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# Anthropogenic Currents and Shoreline Water Quality in Avalon Bay, California

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S Supporting Information

**ABSTRACT:** Shoreline concentrations of fecal indicator bacteria (FIB) and fecal indicator viruses (FIV) in Avalon Bay (Catalina Island, California) display a marked diurnal pattern (higher at night and lower during the day) previously attributed to the tidal flux of sewage-contaminated groundwater and the tidal washing of contaminated sediments, coupled with light and dark die-off of FIB and FIV (Boehm, et al., *Environ. Sci. Technol.* **2009**, *43*, 8046−8052). In this paper we document the existence of strong (peak velocities between 20 to 40 cm/s) transient currents in the nearshore waters of Avalon Bay that occur between 07:00 and 20:00 each day. These currents, which have a significant onshore component, are generated by anthropogenic activities in the Bay, including prop wash from local boat traffic and the docking practices of large passenger ferries. A budget analysis carried out on simultaneous measurements of FIB at two cross-shore locations indicates that anthropogenic currents contribute to the diurnal cycling of FIB concentrations along the shoreline, by transporting relatively unpolluted water from offshore toward the beach. The data and analysis presented in this paper support the idea that anthropogenic currents represent a significant, and previously overlooked, source of variability in shoreline water quality.


## ■ INTRODUCTION

Fecal indicator bacteria (FIB) are used to assess bathing water quality at recreational beaches throughout the world.[2] Their widespread adoption as water quality indicators is based on several considerations, including their presence at high concentrations in sewage and other fecal waste and epidemiological studies that suggest a dose−response relationship between recreational waterborne illness and FIB concentrations at freshwater and marine bathing beaches, particularly in settings where the source of FIB is partially treated or untreated human sewage.[3,4] Currents are an important feature of a site's physical setting that can strongly influence the sources, spatiotemporal variability, and public health significance of FIB concentrations measured along the shoreline.[5] Because currents transport water parcels from one location to another, they link sources of fecal pollution (e.g., drains, sewage outfalls) to receptors (e.g., humans recreating at a beach) or, conversely, replace and disperse contaminated water along the shoreline with clean water from offshore.[6−8] Currents also mobilize sediment-associated FIB and pathogens into the overlying water column by the generation of fluid shear at the sediment bed, and affect light and dark inactivation rates through the resuspension of fine particles.[9] Although significant progress has been made in understanding the relationship between shoreline water quality and nearshore currents along unsheltered beaches where large breaking waves determine the direction and magnitude of alongshore and cross-shore (rip) currents,[7,10,11] relatively less is known about sheltered embayments where water quality is often very poor.[12]

This study describes field measurements of currents and water quality in Avalon Bay, a tidal embayment in southern California where shoreline waters at several popular recreational beaches frequently test above state and federal water quality criteria guidelines. The objectives of the study were to (1) characterize currents, winds, waves, and density stratification in Avalon Bay; (2) measure cross-shore FIB concentration gradients very close to shore; and (3) estimate from these data the relative contribution of cross-shore advection and light and dark die-off to diurnal variations in shoreline water quality at Avalon's most popular bathing beach.

## ■ SITE DESCRIPTON

Avalon Bay is located on the southeast side of Catalina Island (area 200 km$^2$), at approximately 33°20.9′ N, 118°19.5′ W

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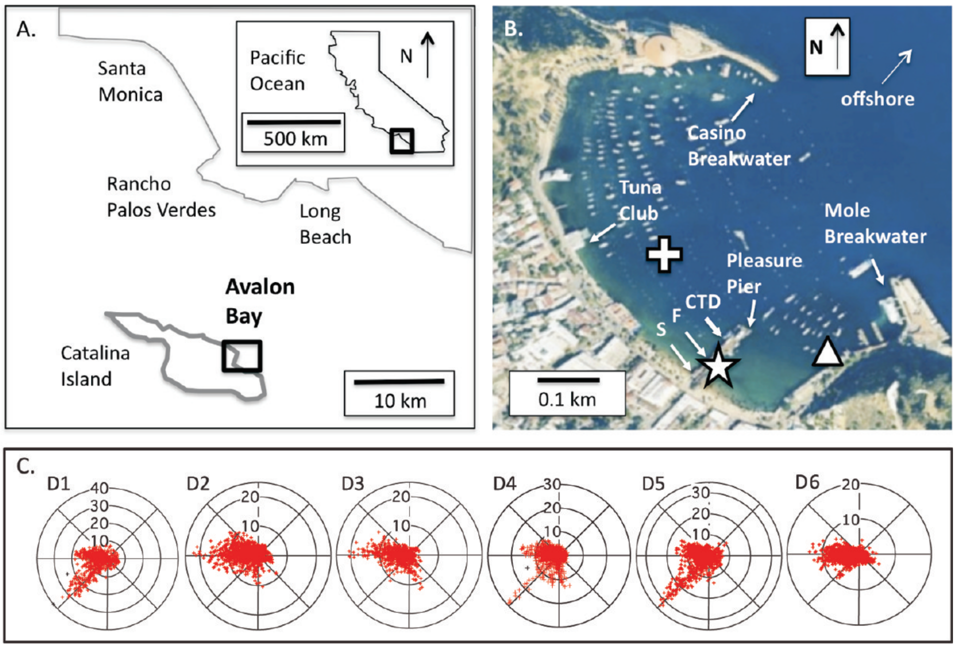


