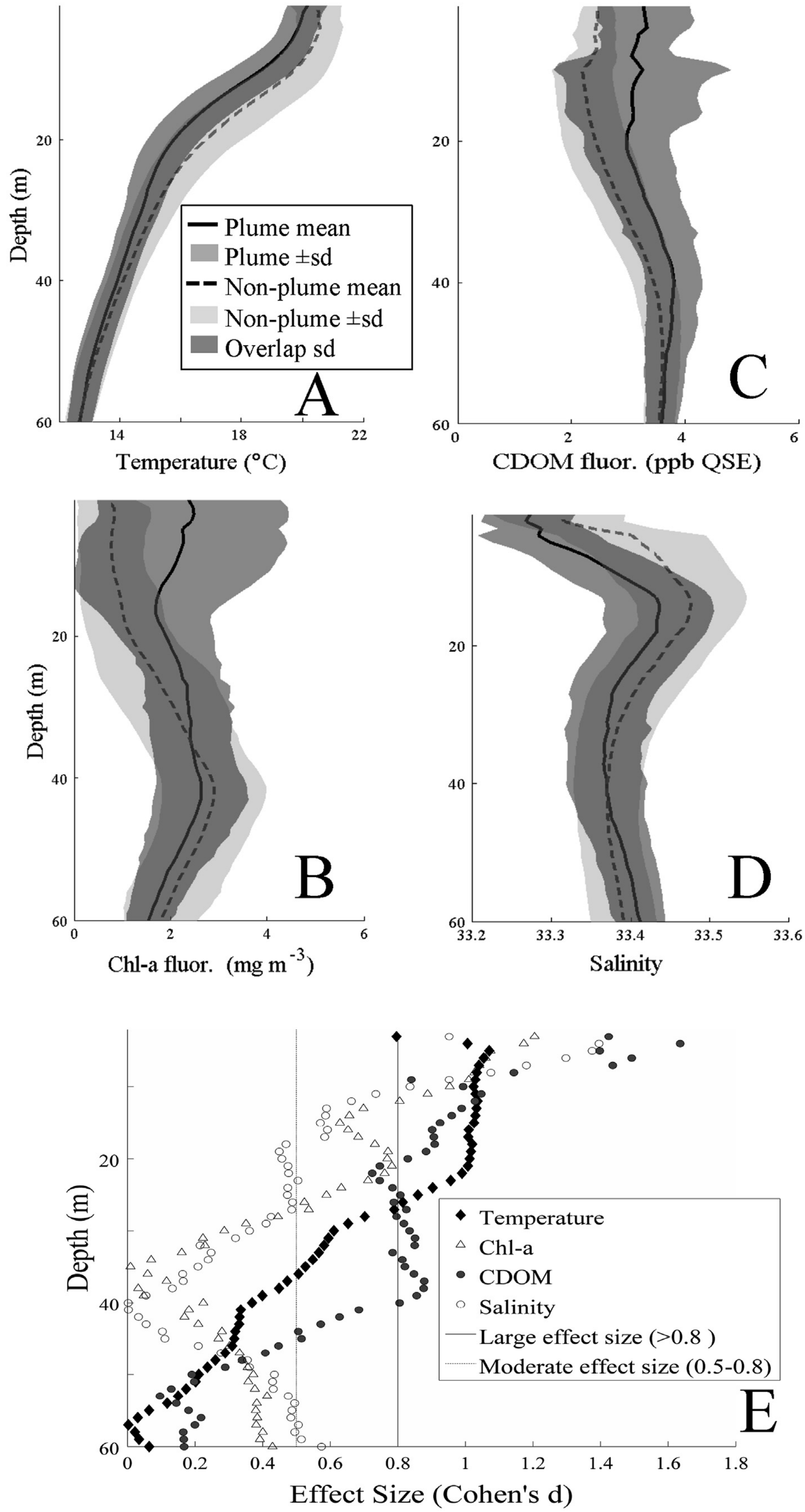

Fig. 6. Glider mean plume profiles and mean non-plume profiles of temperature (A), chlorophyll-*a* fluorescence (B), CDOM fluorescence (C), and salinity (D) ± a standard deviation from throughout the diversion. Also, shown is the profile of the estimated depth dependent effect size (Cohen's d) of each variable (E).

