

Chapter 22

Observing, Monitoring and Evaluating the Effects of Discharge Plumes in Coastal Regions

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Abstract Our ability to predict, observe, and monitor the performance of ocean outfall discharges is rapidly transforming through advances in numerical modeling, remote sensing and underwater vehicle technology. The rapid implementation of sensor and AUV technology has transformed our ability to monitor effluent plumes from coastal discharges of both brine and wastewater. Advances in remote sensing technology provide new views of anthropogenic discharges into coastal seas and oceans. Improved spatial and temporal resolution of coastal models provides more comprehensive dispersion estimates from these discharges. The combined capabilities now provide more detailed observations of the oceanographic processes affecting the dispersion of these discharges and produce statistical maps of the dispersion of properties related to the effluents. These results will contribute to management and design of ocean outfalls and enable better interpretation of discharge effects on coastal ocean ecosystems.

22.1 Introduction

The disproportionate growth of coastal populations globally places increased stresses on the coastal environment (Turner et al. 1996). The increase in population often outpaces the increase in infrastructure resulting in increased loads of terrestrially derived contaminants into coastal oceans and seas. The effects of these discharges can endanger both human health and coastal ecological health, including coastal fisheries (Islam and Tanaka 2004).

Effective wastewater treatment coupled with appropriately designed wastewater discharges provides one mechanism for reducing the effects of coastal contamination

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from populated areas. However, both the design of discharges and appropriate evaluation of the effectiveness of these discharge systems requires sampling and observational capabilities that have only come into maturity within the last few years (Rogowski et al. 2013; Smith et al. 2011).

In order to detect and map ocean discharge effluent dispersion sensors are required that can unambiguously differentiate the characteristic signatures from the discharge affected water from the variations that occur in natural ambient water. It has taken time and innovation to develop appropriate sensors. Even now, with recent sensor progress, not all relevant variables such as bacteria, viruses and specific chemical contaminants of interest can be detected. Therefore, inference of the concentrations and dispersion of contaminants depends on significant correlations between variables that can be easily measured in situ and variables that are elusive or can only be measured in the laboratory.

Public health concerns in the coastal environment usually relate to microbial contamination, especially human pathogens (California Environmental Protection Agency 2012), and to toxins that derive from algal blooms and are often communicated to humans through seafood consumption. The connectivity between human health and human pathogen contaminated coastal waters has been clearly documented (Haile et al. 1999). Sewage outfall discharges are an obvious source of human pathogens to the coastal ocean and the bacteria within these discharge plumes may remain active for several days following discharge (Paul et al. 1997). Toxic or harmful algal blooms are often associated with significant anthropogenic nutrient inputs (Anderson et al. 2008). Sometimes this linkage is less than clear in that it has been shown that in the coastal region of Southern California that the wastewater outfalls contribute a significant amount of inorganic nitrogen into the upper layer of the ocean (Howard et al. 2012).

Detection of change in coastal ecosystems due to chronic contaminant loading often requires more time to establish than is required to detect public health issues. Often, by the time the environmental response to anthropogenic discharge is discovered, the overall effect on the ecosystem may be irreversible. Anthropogenic nutrients that come from sewage effluent, river discharge or groundwater pathways have been suggested to be responsible for the decline of coral reef ecosystems in many locations around the world.

22.2 Approach

Recent advances in sensors, vehicles and modeling techniques have transformed our ability to predict, map and monitor the ocean outfall discharge plumes. These capabilities have resulted in the ability to create more comprehensive statistical products from both modeling and observations that can assist planning, design and implementation of future ocean outfall infrastructure.

22.2.1 Sensors

Beginning in the late 1970s and 1980s sensors began to become available that facilitated the transition in our ability to readily detect outfall plumes in the ocean. Prior to that sampling of ocean plumes required the obtaining of water samples for laboratory analyses of inorganic nutrients, microbial indicator organisms and other relevant constituents that could be measured. Currently there are many sampling technologies available and the proper approach to monitoring and tracking the discharge plumes depends upon the type of discharge (cooling water, desalination brine, or wastewater effluent) and the level of treatment prior to discharge. We use wastewater as a primary example of the capabilities.

Early efforts using CTDs, transmissometers and fluorometers provided the capability to begin to discriminate between effluent plumes in situ and in real time based on the simple partitioning of particles between chlorophyll fluorescent phytoplankton particles and non-phytoplankton particles (Wu et al. 1994). While this analysis was useful, the results were sometimes ambiguous because there can be alternative sources of lower salinity water and suspended particles in the coastal ocean. Subsequent efforts used more sophisticated optical instrumentation that included in situ spectrophotometers and multi-wavelength fluorometers to demonstrate that certain fluorescent signals coming from the dissolved organic constituents of effluent plumes may provide a more specific unique identification of effluent plumes (Petrenko et al. 1997). Following on the multi-spectral fluorescence results, fluorometers that measure colored dissolved organic matter (CDOM) have been adopted for effectively mapping effluent plumes off of Southern California (Rogowski et al. 2013). Although surface runoff may be an additional source of CDOM in the coastal system (Reifel et al. 2009), that runoff is generally constrained to the surface layer of the ocean and can readily be differentiated from the submerged sewage effluent plume via a multidimensional analysis of temperature, salinity, depth and CDOM.

Sensors continue to evolve. Recent developments include a sensor to detect nitrate concentration in the ocean (Johnson and Coletti 2002). While this sensor provides an additional resource in the ocean observing tool box, most often the primary form of nitrogen in wastewater outfalls is ammonium (Jones et al. 1990). At present there is not a rapid, in situ methodology for detection of ammonium in seawater that can resolve ammonium concentrations consistent with physical and optical sensors. Other new technologies include the development of in situ samplers and sensors that have telemetering capabilities. The MBARI Environmental Sample Processor (ESP) enables in situ water sample processing and processing including taxonomic identification of harmful algal species, human pathogens, and detection of toxins such as domoic acid (Scholin et al. 2006, 2009). Under water mass spectrometers have been developed that are capable of resolving gases, volatile organic carbon compounds, and semi-volatile compounds and can be deployed on larger autonomous vehicles (Camilli and Duryea 2009; Camilli et al. 2010; Short et al. 2001; Wenner et al. 2004).

