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Moored Systems for Time Series Observations of Bio-optical and Physical Variability in the Coastal Ocean

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Abstract

Recently, multi-variable moored systems (MVMS) have been developed to study the ecology and physics of the upper ocean. Concurrent MVMS measurements provide time series of beam attenuation coefficient, stimulated and natural chlorophyll fluorescence, photosynthetically available radiation, and dissolved oxygen along with currents and temperature. MVMS data have been obtained during experiments in the Sargasso Sea (34°N 70°W) and south of Iceland (59°N 21°W). This series of *in situ*, high frequency, long-term observations are the first of their kind in the open ocean and provide an impetus for similar observations relevant to studies of optical variability, primary production, particulate fluxes, and pollution in other oceanographic environments. We are presently utilizing MVMS systems to study problems related to the discharge of wastewaters into the coastal marine environment near Los Angeles. The overall goal of our efforts is to determine how particulate distributions in the vicinity of an ocean outfall change in response to physical and biological processes. These efforts include a benthic component which concerns the resuspension of bottom sediments in response to various physical forcing conditions and a water column component which involves the variability and distributions of effluent and phytoplankton (and their detrital products) particulate matter and their effects upon the subsurface light field.

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Introduction

Many of the major coastal municipalities in the United States and abroad discharge wastewaters into the marine environment; however, the effects of these discharges remain largely unknown. The discharges receive varying degrees of treatment and the locations of the outfalls are generally selected so as to minimize negative impacts to the environment. The dispersion of effluent and associated pollutants in the ocean is primarily affected by 1) the design of outfall diffusers and 2) the oceanic processes which affect mixing and advection. There are several vexing issues concerning these discharges. For example, the effluent of an outfall is typically rich in nutrients which should generally cause increased primary production. However, the particulates associated with the outfall reduce the ambient light level which should cause reduced primary production. Clearly, the time and space scales of primary production are closely tied with both the characteristics of the outfall plume and the ambient physical and bio-optical conditions. In regard to the benthos, rapid dispersion of particulates is generally desirable in order to reduce levels of concentrations of harmful organic and inorganic materials. On the other hand, it is desirable to cover older, more harmful particulates in the bottom sediments with more recent, less harmful particulates.

Much of the previous work, primarily using laboratory and theoretical models, in this area has focused on the design of outfall systems in order to maximize initial dilution of the effluent (e.g., Fischer et al., 1979). Within the past few years, we have done several field studies to examine the variability of physical, chemical, and biological variables in the vicinity of an oceanic diffuser system near Los Angeles (Siegel et al., 1988; Jones et al., 1990; Washburn et al., 1990; Jones and Washburn, 1991; Wu et al., 1991). These unique studies have addressed questions concerning the dispersion of the buoyant effluent of the Los Angeles County outfall. As a result of this work, we have been able to characterize the nature of the dispersion of effluent (e.g., dilution factors) in the far field (on order of 100m to 10km) of the diffuser under several oceanic conditions. In addition, we have begun to address some of the issues concerning the resuspension of sediments associated with the outfall plume (Washburn et al., 1990).

The problems which we are addressing concern the evolution of particulate distributions, both in the water column and in the benthic boundary layer, in the vicinity of the Los Angeles County outfall as forced by physical and biological processes. Particulates discharged from the outfall have been observed both in the water column and in sediments on the sea floor in the vicinity of the outfall. In the past, particulates have often contained potentially environmentally harmful substances including DDT, heavy and trace metals, and bacteria and viruses. The fate of the discharged particulates generally depends on their sizes and buoyancies along with currents and mixing activity. Some of the more harmful substances such as DDT are no longer discharged. While subsequent discharges of particulates may have buried some of the more harmful sediments (such as heavy metals and DDT), the re-exposure of these harmful particulates is of immediate concern (see Sediment Dynamics Workshop Group (SDWG), 1987). It is hypothesized that re-exposure and resuspension of these previously deposited materials would most likely occur during periods of strong physical forcing such as wind events which would result in increased currents and mixing activity. The strong physical forcing would also contribute to reduced deposition rates of particulates being discharged during the events.