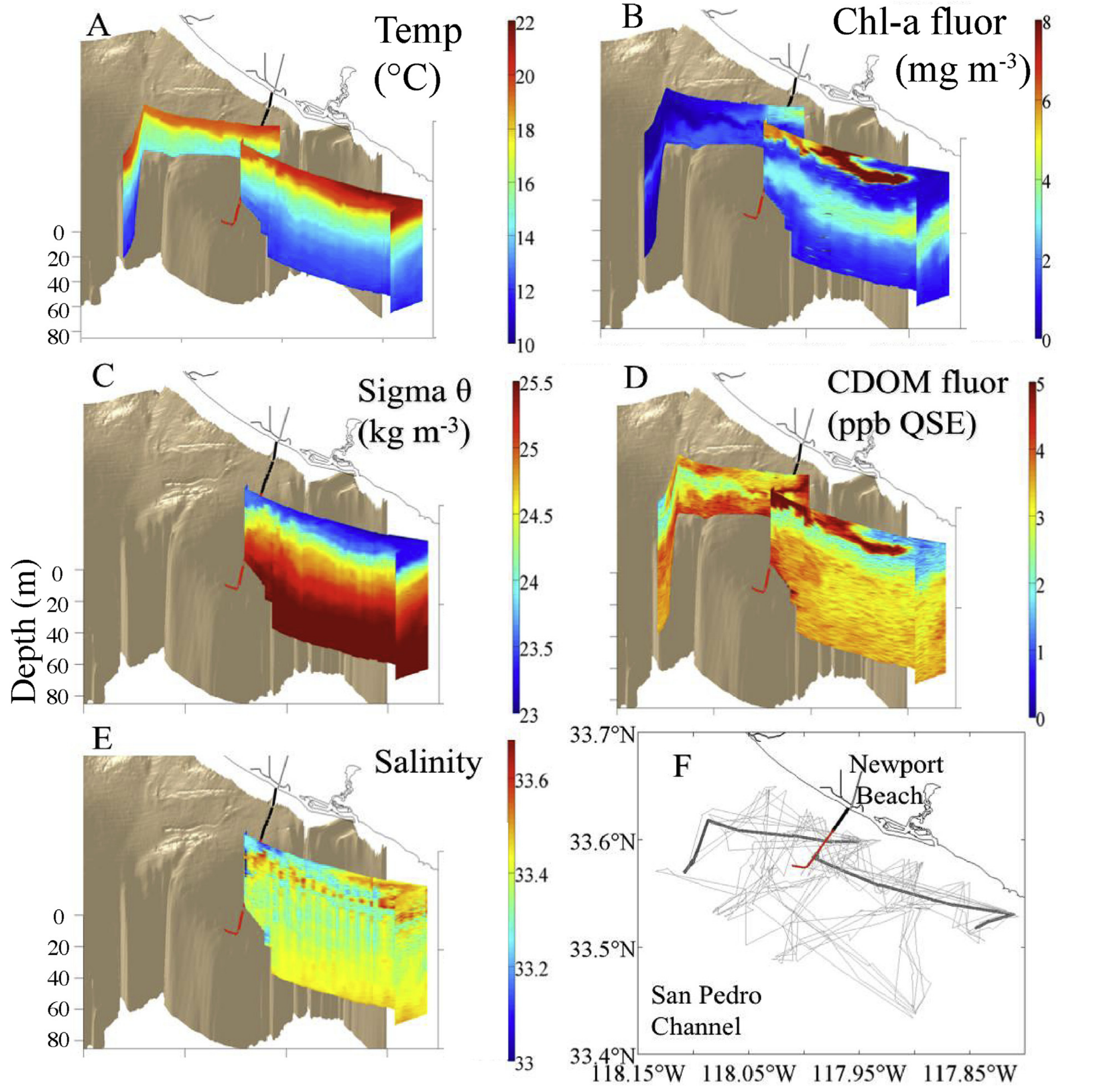

Fig. 7. An example of glider curtain plots obtained during the diversion (29 September to 3 October) showing temperature (A), chlorophyll-*a* fluorescence (B), Sigma θ (C), CDOM fluorescence (D) and salinity (E). Map of glider paths (F) occupied during the diversion corresponding to curtain plots are depicted in dark grey, and all transects in light grey.

4. Discussion

4.1. Impact of effluent diversion on phytoplankton biomass

Multiple data sources using *in-situ* sensors and satellite imagery enabled us to characterize the impact of a three-week effluent diversion by OCSD with high spatial and temporal resolution. The diversion produced a small, local phytoplankton response at the near-shore effluent discharge. This response was less pronounced than predicted by the pre-diversion Environmental Impact Report (OCSD, 2011). Those predictions were based on an earlier diversion in the region (Hyperion Treatment Plant of the City of Los Angeles), however, where a massive phytoplankton response occurred with chlorophyll-*a* >100 mg m^{-3} (Reifel et al., 2013).