New remote sensing technology provides additional capabilities beyond the early ocean color observations. Ocean color measurements, synthetic aperture radar (SAR), and thermal sensors are capable of detecting signatures from various types of discharges, particularly surfacing discharges. Ocean color measurements provide a unique tool for detecting the ocean color signature from surfacing effluent plumes and from coastal freshwater discharges. Similar to in situ sensing, the signatures of effluent and coastal freshwater plumes, dissolved organic matter absorption and suspended particulate matter are readily detected by ocean color measurements [e.g. Kratzer et al. 2008; Coble 2007; Svejksky et al. 2010; D'Sa and Miller 2003]. Spatial resolution of the major ocean color satellites may be too coarse for detection of some discharges, but airborne imagers such as the AVIRIS or PRISM sensors (Lee et al. 1994), and the HICO imager (Corson et al. 2008) on the International Space Station provide a combination of better spectral resolution and spatial resolution. However, both of these hyperspectral, high spatial resolution sensors lack the ability to routinely monitor a given region for extended periods of time. The Korean GOCI satellite has demonstrated the capability of a geostationary instrument for tracking the dispersion of an effluent field discharged from a ship (Hong et al. 2012). GOCI can obtain up to 8 images per day with spatial resolution of 500×500 m, better than the resolution of MODIS' color bands. But GOCI's coverage area is limited to the region surrounding the Korean peninsula bounded by the East/Japan Sea, Tsushima Strait and Yellow Sea. Additional geostationary satellites in different regions will facilitate the capabilities in other areas where there are significant stressors to the coastal ocean.

22.2.2 *Vehicles*

Through the last few years autonomous vehicles have gained sufficient reliability and endurance to be used for a range of time and space scales and have greatly influenced research approaches. Prior to the development of these vehicles, the field was dependent on the use of traditional station sampling and towed platforms requiring the use of research vessels and significant personnel activity at sea. Autonomous vehicles modify the role of personnel from those needed for the physical acquisition of samples and data to primarily preparation, planning and data analysis.

The simultaneous development of low energy, rapid-sampling sensors and autonomous vehicles has facilitated a dramatic shift in our ability to map and monitor submerged brine discharge and wastewater effluent. Two major types of vehicles provide similar, but complementary types of observations discharge plumes (Fig.22.1). Propelled vehicles, such as the Hydroid Remus, Isurus, or Mares, provide relatively synoptic surveys discharge plumes (Rogowski et al. 2012, 2013; Ramos and Neves 2008). Buoyancy propelled ocean gliders, while not synoptic over their entire survey, can provide a longer term monitoring tool that is capable of weeks to months of sustained monitoring (Todd et al. 2009; Seegers et al. 2014). Depending on the sensor payload, both propelled and glider vehicles can provide characterization

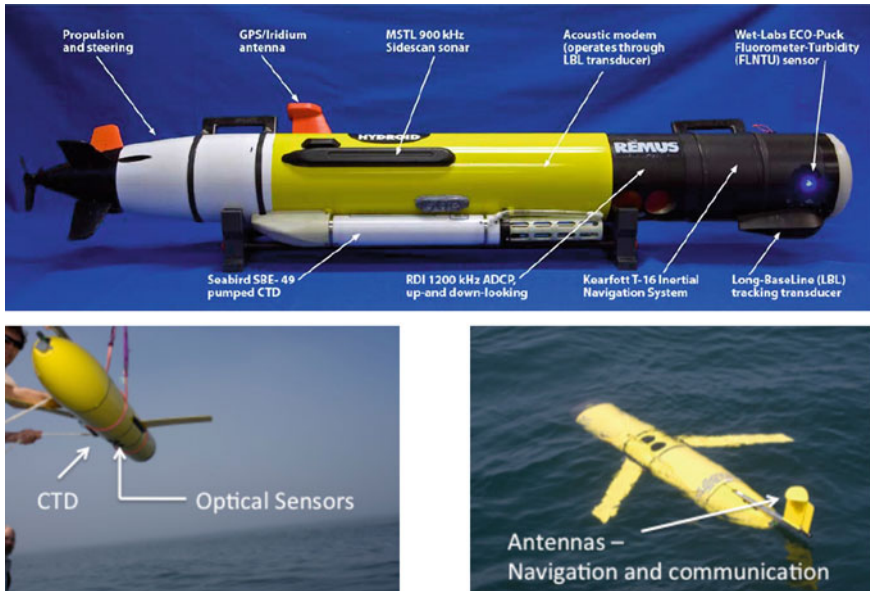


Fig. 22.1 Two types of vehicles that have been used for mapping of wastewater outfall plumes. The *top panel* shows a Kongsberg Remus-100 propelled vehicle equipped with sensors and can provide relatively synoptic maps of a effluent plume. The two *lower panels* shows a Webb Research Slocum glider equipped with a CTD, multi-channel fluorometer, and multi-wavelength backscatter sensor that can be used for long term characterization of effluent plumes

and mapping not only of the discharge plume, but of related environmental variables including temperature, salinity, density, suspended particles, phytoplankton chlorophyll, nitrate nitrogen, ambient light field (radiometry), etc. (Rudnick and Perry 2003). Gliders, in particular, can also provide a near real-time, spatial-temporal data stream of physical data than provide input into data-assimilating four-dimensional coastal physical and ecosystem models that can provide both nowcasts and forecasts of environmental processes in the coastal ocean (Chao et al. 2008).

In the example that is discussed below, the Teledyne-Webb Slocum glider carried a Seabird CTD and two WETLabs EcoTriplet pucks. One puck was configured with three fluorometers (chlorophyll, colored dissolved organic matter (CDOM), and phycoerythrin (PE)). The PE fluorometer can be used for tracer studies using Rhodamine WT because the wavelengths on the PE fluorometer fit the absorption and fluorescence wavelengths for Rhodamine WT, which is a dye that is commonly used in short-term coastal wastewater tracer studies (Bogucki et al. 2005). A second Eco Triplet was fitted with 3 optical backscatter channels selected for 532, 660, and 880 nm. These particular wavelengths were chosen because they are wavelengths where there is minimal absorption by phytoplankton and organic matter. These gliders can also be equipped with dissolved oxygen optodes and nitrate sensors.

22.2.3 Models

Until recently, modeling plumes from various types (thermal, wastewater, desalination brines) of discharges was divided into more empirical near-field models that provided fundamental characteristics of the near-field plume (Roberts et al. 2011) and larger scale ocean circulation models that could provide the far field dispersion, but not the smaller scale entrainment and/or nearshore interactions (Blumberg and Connolly 1996). Improvements to the resolution and parameterization of ocean circulation models has led to the ability to model discharge plumes in the coastal ocean at the scale near to the scale of the larger outfall diffusers (Uchiyama et al. 2014). Uchiyama et al. (2014) created a nested Regional Ocean Modeling System (ROMS) that provided coupling between large scale ocean processes and small scale, 75 m horizontal resolution. The problem that now arises is that the models are capable of providing results at resolutions that exceed our observational capabilities. Nevertheless, these small-scale models now provide a source for meaningful statistics that can be used in the design and management of coastal discharges with relevant forcing from local to large scale ocean processes.

