Estuarine, Coastal and Shelf Science xxx (2016) 1–11

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

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

Bridget N. Seegers [a, b, c, *], Elizabeth N. Teel [a], Raphael M. Kudela [d], David A. Caron [a], Burton H. Jones [a, e]

[a] Department of Biological Sciences, University of Southern California, 3616 Trousdale Parkway, AHF 301, Los Angeles, CA 90089-0371, USA
[b] NASA Goddard Space Flight Center, Code 616, Greenbelt, MD 20771, USA
[c] GESTAR/Universities Space Research Association, 7178 Columbia Gateway Drive, Columbia, MD 21046, USA
[d] Ocean Sciences and Institute for Marine Sciences, University of California, Santa Cruz, 1156 High Street, Santa Cruz, CA 95064, USA
[e] King Abdullah University of Science and Technology, 4700 KAUST, 23955-6900, Thuwal, Saudi Arabia

ARTICLE INFO

Article history:
Received 22 October 2014
Received in revised form
8 April 2016
Accepted 20 June 2016
Available online xxx

Keywords:
Phytoplankton
Waste-water treatment
Sewage
Outfalls
AUVs
Southern California Bight

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

* Corresponding author. Department of Biological Sciences, University of Southern California, 3616 Trousdale Parkway, AHF 301, Los Angeles, CA 90089-0371, USA.
E-mail address: bridgetseegers@gmail.com (B.N. Seegers).

http://dx.doi.org/10.1016/j.ecss.2016.06.019
0272-7714/

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

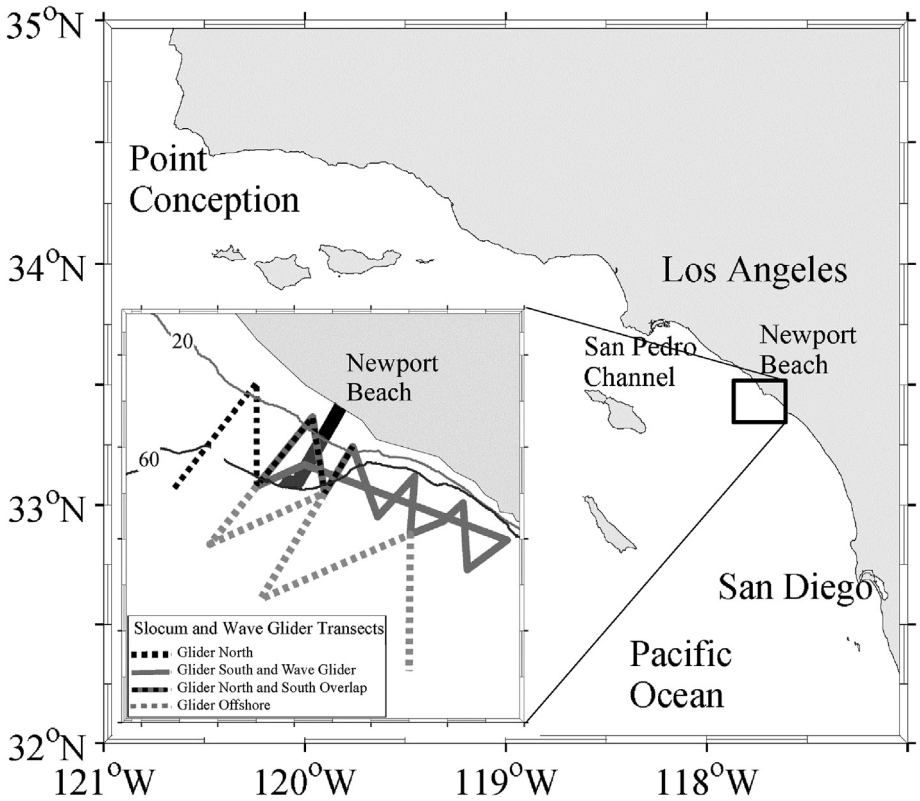

Fig. 1. Southern California Bight with inset indicating the study area for the Orange County Sanitation District diversion. Transect lines are indicated for the Slocum glider and Wave Glider in San Pedro Bay near Newport Beach. Primary outfall pipe (bold dark grey), diversion outfall (bold black), and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

Please cite this article in press as: Seegers, B.N., et al., Glider and remote sensing observations of the upper ocean response to an extended shallow coastal diversion of wastewater effluent, Estuarine, Coastal and Shelf Science (2016), http://dx.doi.org/10.1016/j.ecss.2016.06.019