**Figure 1.** (A) Map showing the location of the field site in Avalon Bay, Catalina Island, California. (B) Location of instrument deployments near the Mole (triangle), Pleasure Pier (star), and Tuna Club (cross), FIB sampling sites at the shoreline (S) and float (F), and CTD deployment (CTD). (C) scatter plots of depth-averaged currents (cm/s) measured at the Pleasure Pier site by an upward looking ADCP during deployments D1 through D6.

**Table 1. Deployments of Upward Looking Acoustic Doppler Current Profilers (ADCPs) in Avalon Bay**

| deployment[a] | time period | instrument elevation (MLLW, m) | instrument |
|---|---|---|---|
| D1, Pleasure Pier | 2/11/09 to 2/19/09 | −3.79 | ADCP-1200 kHz |
| D2, Pleasure Pier | 3/10/09 to 3/23/09 | −3.83 | ADCP-1200 kHz |
| D3, Pleasure Pier | 3/25/09 to 4/3/09 | −3.89 | ADCP-1200 kHz |
| D4, Pleasure Pier | 4/6/09 to 4/17/09 | −3.88 | ADCP-1200 kHz |
| D5, Pleasure Pier | 4/25/09 to 5/11/09 | −4.04 | ADCP-1200 kHz |
| D6, Pleasure Pier | 5/28/09 to 6/13/09 | −4.1 | ADCP-1200 kHz |
| Bay-wide, Mole | 10/23/09 to 10/26/09 | −8.37 | ADCP-1200 kHz |
| Bay-wide, Pleasure Pier | 10/23/09 to 10/26/09 | −3.82 | ADCP-1200 kHz |
| Bay-wide, Tuna Club | 10/23/09 to 10/26/09 | −7.17 | ADCP-600 kHz |

[a] Latitude and longitude for Pleasure Pier (33.3439094, −118.3246538), Mole (33.344008, −118.322905), and Tuna Club (33.3456616, −118.3255174).

(Figure 1A). The site has a Mediterranean climate typical of coastal southern California, with warm (17−28 °C) dry summers and cool (9 to 18 °C) wet winters; an average of 3−8 cm of rain falls in a typical month in the wet season, from November through March.[13] The Bay experiences 1−2 m mixed-tides that vary in amplitude with the spring-neap cycle. Beaches within the Bay are sheltered from large waves present on the open coast, and are characterized by a ratio of tide range to wave height typically >3. Two breakwaters flank the entrance to Avalon Bay (Casino and Mole, Figure 1B); despite the presence of these breakwaters, there is vigorous tidal exchange of water between the Bay and ocean, and significant within-Bay turbulent mixing and advective transport.[14] The City of Avalon (area 6.9 $km^2$) is the largest town on the island with 3500 year-round residents, and its primary source of revenue is tourism. On a typical summer day 17,500 tourists arrive via ferry, cruise ship, or personal vessel, and up to 400 vessels are moored in Avalon Bay. The City's sewage is piped to a wastewater treatment plant (WWTP) south of town that has a treatment capacity of 4.5 x$10^6$ L/d. The main beach area of Avalon Bay has suffered chronic water quality problems, with FIB concentrations frequently exceeding State and Federal guidance criteria for marine bathing waters. Furthermore, water testing along the shoreline reveals the presence of several indicators of human waste, including human fecal-specific *Bacteroidales* and human enterovirus.[1,15] A series of studies have implicated sewage-contaminated shallow groundwater as a primary source of FIB in the nearshore region, which appears to enter the bay from the shoreline during falling tides.[1,15]