22.3 Examples from Modeling and Observation Efforts

Coastal models with increased spatial and temporal resolution are providing significant insights into dispersion processes in the coastal seas. The results shown by Uchiyama et al. (2014) provide an example of results from an extended model run that includes large scale forcing and local winds. Figure 22.2 shows three examples of dispersion from two large outfalls in the Los Angeles/Orange County region of the Southern California Bight. A number of features are evident in these examples. Three example snapshots from the Orange County Sanitation District's (OCS D) offshore outfall diffuser, located at about 60 m water depth, are shown in the left hand panels and three snapshots from the City of Los Angeles' Hyperion Treatment Plant (HTP) outfall are shown in the right-hand 3 panels. Several conclusions come from these results. Initial dispersion from the outfalls tends to be alongshore in either direction, depending on the prevailing currents and the associated tidal modulation of the mean currents. At times the dispersion can appear quite simple in the alongshore direction as in the example from the OCS D outfall on September 22, 2006. What is not readily apparent in the figure is that there is an additional outfall from the Los Angeles County Sanitation District that discharges 300–400 million gallons per day ($1.1\text{--}1.5 \times 10^6 \text{ m}^3/\text{day}$) of treated wastewater. The outfall is located on the left side of the map where the OCS D plume passes over the Palos Verdes shelf. Thus in a region where there are multiple large outfalls along the coast, the

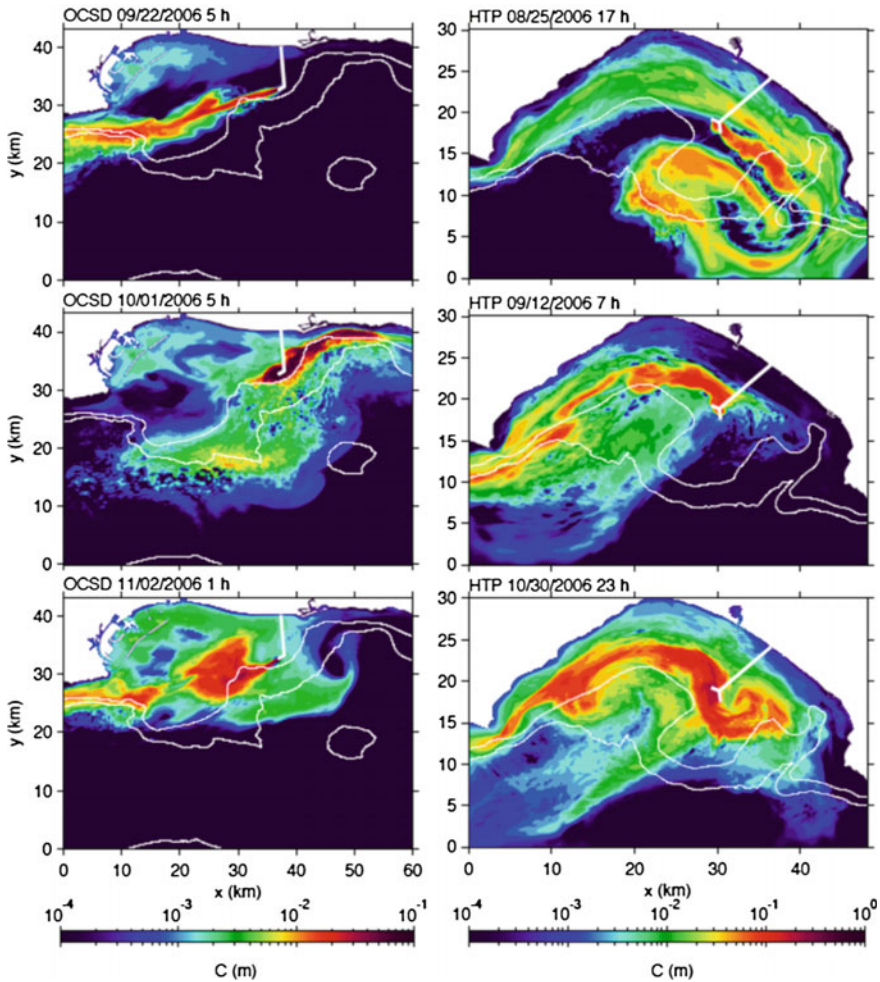


Fig. 22.2 Images of the instantaneous distribution of effluent from two submerged coastal outfalls based on a high resolution ROMS model developed at UCLA (Uchiyama et al. 2014). The three *left hand panels* show dispersion from the Orange County Sanitation District's offshore outfall located in about 60 m water depth. Each panel shows a different distribution taken from different times in the model run. The times are indicated above each panel. The set of images on the *right* are snapshots based on the model of dispersion from the City of Los Angeles' Hyperion Treatment Plant outfall, also located in about 60 m water depth. Again, the 3 snapshots provide distinct dispersal patterns from different times in the model run

plumes may occasionally overlap with one another, and possibly mix with each other. At other times the pattern of dispersion is more complex as the result of the varying currents and associated stratification in the region. The effect of stirring and stretching of these plumes due to current variations is especially evident in examples

from the HTP discharge in Santa Monica Bay. Finally, it is clear that the dispersion processes can transport the effluent plumes for distances that extend for tens of kilometers. It is difficult to map these types of distributions with traditional ship-based sampling. Towed undulating vehicles provide an alternative method for rapid detection of these plumes, but to capture the many patterns of the plume would require extensive days at sea for the ship and its associated vehicle.

22.3.1 AUV Mapping

As previously mentioned, propelled autonomous underwater vehicles (AUVs) provide a means for rapid, synoptic mapping of effluent plumes. Rogowski et al. (2011) used the Remus-100 vehicle equipped with a CTD and fluorometers to map out the discharge from San Diego's Point Loma ocean outfall where the discharge depth is about 93–95 m. Rogowski et al. (2012) showed that effluent dilution could be computed from the CDOM concentration and created dilution cross-sections from the CDOM maps obtained with the resulting maps obtained with the AUV. An example of a CDOM map obtained over the course of several hours is shown in Fig. 22.3.

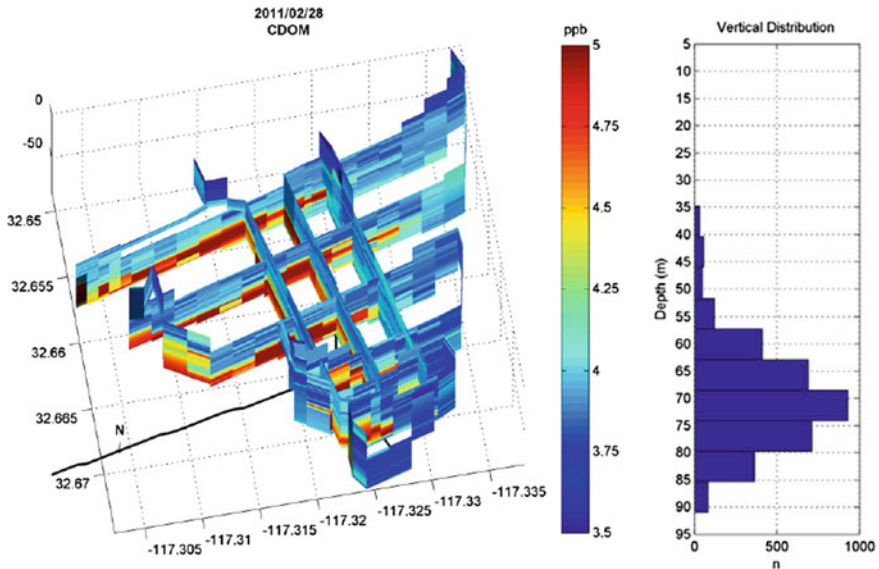


Fig. 22.3 Three-dimensional curtain plot of the distribution of CDOM, a tracer for wastewater effluent, from the San Diego Point Loma outfall. The data was obtained with a Remus AUV equipped with a CDOM fluorometer and other sensors (Rogowski et al. 2012)