Another important aspect which we are studying concerns the effects of effluent discharge and resuspension on primary production in the vicinity of the outfall. The presence of the outfall could have several effects on the abundances and distributions of phytoplankton. The outfall effluent has nutrient concentrations greater than those of the naturally occurring waters and thus phytoplankton concentrations would tend to be enhanced. On the other hand, the light intensity would be depressed because of the particulates associated with the effluent (and perhaps secondarily by the increased light absorption by the phytoplankton), thus acting to reduce production. During storms, it is likely that nutrient rich particulate materials would be entrained from depth and lead to enhanced primary production. At the same time, however, the increased turbidity and light attenuation would tend to suppress production. Because of the various competing processes, it is important to obtain data over sufficiently long time periods to encompass the multiplicity of environmental situations. Bio-optical time series data are essential input parameters for primary production estimates and models.

Background of present study

The Los Angeles County Sanitation District (LACSD), like many other similar municipal organizations in the United States and around the world, utilizes submerged ocean outfall systems to dispose of sewage wastewaters. This method of disposal has several advantages in terms of economy and minimization of societal impact. Although the ocean enables relatively rapid dilution of harmful organic and inorganic substances, the concentrations of the substances and the potential exposure of these substances to the large population of the Los Angeles metropolitan area are of considerable importance. It should be re-iterated that although the present study focuses on the Los Angeles coastal region, the problems addressed are relevant to most major coastal municipalities and can provide important oceanographic information on scales rarely examined in such great detail.

A brief description of the outfall of specific interest here provides some insights into the scope of the problems we are addressing. The Los Angeles County outfall discharges effluent at a rate on order of 350 million gallons per day (or 1.4 million cubic meters per day). The city of Los Angeles discharges at a comparable rate at another site approximately 25km upcoast (following 60m isobath) of the county outfall. Submerged multi-port diffusers (approximating line sources) are located on the ~60m isobath about 2km offshore of White's Point (see Fig. 1 of Wu et al., 1991). The diffusers have been carefully designed to maximize diffusion with the initial dilution ratio being about 100:1 (Fischer et al., 1979) but varying between 80:1 to 300:1 (Mearns and Young, 1983). The effluent rises as a buoyant plume with continuing dilution through mixing with ambient ocean waters. The diluted wastewaters continue to disperse through mixing and advective processes which are highly dependent on both the characteristics of the plume (e.g., buoyancy, etc.) and the prevailing physical oceanographic conditions (e.g., currents, stratification, etc.; see Jones et al., 1990; Washburn et al., 1990; Jones and Washburn, 1991; Wu et al., 1991). The spatial extent of the concentrations of substances (including bacteria) and particulates (through beam attenuation coefficients) associated with the wastewater plume have been described by Jones et al. (1990), Washburn et al. (1990), Jones and Washburn (1991), and Wu et al. (1991). The transport of particulates bearing both harmful inorganic (e.g., heavy and trace metals) and organic (e.g., bacteria and viruses) materials is of interest. The trajectories and residence times of these materials and their dispersal is of concern for public health reasons. The problem of sediment transport and re-exposure of previously deposited effluent particulates for the White's Point region has been reviewed in inconsiderable detail elsewhere (see SDWG, 1987, for summary of benthic related studies).

The White's Point sewage outfall was a primary source of heavy metals and DDT on the Palos Verdes Shelf in the past. However, the mass emission of about 41,000 metric tons of particulates (containing virtually no DDT or heavy metals) in 1986 was less than 25% of that of 1970. The reduced discharge rate has had the effect of decreasing the rate at which previously deposited highly contaminated sediments containing high concentrations of trace metals and DDT are being buried (see SDWG, 1987). The SDWG reported that the highly contaminated sediments are generally buried under ~10-20cm of less contaminated recent sediments with these thicknesses decreasing to ~0-5cm toward both shallower and deeper waters. This has serious implications as the layer of highly contaminated sediments (estimated 200 metric tons or 2 X 10^5 kg of DDT) is exposed in some regions and nearing exposure over a greater area. The SDWG has suggested that the erosion of the contaminated layer began in the early 1980's and that it is likely that storms and subsurface currents have been responsible for this effect. It should be noted that we have observed high turbidity layers (apparently not associated with the effluent plume) with spatial extents greater than 3km during moderate current conditions (7cm/sec) (Washburn et al., 1990).