## ■ METHODS

**Pleasure Pier Deployments.** An upward-looking acoustic Doppler current profiler (ADCP, 1200kHz Workhorse Monitor, RD Instruments, Poway, CA) was mounted to a submersible tripod (Sea Spider, Ocean Sciences, Oceanside, CA) and hoisted over the southeast (downcoast) side of a commercial and recreational pier called the "Pleasure Pier" (white star, Figure 1B) until it came to rest on the seabed in 4−6 m of water. The ADCP was deployed 6 separate times (referred to as deployments D1 through D6) over a four-month period from February through June 2009; each deployment lasted between 9 and 17 days (Table 1). Between deployments, data were downloaded from the instrument and the transducers were cleaned. The ADCP was set to record horizontal currents in 55 depth bins, each 0.25 m in vertical extent, at a nominal sampling frequency of 1 Hz. Coincident with the ADCP deployment, wind speed and direction were measured with a weather station (HOBO U30-NRC, Onset Corporation, Bourne, MA) located on top of the lifeguard headquarters on the Pleasure Pier at a nominal sampling frequency of 0.0011 Hz. Time series of measured parameters were smoothed and interpolated (and in the case of the ADCP data, component depth-averaged) to a final sampling frequency of 1/5 $\text{min}^{-1}$ using custom codes implemented in the data analysis program Igor Pro (v 6.12, Wavemetrics, Inc., Lake Oswego, OR).

**Bay-Wide Deployment.** On October 23−26 (2009) three bottom mounted upward-looking ADCPs were deployed at the following locations in Avalon Bay: (1) 1200 kHz ADCP was deployed in 4−6 m of water at the Pleasure Pier location described above (white star, Figure 1B); (2) 1200 kHz ADCP was deployed in 8−10 m of water near the Mole breakwater (white triangle, Figure 1B); and (3) 600 kHz ADCP was deployed in 7−9 m of water near the Tuna Club (white cross, Figure 1B). Time stamped video images of ferries docked near the Mole breakwater were obtained from a City of Avalon security camera mounted approximately 25 m above sea level.

**Principal Component Analysis of Depth-Averaged Currents.** The first principal component of depth-averaged currents was computed for each ADCP deployment as follows. A data matrix was prepared from time series of the demeaned east- and north-components of the depth-averaged currents. A covariance matrix was then computed from the data matrix, and eigenvalues and eigenvectors were computed from the covariance matrix (Matlab, 7.0, Natick, MA). The eigenvector associated with the largest eigenvalue (i.e., the "first principal component") indicates the direction over which the depth-averaged current fluctuates the most.

**Significant Wave Height and Average Wave Period.** Significant wave height and average wave period were calculated from the raw (i.e., not smoothed) water elevation measurements recorded by the ADCP during deployments D1−D6 at the Pleasure Pier. Water elevation measurements, which were recorded at a nominal sampling frequency of 1 Hz, were interpolated to an evenly spaced time series with a fixed sampling frequency of 1 Hz. The evenly spaced water elevation data ($\eta$) were then divided into a sequence of contiguous 10-min time periods and for each 10-min time interval the significant wave height was computed from the zeroth moment $m_0$ of the spectral density $S_\eta$ of the water elevation data:[16]

$$H_s(t) = 4\sqrt{m_0} = 4\sqrt{\int S_n(f)df} \tag{1}$$

The average wave period $T_s(t)$ was estimated from $T_s(t) = (m_0/m_2)^{1/2}$, where $m_2$ is the second moment of the spectral density of water elevation $m_2 = \int f^2 S_\eta(f)df$ and $f$ is frequency.[16] Because the sampling frequency of our ADCP was set to 1 Hz, the Nyquist frequency is 0.5 Hz, which implies wave periods of less than 2 s cannot be resolved with our instrument setup.[17]