22.3.2 Resolving Plumes Dispersion with Autonomous Gliders

Gliders provide another AUV tool for maintaining persistent observations of a coastal region where an outfall diffuser or other type of discharge might be located. While gliders do not have the speed of the propelled vehicles, they have the ability to maintain a multi-week to multi-month deployment with horizontal speeds of about 1 km per hour. Webb gliders have been used actively since 2009 to provide monitoring of the region offshore from the Orange County Sanitation District's Wastewater Treatment Plant discharging into San Pedro Bay south of Los Angeles, California, USA (Fig. 22.4). The basic pattern was a zigzag through the area that required 3–4 days to complete. While the overall pattern was not synoptic, individual transects or portions thereof within the overall pattern provide some synopticity. Overall, the observations provide an extended time series that can be used to provide statistics of the distributions of both water quality measures (temperature, salinity, density, chlorophyll concentration, suspended particulate distributions via optical backscatter) and specific effluent tracers such as CDOM.

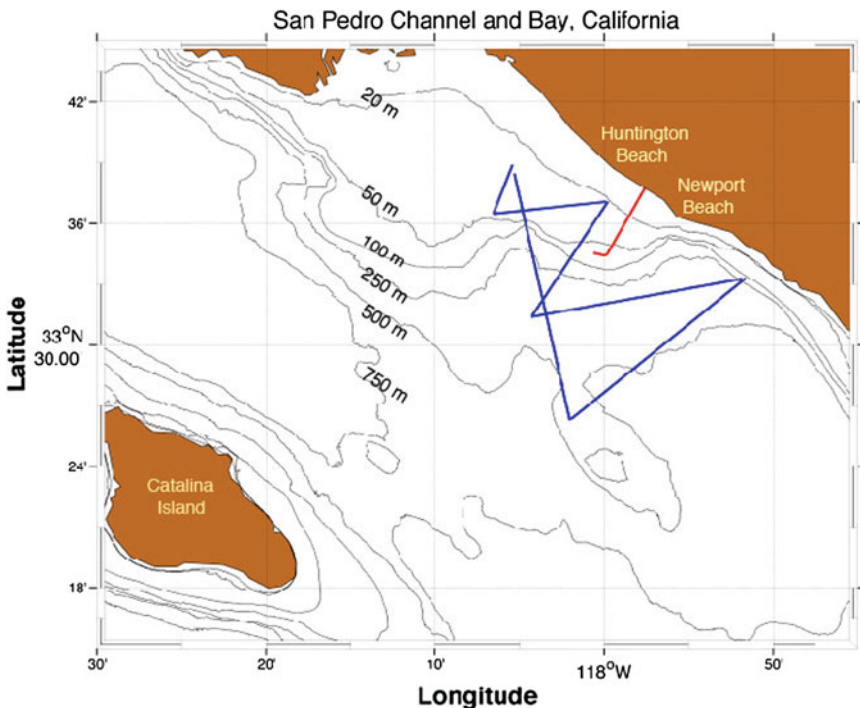


Fig. 22.4 Map of San Pedro Channel/San Pedro Bay region offshore from the cities of Huntington Beach and Newport Beach. The red line is the Orange County Sanitation District's offshore outfall discharging at approximately 57 m depth beneath the surface. The blue line is the programmed track for the glider AUV that was used to map the region between March and June 2010

A single traverse of the pattern provides a 3-dimensional snapshot of the plume over the course of the survey. In one survey from April 7 to 9, 2009, the effluent plume, indicated by the distribution of CDOM, can be observed 10–20 km away from the discharge source, as shown in Fig. 22.5. The figure shows four variables

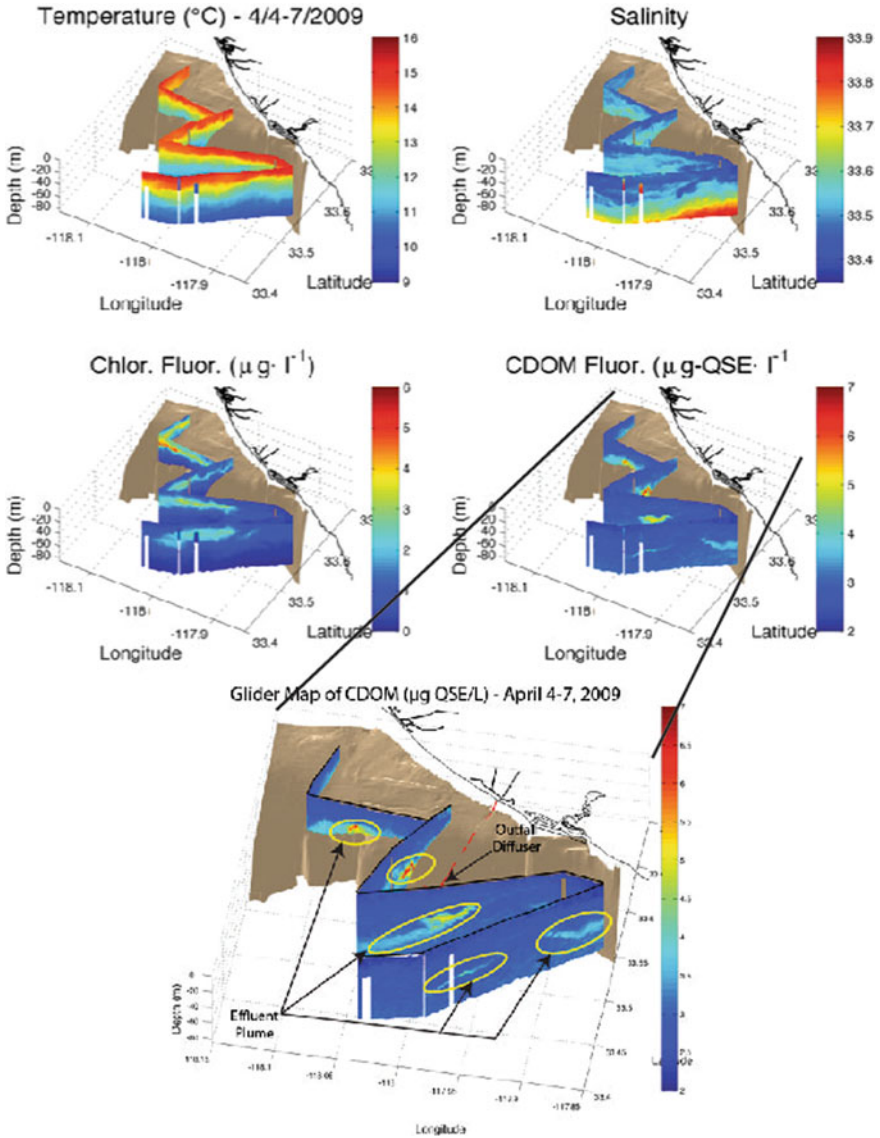


Fig. 22.5 A glider map following the pattern in Fig. 22.4 for the period of April 4–7, 2009. The plot is a 3-dimensional projection of the data where the *tan area* represents the bottom topography and the *black lines* represent the coastline. The outfall location is indicated by the *red line* along the sea bottom in the bottom CDOM panel