During previous studies, our group collected current and temperature data using vector measuring current meters (e.g., Steele, 1986; Steele and Bratkovich (see SDWG Report)). Monthly mean currents were ~12cm/sec at a depth of 34m during

February-April at the mooring site near the White's Point outfall (~2km upcoast) on the 60m isobath used by our group in 1985 (e.g., Steele, 1986). This is the same site we are occupying for the present study (see Fig. 1 of Wu et al., 1991). The currents were primarily directed alongshore, generally upcoast but also downcoast with maximum speeds of ~30cm/sec. The cross-shelf component was considerably weaker (generally <10cm/sec). It is important to note however that there was nearly equal probability of onshore versus offshore flow, which has important implications for the shoreward transport of potentially harmful substances such as bacteria and viruses. Spectra for the alongshore and cross-shelf components of currents indicated significant energy levels at the semi-diurnal and diurnal tidal frequencies. Our group's data suggest that it is possible that nearly continual erosion is occurring with the more intense forcing episodes resulting in significantly greater erosion of the sediments (Washburn et al., 1990; Wu et al., 1991).

The SDWG has also indicated that sediments near the outfall are characterized by the absence of oxygen, nitrite, and nitrate and the presence of hydrogen sulfide in the upper centimeters of sediment. Finally, the SDWG has stated that the reduction of solid emissions from the outfalls will lead to increased risk of biological excavation of deeper lying contaminants. For these reasons, the turbidity and primary production of waters in the vicinity of the outfall are of interest to local sanitation districts. In addition, they are interested in minimizing the degradation of the light field. It should be noted that the entire ecosystem, including higher trophic levels, in the vicinity of the outfall is dependent both on the primary production and the light field.

The attenuation of light in the water column of interest here is affected by 1) pure seawater, 2) living particulate matter (phytoplankton), 3) non-living detrital matter associated with marine organisms, 4) dissolved organic matter, and 5) effluent particulate matter. The particulate fields associated with the outfall effluent are significant and have been mapped using beam transmissometer measurements (Jones et al., 1990; Washburn et al., 1990; Jones and Washburn, 1991; Wu et al., 1991). Vertical contour sections of beam attenuation coefficient (c in m^{-1}) along the ~60m isobath (sampling done along dashed line shown in Fig. 1 of Wu et al., 1991) were done during a weak current regime (~1cm/sec upcoast; case 1) and during a stronger current regime (~7cm/sec downcoast; case 2). High values of the beam attenuation coefficient were associated with the effluent from the two diffusers which was evident for case 1. When the currents were greater (case 2), there was considerably more dispersal of the effluent (lower values of the beam attenuation coefficient). Interestingly, clouds of sediment were evident during this period. The particulates associated with the effluent were distinguished from those of the sediments by considering salinity-beam attenuation coefficient scatter plots. Beam transmission data can be used to infer particulate concentrations to some degree (e.g., Spinrad, 1986). However, they cannot be used to distinguish between living (e.g., phytoplankton) versus non-living materials and because the measurement depends on the optical properties of the particles (e.g., size distribution, refractive index, etc.), it is important to collect *in situ* water samples to develop robust relationships between the observed beam attenuation coefficient and the inferred particle concentrations. *In situ* fluorometer data have also been obtained and can be used to distinguish the phytoplankton component from other components (effluent and sedimentary particulates).