**Shoreline Budget for Fecal Indicator Bacteria.** To evaluate the relative contribution of die-off and advection by water currents to diurnal cycling of FIB concentrations in Avalon Bay, a field experiment was conducted as follows. Beginning October 28 (2008) at 22:40 local time, Bay water samples were collected simultaneously at two cross-shore sites every 30 min for approximately 2.5 days. These two sampling sites were located adjacent to the Pleasure Pier: (1) at the shoreline in approximately ankle-deep water (site S in Figure 1B), and (2) at a floating dock attached to the Pleasure Pier in approximately 3−5 m of water depending on the tide level (site F in Figure 1B). Because the shoreline site moved up and down the beach face with the tide, the distance between these two sampling sites varied continuously over the study. All water samples were collected from the surface of the water column in sterile Nalgene bottles, capped, immediately placed in an iced cooler, and analyzed within a holding time of 6 h at a field laboratory located at Avalon City Hall for *Escherichia coli* (EC) and enterococci bacteria (ENT) using defined substrate tests known commercially as Colilert-18 and Enterolert, implemented in a 97-well quanti-tray format. These tests provide a quantitative estimate for the concentration of FIB in a sample in units of most probable number (MPN) per 100 mL of sample. The Colilert-18 and Enterolert tests were run after diluting the original samples 1:10 into deionized water; for this choice of dilution, the lower and upper limits of detection for the Colilert-18 and Enterolert tests were 10 and 24192 MPN/100 mL, respectively. During approximately one-fifth of the sampling events, replicate water samples were collected at both the shoreline and float sites. FIB measurements at the two cross-shore sites were used to estimate the magnitude of cross-shore advection and die-off terms in the advection-diffusion equation (c.f., eq 3 in ref 18):

$$y\text{-advection}\ [\text{MPN}/100\ \text{mL h}^{-1}] = V(t)\frac{\Delta c(t)}{\Delta y(t)} \tag{2a}$$

$$\text{Die-off}\ [\text{MPN}/100\ \text{mL h}^{-1}] = (k_{Sun}I_{UVB}(t) + k_{Dark})C(t) \tag{2b}$$

These two equations yield estimates for the instantaneous contributions of cross-shore advection (eq 2a) and light and dark mortality (eq 2b) to change in FIB concentration at the shoreline (in units of MPN/100 mL $\text{h}^{-1}$). Variables in these equations represent the cross-shore velocity $V(t)[\text{ms}^{-1}]$ (positive values denoting offshore), difference between FIB concentrations measured at the float and shoreline $\Delta C(t) = C_{Float}(t) - C_{Shore}(t)$ $[\text{MPN m}^{-3}]$, cross-shore distance between the float and shoreline sites $\Delta y(t) = (y_{Float} - y_{Shoreline}(t))[\text{m}]$ where $y$ is a cross-shore coordinate (positive values denoting offshore), rate constant for solar-mediated die-off $k_{Sun}[s^{-1}I_{UVB}^{-1}]$, UVB intensity $I_{UVB}[\text{mW}^{-2}]$, and rate constant for dark die-off $k_{Dark}[\text{s}^{-1}]$. The cross-shore distance between sampling sites $\Delta y$ was estimated expost facto from the local slope of the beach and NOAA predictions of tide level for the study period.[19] Values for the die-off rate constants were adopted from a previous study in Avalon Bay:[1] $k_{Sun} = 6.9 \times 10^{-5}$ (EC) and $8.1 \times 10^{-5}$(ENT) $\text{s}^{-1}\ I_{UVB}^{-1}$, and $k_{Dark} = 9.3 \times 10^{-6}$ (EC) and $1.5 \times 10^{-5}$ (ENT) $\text{s}^{-1}$. Hourly values of $I_{UVB}(t)$ were estimated from the simple model of the atmospheric radiative transfer of sunshine (SMARTS).[20] A downward looking ADCP was deployed from a small research boat (docked at the Pleasure Pier) during this study; however, these data were contaminated by noise from the pitch and roll of the boat and could not be used to estimate values for $V(t)$. Therefore, $V(t)$ was estimated from the average weekday cross-shore velocity measured at the Pleasure Pier during the 4-month deployment described above. FIB concentration in eq 2b was set equal to the FIB concentration measured at the shoreline site, $C(t) = C_{Shore}(t)$. To evaluate the degree of density stratification, conductivity−temperature−depth (CTD) profiles were carried out every 30 min for the period October 29−31 (2008) with a SeaBird 19 Plus CTD Profiler (Sea-Bird Electronics, Inc., Bellevue, WA) deployed from a 17-foot research boat docked on the northwest side of the Pleasure Pier. Downcast data from the CTD were used to compute a quantitative measure of density stratification called the buoyancy frequency:

$$N = \left(-\frac{g}{\rho_0}\frac{\partial \rho}{\partial z}\right)^{1/2} \quad (3)$$

where $g$ is gravitational acceleration, $\rho_0$ is the average density over the period of measurement, $\partial\rho/\partial z$ is the vertical density gradient, and the height $z$ is measured from the bottom of the water column.