that are measured by the USC glider. The CDOM distribution indicates that away from the outfall the plume CDOM concentration decreased presumably due to farfield ambient mixing processes. The plume, in this case, was distributed as several thin patches having cross-shelf spatial extents of several kilometers. These patches were located beneath the pycnocline, satisfying the design specifications that the plume be submerged beneath the pycnocline for a significant fraction of the year. As Rogowski et al. (2012) have demonstrated, dilution maps can be created from the CDOM concentration, provided that calibrations are carried out with the source effluent. These types of results become important for the operators of wastewater treatment plants that discharge into the coastal ocean. The resulting dilution field can help to validate the performance of their outfall diffusers and therefore, establishing compliance with their discharge permits.

An individual cross-shelf transect near the outfall provides an example of the detail that can be resolved from the glider survey (Fig. 22.6). The length of a glider's dive cycle is approximately three times the dive depth. So a dive to 40 m has a horizontal resolution of about 120 and 100 m dive has a nominal horizontal

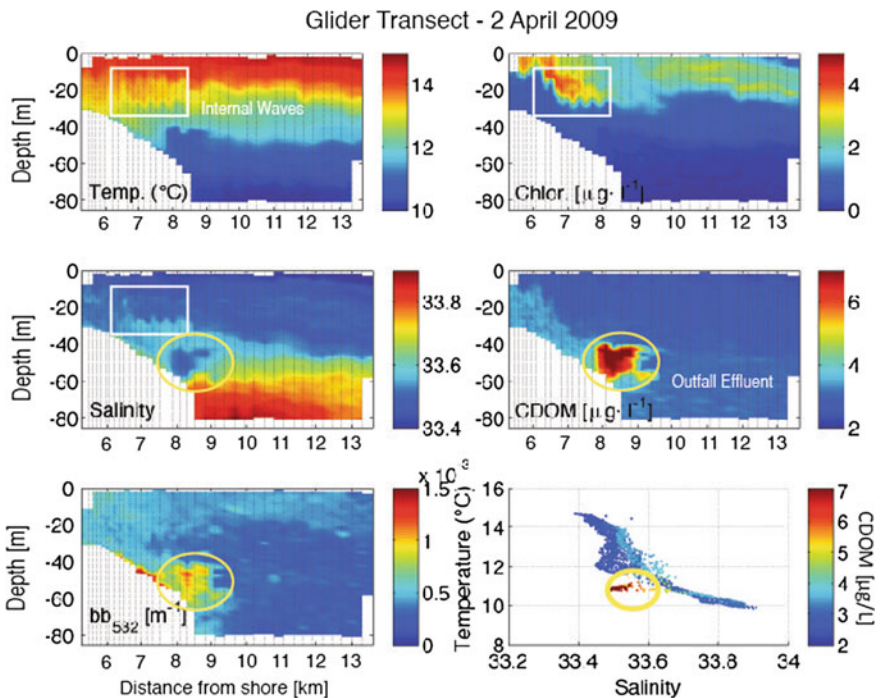


Fig. 22.6 A single cross-shelf section from the glider monitoring of the San Pedro region nearest the OCSO outfall. The continental shelf is indicated by the *white area* in the *lower left hand portion* of each panel. The *white box* outlines an area where internal waves are evident. The *yellow oval* outlines the nearfield region of the outfall plume nearest the outfall diffuser

resolution of 300 m at either surface or bottom of the dive and 150 m at mid-depth. Because the glider passed near the northwest end of the outfall diffuser, the effluent plume is clearly evident in the section (indicated by the yellow oval in Fig. 22.5). The plume is characterized by lower salinity, elevated CDOM concentrations, elevated suspended particle concentration as indicated by the optical backscatter (b_b532), and lower chlorophyll concentration. The lower concentration of chlorophyll results from entrainment of ambient water from the discharge depth that is below the region of high chlorophyll. The CDOM concentration of the plume is higher than the CDOM concentrations offshore between the surface and 85 m. A region of elevated CDOM extends from the shelf break toward the coast within about 10 m of the bottom. Although there are not supporting current meter observations for this period, the CDOM pattern suggests shoreward transport of the effluent plume near the bottom. This type of transport is consistent with near bottom transport driven by internal tides that are frequently observed on the San Pedro continental shelf (Noble et al. 2009). As this feature advects shoreward it rises in elevation above the sea bottom to within 10 m from the surface, as can be seen in the portion of the section nearest the coast (left hand side of sections in Fig. 22.6).

An additional process that is resolved in this section is the presence of internal waves in the thermocline. The internal waves are apparent in several of the measured properties including temperature, chlorophyll, salinity, density (not shown), and subtly in optical backscatter (b_b532) (Fig. 22.6, indicated by white rectangle). The waves first appear just shoreward of the shelf break to about the 30 m isobath where the water column appears to become more mixed, perhaps due to the breaking of the internal waves. The vertical amplitude of these waves is about 5–6 m.

22.3.3 *Providing Regional Statistics*

By sustaining measurements over extended periods of time (weeks–months), it becomes possible to statistically characterize the environment where the discharge is occurring and when the discharge is present to create statistical maps of the presence or impact of the discharge plume. An example in Fig. 22.7 of a statistical analysis of glider observations is from a 3 months deployment between March and June 2010. The region of sampling is the same region that was described above in San Pedro Bay, California.

A three-dimensional projection of the statistical mean and standard deviation fields is shown in Fig. 22.7. The view in this panel is looking toward the coast from the west. Density (left hand panels) and CDOM concentration (right hand panels) are shown in this example. The bottom panels show the number of glider passes that were obtained. The mean and standard deviation panels only display the areas where 10 or more passes are included in the statistics.