There are several interesting processes which can possibly occur in the vicinity of the outfall. For example, the effluent has high concentrations of discharged particulates, thus reducing the light field and impairing primary production. However, the effluent also has elevated concentrations of the nutrients ammonia and phosphate, thus enhancing production. These two competing effects set up a classic question: Is the primary production limited by nutrients or light? Clearly, the time and space scales of variability of the discharged particulate field are important in establishing the accompanying distribution of primary production. To our knowledge, no observations of the relevant bio-optical parameters have been done yet. We are in the process of obtaining concurrent data on appropriate time and space scales in order to examine the impact of the outfall effluent on both the light field and primary production.

There have been several studies in the vicinity of the White's Point outfall which collectively provide an excellent starting point to address the questions posed here. It should be noted that the White's Point outfall region is one of the (if not the) most frequently studied outfalls in the world and thus it is an extremely attractive area for our studies in terms of the potential for scientific advancement as well as societal impact.

Present observational activities

The present field effort entails multi-variable moored system (MVMS) time series measurements of physical and bio-optical variables (Fig.1). The MVMS mooring data will be complemented with spatial mapping data analogous to the mooring data, benthic flux data, viral data, and benthic sediment core data being obtained collectively by several collaborators (e.g., Jones, 1991; Wu et al., 1991; Berelson, 1991; Fuhrman, personal communication; LACSD). The goals of the study are to 1) improve understanding of the marine environment where discharges are made, 2) characterize the fate and potential effects (e.g., variations in toxicity and primary production) of discharges in the marine environment under a variety of oceanic conditions, and 3) acquire data sets which can be used for modeling of discharges and their effects on the environment.

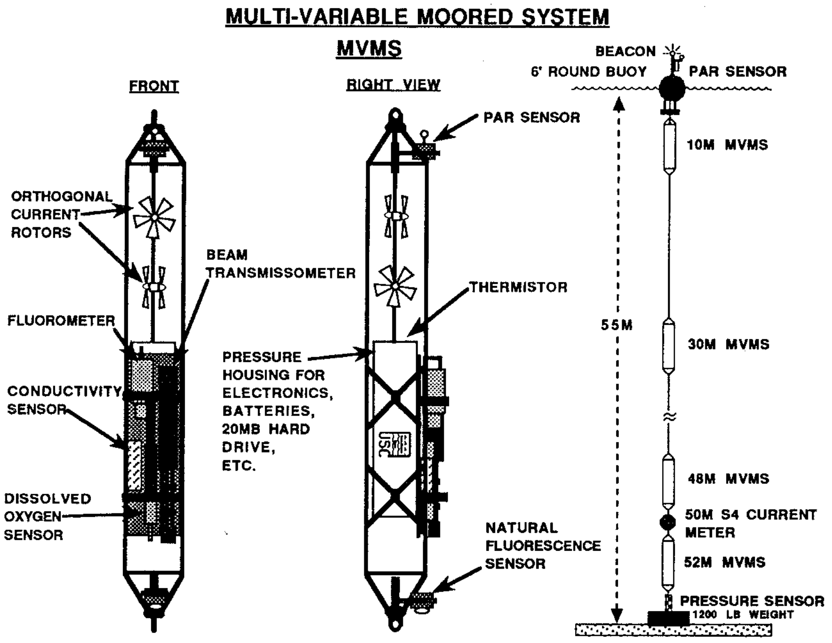

Figure 1. The multi-variable moored system (MVMS) and the White's Point mooring array including MVMS's, a surface PAR sensor, an S4 current meter, and a bottom pressure sensor. Schematic is not to scale.

The MVMS was developed within the past few years (Dickey, 1988; Dickey et al., 1990, 1991; Dickey, 1991). These systems were successfully utilized to collect physical and bio-