Autonomous observations in this study indicated the modest phytoplankton response and short-term impacts of the diversion could be explained, in part, by high mixing rates of the plume into surrounding coastal waters. High dilution rates would limit nutrient concentrations from the effluent and reduce the potential for a large phytoplankton response. Elevated CDOM fluorescence from glider profiles showed the plume was often mixed throughout the surface 40 m (Fig. 6C) compared to the dense surface plume that was observed during the earlier Hyperion diversion (Reifel et al., 2013). Warm ambient ocean water minimized density differences between effluent and the surrounding ocean, possibly allowing increased mixing of low salinity effluent throughout the surface layer.

Differences of coastline topography and the design of the near-shore outfalls for Hyperion and OCSD may also contribute to higher mixing rates of effluent plumes at the OCSD secondary outfall. A

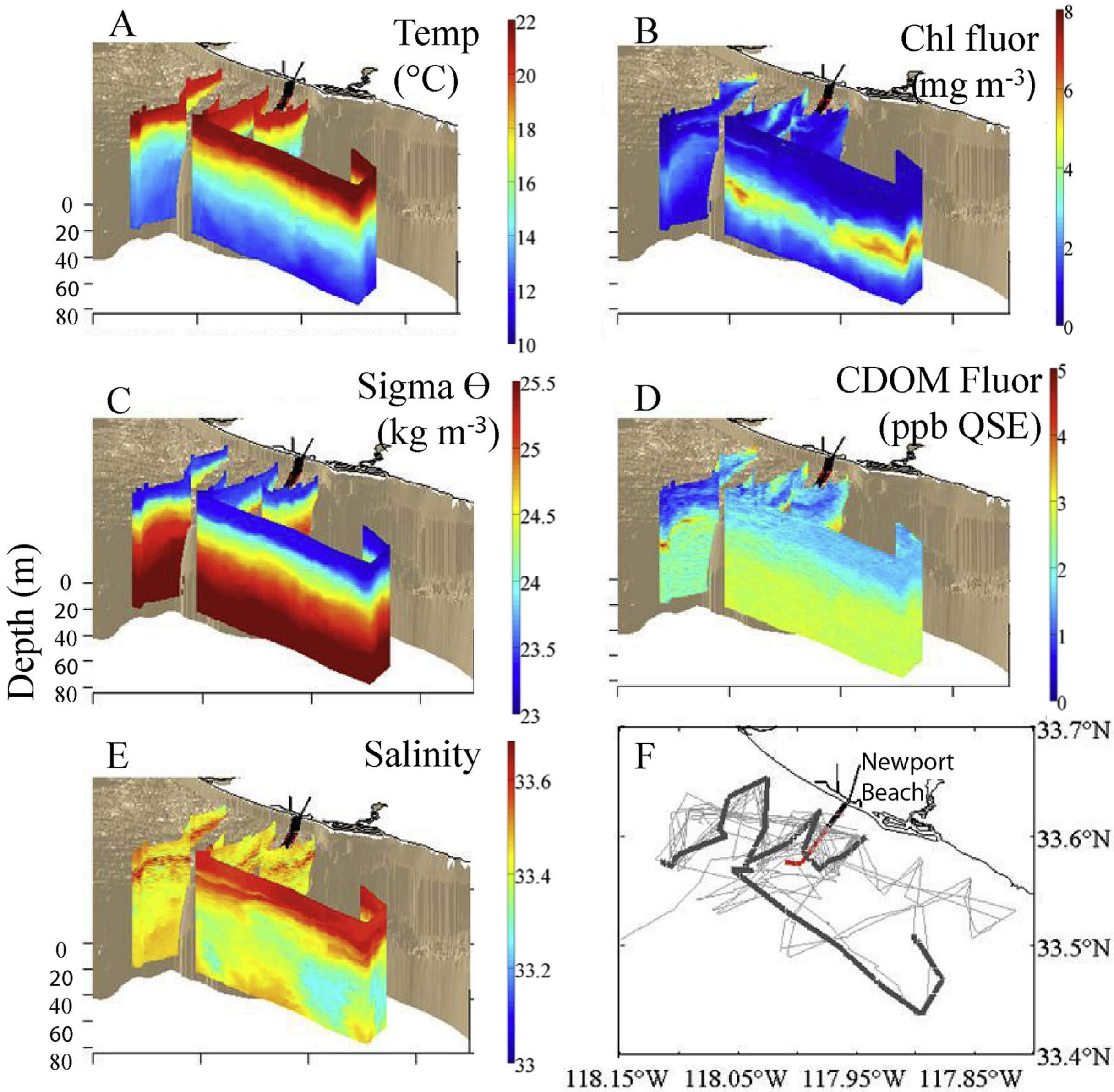

Fig. 8. An example of post-diversion glider curtain plots from 5 to 8 October (3–6 days post-diversion) showing temperature (A), chlorophyll-*a* fluorescence (B), Sigma θ (C), CDOM fluorescence (D) and salinity (E). The map (F) of the transect line presented here for the curtain plots is depicted in dark grey, and all transects conducted during the post-diversion period are shown in light grey.