Density distribution was relatively uniform over the area during this period. The variability of density is highest in the surface layer and over the shelf. An area of secondary variability occurred in the subsurface region of the pycnocline offshore

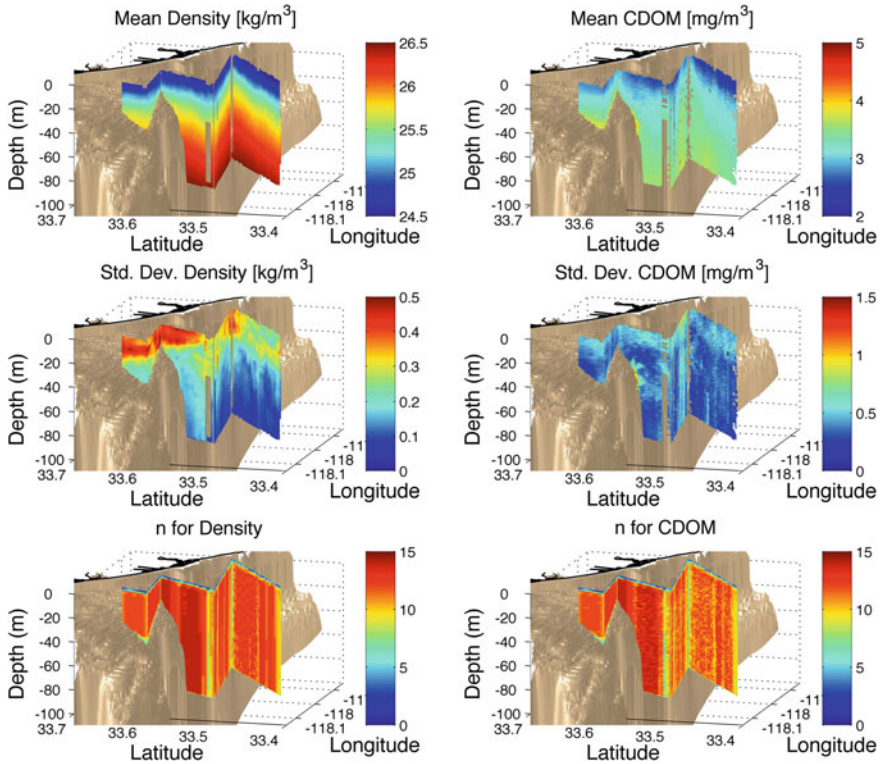


Fig. 22.7 An example of the curtain plot of mean and standard deviation from a total of 15 glider traverses of the overall pattern in Fig. 22.4. The number of occurrences for each gridded data point used in the statistics is indicated in the *bottom panels* where *n* is the number of occurrences for each grid point. The gridded mean and standard deviation panels only display data where *n* is equal to or greater than 10

from the shelf break. Pycnocline location and variability is important to the vertical dispersion of a buoyant discharge and the location of pycnocline variability is important to the effluent dispersion. CDOM also generally shows a stratified distribution with low levels in the upper layer and increasing with depth. This type of distribution is typical in the ocean where near surface organic matter is oxidized by the incoming solar radiation. Higher concentrations are evident near the outfall and close to the coast in either direction from the outfall. The standard deviation indicates where regions of higher variability occur. Again, the area near the outfall is highly variable, and there is a subsurface region to the south (to the right in the image) where high variability is observed near the coast.

Similar to the snapshots shown in Fig. 22.5, an individual transect can be examined for its statistical structure. Using the same transect location that was shown in Figs. 22.4, 22.5 and 22.6, closer inspection of binned data along a single transect line detail can be looked at statistically over time. Figure 22.8 shows the sections of

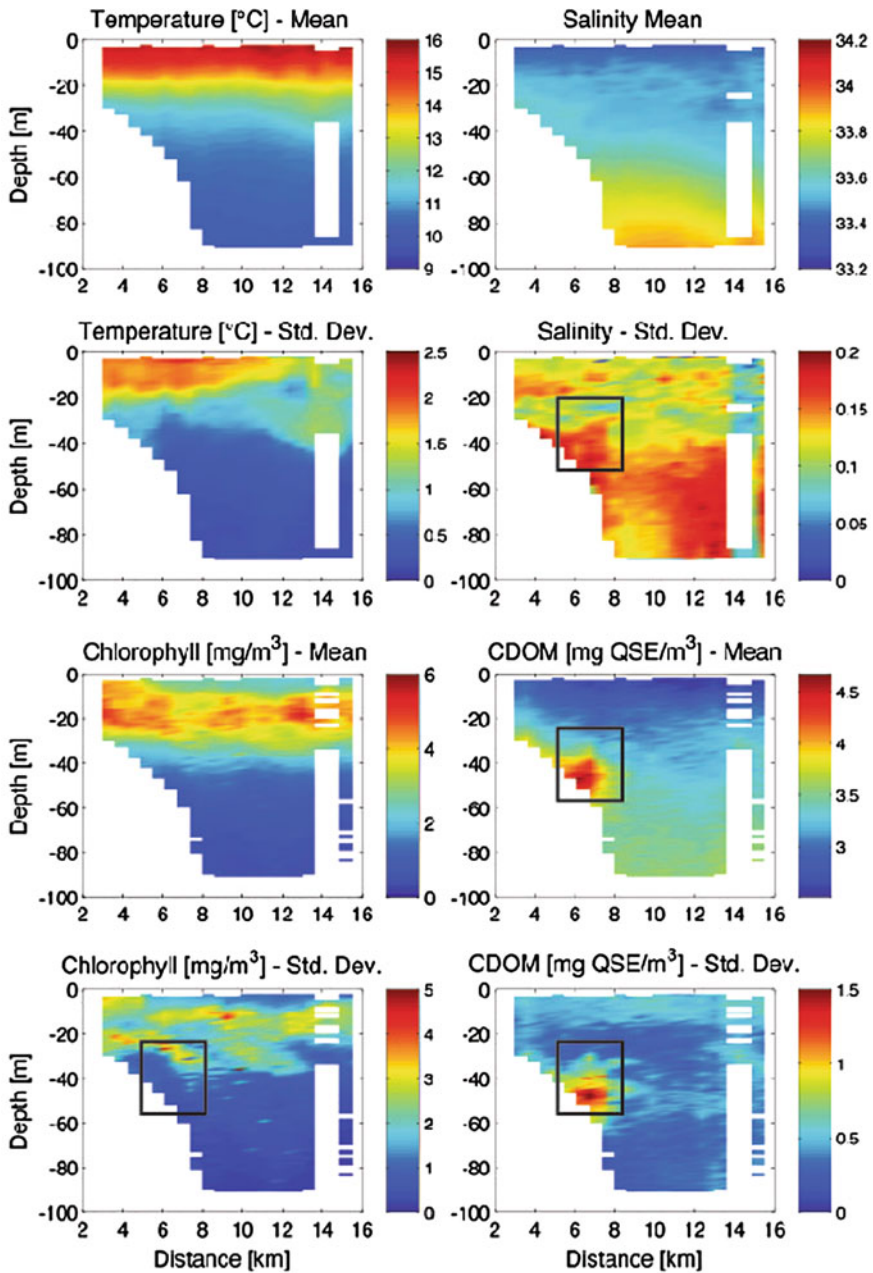


Fig. 22.8 These panels are the statistical distributions for the transect nearest the outfall diffuser. As in Fig. 22.7, only grid points where $n \geq 10$ are shown. The *black box* outlines the area most directly affected by the wastewater discharge

the three-month mean and standard deviation for the variables of temperature salinity, chlorophyll, and CDOM. The mean fields of temperature and salinity do not provide a strong signature from the discharge plume, while the mean CDOM pattern clearly shows high values near the outfall diffuser over the outer shelf. Both the mean and variability are high in this region. The extension of an elevated standard deviation offshore from the outfall, suggest that the plume often extends seaward from the discharge remaining at an equilibrium depth. The shoreward extension of the standard deviation also suggests that this is a recurrent process. Interestingly, the low standard deviation of chlorophyll near the discharge and extending shoreward a bit may indicate that discharge entrainment of the deeper ambient seawater is influencing the chlorophyll concentration in this area. Because it is difficult to match individual snapshots between observations and model runs, the statistics of both may provide a more accurate characterization of the similarity between model and data, as Uchiyama et al. (2014) have described.