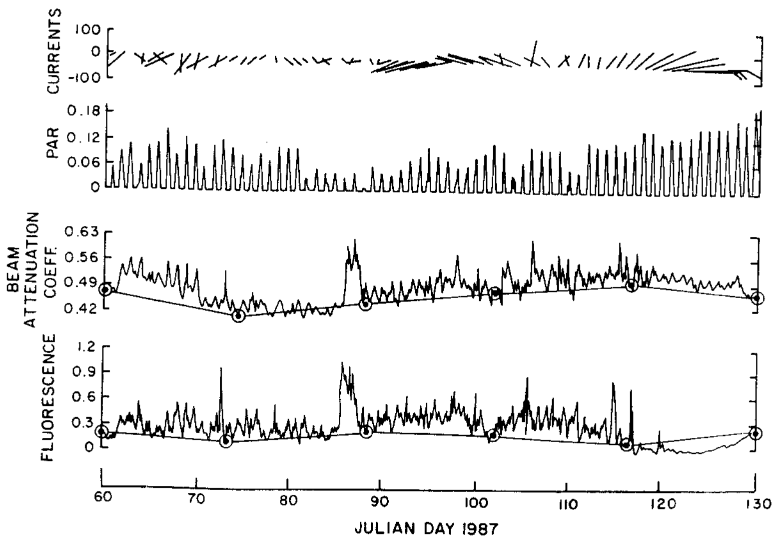

Figure 2. Time series current (daily averages) and bio-optical data (2h averages) collected with MVMS's in the Sargasso Sea in the spring of 1987 on an MVMS located at 20m depth. Parameters include: currents, photosynthetic available radiation (PAR), beam attenuation coefficient, *in situ* fluorescence, and dissolved oxygen.

optical time series data (sampling once per minutes) at 7-8 depths in the upper 160m in the Sargasso Sea for a 9 month period in 1987 (during the Biowatt experiment). The data set is presented elsewhere (Dickey et al., 1990; Hamilton et al., 1990; Dickey et al., 1991; Dickey, 1991); however, a portion is briefly described here for background. Time series of daily currents and 2h filtered photosynthetic available radiation (PAR), beam attenuation coefficient, and chlorophyll fluorescence for an MVMS (Biowatt data) at 20m are shown in Fig. 2. The bio-optical variables (beam attenuation coefficient and chlorophyll fluorescence) exhibit strong diurnal rhythms and large episodic changes with phytoplankton blooms and cessations. Bi-weekly subsampled data points are indicated in order to illustrate the importance and necessity of high frequency sampling (see Dickey et al., 1991; Dickey, 1991).

A mooring was recently (January 3, 1991) placed at the ~55m isobath approximately 2km upcoast of the Los Angeles County outfall diffusers which are also within a few meters of this isobath (see Fig. 1 of Wu et al., 1991). Mooring measurements will continue through early March, 1991. This is the site which we have used in our previous outfall studies (e.g., Steele, 1986; Siegel et al., 1988; Jones et al., 1990; Washburn et al., 1990; Jones and Washburn, 1991; Wu et al., 1991). MVMS units were placed on the mooring at depths of 10m, 30m, 48m and 52m (Fig. 1).

For the present study, MVMS units located at 10 and 30m are being used to measure horizontal currents, temperature, conductivity (for salinity at 10m only), beam attenuation (for water clarity/turbidity), stimulated and natural chlorophyll fluorescence, photosynthetic available radiation, and dissolved oxygen (Fig. 1). Temperature, conductivity, and current data will be used to characterize the physical environment. The beam transmissometer data will be used for particulate concentration and particle production determinations. The photosynthetic available radiation, natural fluorescence, chlorophyll fluorescence, and dissolved oxygen data along with the beam transmissometer data will be used for production determinations (see Dickey, 1991). The salinity (from conductivity and temperature data) and beam transmission data will also be used to distinguish effluent water masses from resuspended bottom particulate laden water masses as we have done in the past.

The 10m instrument resides in the mixed layer and will be particularly important for studying bio-optical processes (e.g., primary production) and its data will be used in combination with the 30m instrument data to determine near surface stratification, shears, advection, etc. The 30m MVMS is important for determining effluent plume characteristics and for primary production determinations as well as for stratification and shears (between both 10m and 30m and between 30m and 48m). It is possible that this particular instrument may at times lie within both the surface mixed layer and the bottom Ekman layer during portions of the winter season.