modeling study of effluent dispersion found Santa Monica Bay documented much higher retention rates when compared to the San Pedro Basin, contributing to higher phytoplankton biomass observed during the Hyperion diversion (Uchiyama et al., 2014). Moreover, the secondary diversion outfall of OCSD includes a long diffuser section that probably increased initial dilution rates (OCSD, 2009) compared to the Hyperion plant that lacks a diffuser discharge. Lagrangian drifters tracked the plume during the diversion using salinity measurements to estimate effluent dilution. These dilutions were generally >100:1 within 500–2000 m of the secondary outfall pipe (Ohlmann, personal communication). In addition, Caron et al. (2017) used salinity measurements on a set of moorings near the discharge to estimate effluent dilution from 100:1 to 1000:1. Comparable dilution estimates for the Hyperion diversion were much lower at 11:1 (Reifel et al., 2013).

Although elevated phytoplankton biomass generally followed effluent plume dispersal throughout the diversion, maximum chlorophyll-*a* measurements were not associated with highest plume concentrations for several reasons: (1) the effluent itself lacked chlorophyll-*a* and we observed the effluent plume diluted or displaced the subsurface chlorophyll-*a* maximum; (2) development of elevated phytoplankton biomass would be expected only after phytoplankton had sufficient time (days) to respond to the nutrient inputs; (3) chemical and biological controls associated with the effluent plume may have limited phytoplankton responses at the highest plume concentrations. Kudela et al. (2017) reported inhibition of photosynthesis by disinfection byproducts released in the plume, and Caron et al. (2017) reported substantial increases of bacterial biomass during the diversion, resulting in significant uptake of nutrients by that assemblage. These factors, together with rapid mixing and movement of the plume documented in this study, precluded the anticipated massive increase of phytoplankton biomass during the OCSD diversion based on the observed response previously from the more northerly Hyperion Treatment Plant diversion.

4.2. Subsurface effluent plume impacts on phytoplankton community

Effluent from the offshore (8 km) outfall of OCSD represents a continuous nutrient input to the San Pedro Shelf spanning > 40 years. During pre-diversion conditions the glider-observed plume reached density equilibrium at 47 m (25.4 kg m^{-3} isopycnal), similar to earlier glider observations in the region (Todd et al., 2009), and to a modeling study that showed the plume stabilized at a depth of 46 m ± 5 m (Uchiyama et al., 2014). Our observations indicate subsurface inputs of anthropogenic nutrients interact directly with the subsurface phytoplankton community (Fig. 2B). Although the extent of plume profiles in our observations is limited, effluent could have a variety of effects in addition to supplying nutrients. The community composition of phytoplankton, including harmful algal bloom (HAB) species, is sensitive to anthropogenic nutrient inputs (e.g. Anderson et al., 2006; Kudela et al., 2008; Loureiro et al., 2009; Glibert et al., 2015). Previous work in the San Pedro Basin demonstrated blooms of toxic *Pseudo-nitzschia* sp. appear in offshore, subsurface waters and can act as seed populations for surface blooms (Seegers et al., 2015). Impacts of effluent on dynamics of the subsurface phytoplankton community thus have ramifications for the San Pedro Basin and deserve further study.

5. Conclusions

The three-week effluent diversion by OCSD to a shallow, nearshore outfall supported a modest stimulation of chlorophyll-*a* in the top 30 m of the water column, although the increase was patchy and short-lived. This phytoplankton response was weaker than anticipated based on a mass balance model and a previous outfall diversion in coastal waters of southern California. The models predicted limited mixing, but observations showed that the effluent plume was often mixed throughout the upper 20 m and at times down to 40 m. Mixing and increased dilution explained, in part, the modest increase of phytoplankton biomass. We suggest the important role of dilution in mediating phytoplankton responses to effluent diversions should be considered by managers to mitigate ecological impacts of outfall repairs and diversions. Our observations demonstrate that subsurface phytoplankton interact with effluent plumes during summer stratified periods characterized by a relatively deep subsurface chlorophyll-*a* maximum. More research is needed to determine long-term impacts of effluent on community composition of phytoplankton, specifically in promoting the occurrence of potentially deleterious HABs.

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