22.4 Discussion

Modern observation and modeling tools are providing an unprecedented level of resolution, monitoring, and analysis of dispersion of various anthropogenic discharges into the coastal ocean. Increased resolution of coastal numerical models provides detailed information on the response of these discharges to the spectrum of processes that influence coastal oceans and seas. As mentioned, numerical models are now of sufficient resolution that it is difficult to provide synoptic observations on the same time and space scales to validate the complexity of dispersion that the models provide. The models are also approaching the scale where they may soon be able to account for the nearfield performance of the discharge plumes.

Autonomous vehicles can provide sustained monitoring of ocean outfall discharges, whether wastewater or desalination brine discharges, for periods from months to years. The combined capabilities of numerical models and vehicles provide data sets that allow for unprecedented statistical evaluation of the influence of these discharges on the coastal ocean. Propelled vehicles such as the Remus-100 (Rogowski et al. 2013; Van der Merwe 2014) or Mares (Ramos 2013) can provide unparalleled synoptic resolution of the nearfield plumes from these discharges. Autonomous gliders, while less synoptic, can be deployed for weeks to months providing an extensive temporal and spatial mapping of effluent dispersion. As demonstrated in Fig. 22.5, gliders can also capture snapshots of key oceanographic phenomena that affect discharge plumes, but whose detection may elude more traditional boat sampling. The incorporation of modern optical sensors now provides unambiguous detection and resolution of wastewater plumes and existing temperature and conductivity sensors provide the capability for resolving brine discharges. Mass spectrometers are being deployed on autonomous vehicles (Camilli et al. 2010) for other applications and should prove beneficial for examining discharge plumes. Combining the types of tools used such as autonomous vehicles,

in situ multi-variable sampler such as the ESP, and new remote sensing tools including geostationary (Hong et al. 2012) and hyperspectral imagers such as HICO can provide a high degree of plume resolution and monitoring (Corson et al. 2008). Such extensive temporal and spatial data sets are amenable to statistical analyses for characterization of the ambient conditions and effluent dispersion of the discharge effluent within the often-complex coastal ocean.

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References

- Anderson, D. M., Burkholder, J. M., Cochlan, W. P., Glibert, P. M., Gobler, C. J., Heil, C. A., et al. (2008). Harmful algal blooms and eutrophication: Examining linkages from selected coastal regions of the United States. *Harmful Algae*, 8, 39–53.
- Blumberg, A. F., & Connolly, J. P. (1996). *Modeling fate and transport of pathogenic organisms in Mamala Bay*. Hawaii, USA: Honolulu.
- Bogucki, D. J., Jones, B. H., & Carr, M. E. (2005). Remote measurements of horizontal eddy diffusivity. *Journal of Atmospheric and Oceanic Technology*, 22, 1373–1380.
- California Environmental Protection Agency, S. W. R. C. B. (2012). Water quality control plan: Ocean waters of California. In C. E. P. A. (Ed.), *State water resources control board*. Sacramento, California: State Water Resources Control Board.
- Camilli, R., & Duryea, A. N. (2009). Characterizing spatial and temporal variability of dissolved gases in aquatic environments with in situ mass spectrometry. *Environmental Science and Technology*, 43, 5014–5021.
- Camilli, R., Reddy, C. M., Yoerger, D. R., Van Mooy, B. A. S., Jakuba, M. V., Kinsey, J. C., et al. (2010). Tracking hydrocarbon plume transport and biodegradation at deepwater horizon. *Science*, 330, 201–204.
- Chao, Y., LiZ, J., Farrara, J. D., Moline, M. A., Schofield, O. M. E., & Majumdar, S. J. (2008). Synergistic applications of autonomous underwater vehicles and regional ocean modeling system in coastal ocean forecasting. *Limnology and Oceanography*, 53, 2251–2263.
- Coble, P. G. (2007). Marine optical biogeochemistry: The chemistry of ocean color. *Chemical Reviews*, 107, 402–418.
- Corson, M. R., Korwan, D. R., Lucke, R. L., Snyder, W. A., & Davis, C. O. (2008). The hyperspectral imager for the Coastal Ocean (HICO) on the international space station. In *IEEE International Geoscience and Remote Sensing Symposium, IGARSS 2008* (pp. 101–104). Piscataway: IEEE.
- D'sa, E. J., & Miller, R. L. (2003). Bio-optical properties in waters influenced by the Mississippi River during low flow conditions. *Remote Sensing of Environment*, 84, 538–549.
- Haile, R. W., Witte, J. S., Gold, M., Cressy, R., McGee, C., Millikan, R. C., et al. (1999). The health effects of swimming in ocean water contaminated by storm drain runoff. *Epidemiology*, 10, 355–363.