## RESULTS AND DISCUSSION

**Pleasure Pier Deployment: Depth-Averaged Currents.** The Pleasure Pier bisects the main beach in Avalon Bay, where most bathers recreate and water quality is historically poor. Depth-averaged currents at the Pleasure Pier displayed one of three dominant patterns (Figure 1C): (1) westward currents with peak velocities between 10 and 20 cm/s (all six deployments); (2) southwestward currents with peak velocities between 10 and 30 cm/s (deployments D1 and D4−D6); and (3) south to south−southeastern currents with peak velocities of 10 cm/s (deployments D2, D3, and D4). Time- and depth-averaged currents at the Pleasure Pier are consistently oriented west or southwest, as are the first principal components of the depth-averaged current, which account for between 61 and 85% of the current variance (Figure S1 and Table S1, Supporting Information (SI)). Given the local strike of the shoreline, these results imply that nearshore currents at the Pleasure Pier are oriented either directly onshore (southwestard currents) or possess a significant onshore component (westward and south−southeastern currents) (Figure 1C).

Currents measured at the Pleasure Pier manifest as discrete pulses that rarely occur before 07:00 in the morning or after 20:00 at night (Figure 2; see also time series for the first principal component loadings in Figures S2 and S3). While there is considerable day-to-day variability, on average four major current pulses occur per day during a typical weekday (black curves in Figure 2B and C) and at least eight major current pulses occur per day during a typical weekend (black curves in Figure 2E and F). Both the west (Figure 2B and E) and southwest (Figure 2C and F) components of the depth-averaged current exhibit this pulsing pattern. During weekdays, these current pulses frequently occur about 30 min after the scheduled arrival times of large (approximately 40 m long) passenger ferries (compare arrival times of ferries in Figure 2A with average current patterns denoted by heavy black curves in Figure 2B and C). The number of scheduled passenger ferries approximately doubles during weekends, as does the number of current pulses measured at the Pleasure Pier (compare Figure 2D, E, and F). In Avalon Harbor, ferries dock at a commercial facility at the Mole Breakwater which is located approximately 200 m to the east−northeast of the Pleasure Pier (see Figure 1B).

However, not all current pulses measured at the Pleasure Pier can be attributed to the arrival of ferries at the Mole. For example,

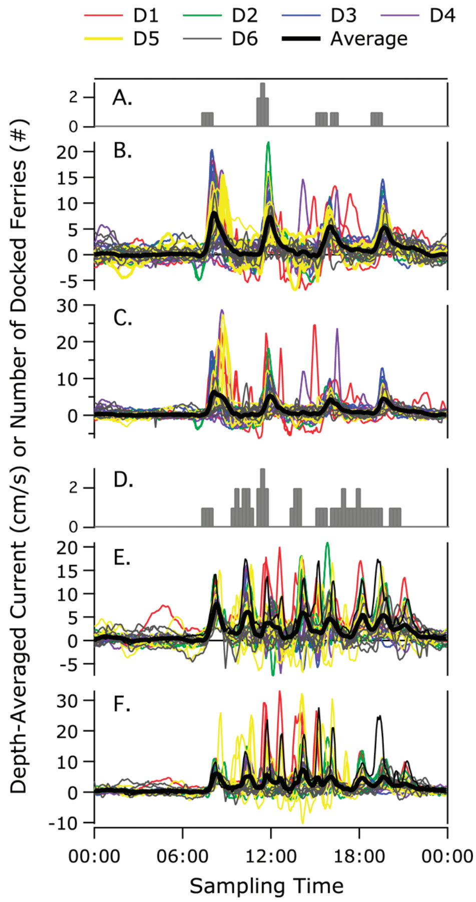


**Figure 2.** Depth-averaged current pulses measured at the Pleasure Pier compared with the docking schedules of large ferries at the Mole. Panels A and D: number of ferries docked at the Mole during a typical weekday (A) and weekend (D). Panels B and C: depth-averaged westward (B) and southwestward (C) currents measured during weekdays at the Pleasure Pier. Panels E and F: depth-averaged westward (E) and southwestward (F) currents measured during weekends at the Pleasure Pier. Dark black curves in Panels B, C, E, and F correspond to the average of all curves shown in a given panel.

during deployment D5, two overlapping pulses occurred most weekday mornings (Figure 2B and C). The first pulse appears to correlate, with a 30 min delay, with the 07:30 ferry, but the second (08:30) pulse does not obviously correlate with the ferry schedule. The second pulse's relative strength (peak velocities of 30 cm/s) and orientation (southwest, parallel to the Pleasure Pier) are consistent with prop wash from a boat docked at the Pleasure Pier.