The instruments at 48 and 52m are being used to collect data relevant to bottom boundary layer and benthic processes. Thus, the measurements will include currents, temperature, and beam attenuation (excluding the other optical measurements described above). The bottom boundary layer can be divided into two separate layers: an inner layer with strong velocity shear in close proximity with the bottom and an outer layer (Ekman layer) which is influenced by rotational effects as well as flow outside the boundary region. An additional current meter (an S4 electromagnetic current meter) will be placed at 50m. This current meter along with the MVMS at 52m will generally reside in the constant stress layer (logarithmic current layer). Using the currents from these bottom instrument depths, time series of bottom stress can be determined. Bottom stress is an important parameter, because values greater than a critical bottom stress will result in resuspension of bottom sediments. This critical stress is dependent upon the density and size of the sedimentary particles and a parameter which is obtained from Shields curves (e.g., Mantz, 1977). The critical current speeds can be estimated using Shields curves and the empirical relation $\tau = 0.03\ \rho U^2$ where ρ is water density and U is the current speed outside the boundary layer (e.g., Weatherly and Van Leer, 1977). Using data taken from the outfall site (Wang, 1988), we estimate the critical speed to be ~2 cm s^{-1} (Washburn et al., 1990). The combination of transmissometer data obtained from 48 and 52m will be important for estimating vertical gradients in particle concentrations which may be used to estimate vertical particle fluxes as well as for estimating near bottom mass transport. The modeling work of Grant and Madsen (1979) suggests that the combination of wave-driven and longer time scale currents is important for sediment resuspension. For this and other purposes (e.g., physical forcing characterization), we are also collecting meteorological data (barometric pressure, wind speed and direction, air temperature, relative humidity, and incident shortwave solar radiation) from a nearby shore station, PAR from the surface mooring buoy, and bottom pressure data using a transducer placed on the bottom weight of the mooring.

The sampling rates for the 2 month observational period are as follows: MVMS - 1 per min, S4 current meter - 1 per 10min, meteorology - 1 per min, and bottom pressure - 1 per 2sec. The time series data will be analyzed using statistical, spectral, and cross correlational techniques. The observational program has the following major components: 1) time series physical and bio-optical measurements obtained from the mooring described here, 2) spatial mapping of *in situ* physical and bio-optical properties (Wu et al., 1991; Jones and Washburn; 1991), 3) aircraft overflights to obtain high resolution color imagery relevant to spatial variability in the phytoplankton distributions (Curt Davis, personal communication) 4) benthic flux sampling (Berelson, 1991) and benthic sediment core sampling (LACSD), and 5) distributional sampling of viruses and their relation to the ecosystem (Jed Fuhrman, personal communication). The suite of measurements are complementary and are intended to enable a comprehensive examination of a multiplicity of inter-related problems of common concern.

Summary

Two major problems are being considered: 1) the effect of a discharged sewage effluent on the subsurface light field and primary production and 2) resuspension of bottom sediments. The study is taking place at a coastal site near Los Angeles (White's Point). The quantification and modeling of these various effects requires critical data which can only be obtained from carefully planned interdisciplinary oceanographic measurements on appropriate time and space scales (e.g., Dickey, 1988; 1990; 1991). Ultimately, the management of wastewater discharges (rates, degree of treatment, etc.) and the inherent decision making process require information which can only be derived from interdisciplinary, process-oriented studies.

The potential benefits of our study include: 1) improved understanding of the marine environment where discharges are made, 2) characterization of the fate and potential effects (e.g., increased toxicity due to resuspension of bottom sediments, enhanced primary production, etc.) of discharges in the marine environment under a variety of oceanic conditions, 3) the acquisition of data sets which can be used for modeling of discharges and benthic processes and their effects on the environment, and 4) the understanding of several important basic oceanographic problems concerning small scale mixing, primary production, and optical properties of the ocean. Finally, future MVMS mooring deployments will be done at the White's Point site in January-February of 1993, at the MLML site south of Iceland in the spring of 1992, and in the equatorial Pacific in 1992-1993.

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