- Hong, G. H., Yang, D. B., Lee, H. M., Yang, S. R., Chung, H. W., Kim, C. J., et al. (2012). Surveillance of waste disposal activity at sea using satellite ocean color imagers: GOCI and MODIS. *Ocean Science Journal*, *47*, 387–394.
- Howard, M. D., Sutula, M., Caron, D., Chao, Y., Farrara, J., Frenzel, H., et al. (2012). Comparison of natural and anthropogenic nutrient sources in the Southern California Bight. In K. Schiff (Ed.), *Southern California coastal water research project—Annual report*. Costa Mesa, California, USA: Southern California Coastal Water Research Project.
- Islam, M. S., & Tanaka, M. (2004). Impacts of pollution on coastal and marine ecosystems including coastal and marine fisheries and approach for management: A review and synthesis. *Marine Pollution Bulletin*, *48*, 624–649.
- Johnson, K. S., & Coletti, L. J. (2002). In situ ultraviolet spectrophotometry for high resolution and long-term monitoring of nitrate, bromide and bisulfide in the ocean. *Deep-Sea Research Part I-Oceanographic Research Papers*, *49*, 1291–1305.
- Jones, B. H., Bratovich, A., Dickey, T. D., Kleppel, G., Steele, A., Iturriaga, R., & Haydock, I. (1990). Variability of physical, chemical, and biological parameters in the vicinity of an ocean outfall plume. In E. J. List & G. H. Jirka (Eds.), *3rd International Conference on Stratified Flows, 1987 Pasadena* (pp. 877–890). CA: American Society of Civil Engineers.
- Kratzer, S., Brockmann, C., & Moore, G. (2008). Using MERIS full resolution data to monitor coastal waters—A case study from Himmerfjorden, a fjord-like bay in the northwestern Baltic Sea. *Remote Sensing of Environment*, *112*, 2284–2300.
- Lee, Z. P., Carder, K. L., Hawes, S. K., Steward, R. G., Peacock, T. G., & Davis, C. O. (1994). Model for the interpretation of hyperspectral remote-sensing reflectance. *Applied Optics*, *33*, 5721–5732.
- Noble, M., Jones, B., Hamilton, P., Xu, J., Robertson, G., Rosenfeld, L., & Largier, J. (2009). Cross-shelf transport into nearshore waters due to shoaling internal tides in San Pedro Bay, CA. *Continental Shelf Research*, *29*, 1768–1785.
- Paul, J. H., Rose, J. B., Jiang, S. C., London, P., Xhou, X. T., & Kellogg, C. (1997). Coliphage and indigenous phage in Mamala Bay, Oahu, Hawaii. *Applied and Environmental Microbiology*, *63*, 133–138.
- Petrenko, A. A., Jones, B. H., Dickey, T. D., Lenaitre, M., & Moore, C. (1997). Effects of a sewage plume on the biology, optical characteristics, and particle size distributions of coastal waters. *Journal of Geophysical Research-Oceans*, *102*, 25061–25071.
- Ramos, P. A. G. (2013). Geostatistical prediction of ocean outfall plume characteristics based on an autonomous underwater vehicle regular paper. *International Journal of Advanced Robotic Systems*, *10*, 289. doi:[10.5772/56644](https://doi.org/10.5772/56644).
- Ramos, P., & Neves, M. V. (2008). Environmental impact assessment and management of sewage outfall discharges using AUV'S. In A. V. Inzartsev (Ed.), *Underwater vehicles*. Vienna, Austria: I-Tech.
- Reifel, K. M., Johnson, S. C., Digacomo, P. M., Mengel, M. J., Nezhin, N. P., Warrick, J. A., & Jones, B. H. (2009). Impacts of stormwater runoff contaminants in the Southern California Bight: Relationships among plume constituents. *Continental Shelf Research*, *29*, 1821–1835.
- Roberts, P. J. W., Hunt, C. D., Mickelson, M. J., & Tian, X. D. (2011). Field and model studies of the Boston outfall. *Journal of Hydraulic Engineering-Asce*, *137*, 1415–1425.
- Rogowski, P., Terrill, E., Otero, M., Hazard, L., & Middleton, W. (Eds.). (2011). Mapping ocean outfall plumes and their mixing using autonomous underwater vehicles, in international symposium on outfall systems, Mar del Plata: Argentina.
- Rogowski, P., Terrill, E., Otero, M., Hazard, L., & Middleton, W. (2012). Mapping ocean outfall plumes and their mixing using autonomous underwater vehicles. *Journal of Geophysical Research-Oceans*, *117*, Doi: [10.1029/2011gc7804](https://doi.org/10.1029/2011gc7804).
- Rogowski, P., Terrill, E., Otero, M., Hazard, L., & Middleton, W. (2013). Ocean outfall plume characterization using an autonomous underwater vehicle. *Water Science and Technology*, *67*, 925–933.
- Rudnick, D. L., & Perry, M. J. (2003). *ALPS: Autonomous and Lagrangian Platforms and Sensors*, p. 64. Workshop Report. <http://www.geo-prose.com/ALPS>.

- Scholin, C., Jensen, S., Roman, B., Massion, E., Marin, R., Preston, C., et al. (2006). The environmental sample processor (ESP)—An autonomous robotic device for detecting microorganisms remotely using molecular probe technology. *Oceans, 2006*(1–4), 1179–1182.
- Scholin, C., Doucette, G., Jensen, S., Roman, B., Pargett, D., Marin, R., et al. (2009). Remote detection of marine microbes, small invertebrates, harmful algae, and biotoxins using the environmental sample processor (Esp). *Oceanography, 22*, 158–167.
- Seegers, B. N., Birch, J. M., Marin, R., Scholin, C. A., Caron, D. A., Seubert, E. L., Howard, M. D. A., Robertson, G. L., & Jones, B. H. (2014). Subsurface seeding of surface harmful algal blooms observed through the integration of autonomous gliders, moored environmental sample processors, and satellite remote sensing in Southern California. *Limnology and Oceanography* (in review).
- Short, R. T., Fries, D. P., Kerr, M. L., Lembke, C. E., Toler, S. K., Wenner, P. G., & Byrne, R. H. (2001). Underwater mass spectrometers for in situ chemical analysis of the hydrosphere. *Journal of the American Society for Mass Spectrometry, 12*, 676–682.
- Smith, R. N., Schwager, M., Smith, S. L., Jones, B. H., Rus, D., & Sukhatme, G. S. (2011). Persistent ocean monitoring with underwater gliders: Adapting sampling resolution. *Journal of Field Robotics, 28*, 714–741.
- Svejkovsky, J., Nezhlin, N. P., Mustain, N. M., & Kum, J. B. (2010). Tracking stormwater discharge plumes and water quality of the Tijuana River with multispectral aerial imagery. *Estuarine, Coastal and Shelf Science, 87*, 387–398.
- Todd, R. E., Rudnick, D. L., & Davis, R. E. (2009). Monitoring the greater San Pedro Bay region using autonomous underwater gliders during fall of 2006. *Journal of Geophysical Research-Oceans, 114*. Art. C06001, Doi:[10.1029/2008jc005086](https://doi.org/10.1029/2008jc005086).
- Turner, R. K., Subak, S., & Adger, W. N. (1996). Pressures, trends, and impacts in coastal zones: Interactions between socioeconomic and natural systems. *Environmental Management, 20*, 159–173.
- Uchiyama, Y., Idica, E. Y., McWilliams, J. C., & Stolzenbach, K. D. (2014). Wastewater effluent dispersal in Southern California Bays. *Continental Shelf Research, 76*(1), 36–52. doi:[10.1016/j.csr.2014.01.002](https://doi.org/10.1016/j.csr.2014.01.002).
- Van der Merwe, R. (2014). *Marine monitoring and environmental management of SWRO concentrate discharge: A case study of the KAUST SWRO plant*. Thuwal: King Abdullah University of Science and Technology.
- Wenner, P. G., Bell, R. J., Van Amerom, F. H. W., Toler, S. K., Edkins, J. E., Hall, M. L., et al. (2004). Environmental chemical mapping using an underwater mass spectrometer. *Trac-Trends in Analytical Chemistry, 23*, 288–295.
- Wu, Y. C., Washburn, L., & Jones, B. H. (1994). Buoyant plume dispersion in a coastal environment—Evolving plume structure and dynamics. *Continental Shelf Research, 14*, 1001–1023.