Assuming that the first principal component of the depth-averaged current vector represents anthropogenic currents, which appears to be the case based on the daytime pulses evident in the first principal component loadings (see Figures S2 and S3), we estimate that between 61 and 85% (depending on deployment) of the measured current variance at the Pleasure Pier has an anthropogenic origin (Table S1).

**Pleasure Pier Deployment: Vertical Current Profiles.** Vertical profiles of horizontal currents measured at the Pleasure Pier typically exhibit one of three patterns: (1) constant speed over the measured portion of the water column; (2) increasing speed toward the surface of the measured portion of the water column; or (3) increasing speed toward the bottom of the measured

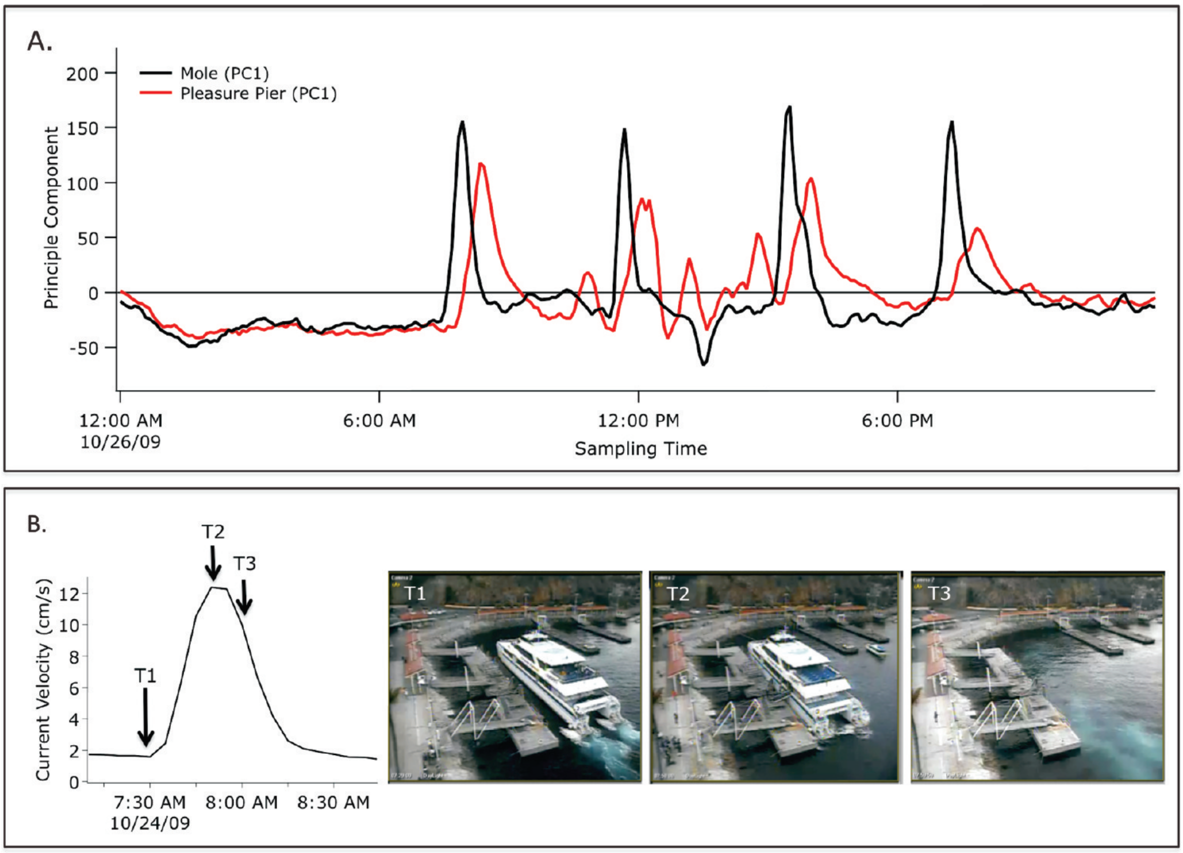


**Figure 3.** (A) Time series of loadings for the first principal component of depth-averaged currents measured at the Mole (black) and Pleasure Pier (red) sites showing the lag in arrival time of current pulses at these two sites. (B) Timing of the onset (T1), peak (T2), and decay (T3) of a single current pulse measured at the Mole relative to coincident images of a docking ferry; these images were taken with a camera looking south from the Mole Breakwater.

portion of the water column (Figures S4−S18, SI). The first two patterns are typical of current pulses that correlate with the arrival of ferries at the Mole, whereas the third pattern is typical of the stronger southwest (pier-parallel) current pulses, and may reflect bottom impingement of momentum jets generated by boats docked at the Pleasure Pier. The ferry-correlated pulses, on the other hand, appear to originate when ferries docked at the Mole continuously apply reverse thrust to force the ferry securely against the dock. Based on field observations described later, this practice has the effect of forcing water up against the shoreline near the Mole, and initiating a momentum and/or gravity-driven clockwise circulation along the outer edge of the Bay. It is this clockwise circulation that appears to be responsible for the ferry-correlated current pulses detected by our ADCP at the Pleasure Pier.

**Pleasure Pier Deployment: Wind and Waves.** Winds measured at the Pleasure Pier have peak speeds of 5−8 m/s (depending on the deployment) and typically follow a diurnal pattern characterized by onshore flow (directed to the south−southwest) during the day and offshore flow (directed to the north−northeast) at night (see Principal Component Analysis in SI Figures S19−S21). Because the wind direction undergoes daily reversals, time-averaged wind vectors at the Pleasure Pier are small in magnitude (<0.5 m/s) and variable in direction (Figure S19, SI). Significant wave heights and average wave periods generally fluctuate between 0.1 and 0.2 m and 6 and 12 s, respectively, except during storm events when wave heights can reach 0.5 m (March 16, 2009, Figures S22−S27, SI). These wind and wave patterns cannot account for the daytime current pulses measured at the Pleasure Pier during deployments D1−D6.

**Table 2. Relative Percent Differences (RPD) Calculated from EC and ENT Concentrations Measured on Replicate Samples (Replicate Samples Collected Simultaneously at Either Site S or F) and Paired Cross-Shore Samples (Samples Collected Simultaneously at Both Sites S and F) (For the Paired Cross-Shore Samples, a Negative RPD Indicates That Concentrations Are Higher at the Shoreline (Site S) and Lower at the Float (Site F)**

| analyte | replicates | | site F − site S | |
|---|---|---|---|---|
| | $N^a$ | $RPD_{ave}$ (%)$^b$ | $N^a$ | $RPD_{ave}$ (%)$^b$ |
| EC | 42 | 3 ± 49 | 102 | −130 ± 79 |
| Log (EC) | 42 | 0.4 ± 16 | 102 | −53 ± 37 |
| ENT | 38 | 15 ± 53 | 102 | −56 ± 76 |
| Log (ENT) | 38 | 5.7 ± 21 | 102 | −22 ± 31 |

[a] $N$, number of paired samples used in the RPD analysis. [b] $RPD_{ave} = (1/N) \sum_{i=1}^{N} 2(X_{1i} - X_{2i})/(X_{1i} + X_{2i})$, where $X_{1i}$,$X_{2i}$ represent the analyte concentrations measured for the $i$th pair of samples. RPD values for paired cross-shore samples were calculated by assigning the float and shoreline concentrations to $X_{1i}$ and $X_{2i}$, respectively.

**Bay-Wide Deployment: Depth-Averaged Currents.** To better constrain the origin of the current pulses measured at the Pleasure Pier, a follow-up study was carried out to evaluate nearshore currents at three locations in the Bay: (1) near where

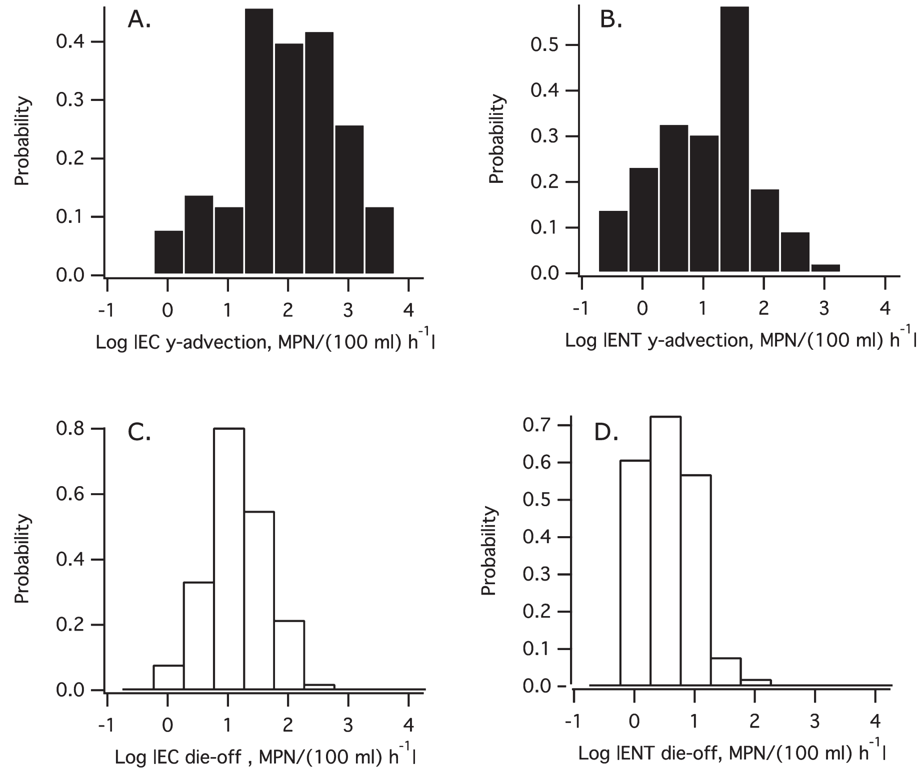


**Figure 4.** Budget analysis comparing the relative magnitude of the cross-shore advective term (eq 2a) and die-off term (eq 2b) in the advection−diffusion equation. Shown are the probability distributions of the cross-shore advection term for EC (panel A) and ENT (panel B), and the probability distributions of light and dark die-off for EC (panel C) and ENT (panel D).

the ferries dock (Mole), (2) at the Pleasure Pier, and (3) northwest of the Pleasure Pier (Tuna Club) (white triangle, star, and cross in Figure 1B). ADCP measurements at the Mole site reveal strong (upward of 25 cm/s) westward currents (Figure S28) that exhibit the same pulsing pattern described above for ADCP measurements at the Pleasure Pier (Figures S29−S30). When the first principal component loadings of the depth-averaged currents measured at the Mole and Pleasure Pier sites are coplotted against time, current pulses are observed to arrive first at the Mole site and then later at the Pleasure Pier site (Figure 3A). Cross-correlation of these two signals reveals that, on average, the Pleasure Pier pulse lags the Mole pulse by approximately 30 min, consistent with the earlier observation that current pulses at the Pleasure Pier frequently arrive 20−30 min after the arrival of ferries at the Mole. Dividing the time lag between Mole and Pleasure Pier (30 min) into the approximate distance separating these two sites (200 m) yields a propagation speed of approximately 10 cm/s, which is similar to peak current speeds measured at both sites. Based on a review of time stamped video images of the ferry dock, the onset of the westward current at the Mole site occurs several minutes after the arrival of a ferry at the dock (T1), peaks after the ferry has been docked for about 20 min (T2), and rapidly decays after the ferry leaves (T3) (Figure 3B). These results are consistent with the hypothesis that at least some of the current pulses measured at the Pleasure Pier are triggered when ferries apply reverse thrust (directing water directly toward the shore) while docked at the Mole. Currents measured at the Tuna Club are oriented parallel to the local strike of the shoreline (northwest−southeast, see scatter plot in Figure S28) and do not exhibit a pulsing pattern (Figure S29). Instead, the first principal component of depth-averaged currents at Tuna Club, which captures 92% of the data variance, displays relatively long (>20 h) periods of either up-coast or down-coast flow (Figure S30).

**FIB Budget Analysis.** Based on the results presented above, currents very close to the shoreline in Avalon Bay appear to be dominated by anthropogenic activities: in particular, ferries docked at the Mole facility and local boat traffic at the Pleasure Pier. The vector of these currents is directed either directly onshore (local boat traffic) or at an approximately 45° angle to the shore (ferry-induced currents), implying significant onshore flow in both cases. To the extent that nearshore waters in Avalon Bay are contaminated by the discharge of sewage-contaminated groundwater, as has been previously hypothesized,[1,15] onshore currents may have a positive impact on nearshore water quality, by transporting cleaner water from the middle of the Bay toward the shoreline. To evaluate if such a mechanism could contribute to the diurnal cycling of FIB and FIV previously observed at this site, we carried out an experiment in which water samples were collected every 30 min for approximately 2.5 days at two locations: (1) the shoreline near the Pleasure Pier, and (2) a short distance (20−50 m, depending on tide level) bay-ward of the shoreline at a float attached to the Pleasure Pier (sites S and F in Figure 1B). Raw data from this field study are presented in the SI (Figure S31). FIB concentrations in these samples were very frequently higher at site S and lower at site F, as evidenced by the large and negative relative percent difference (RPD) calculated for the raw and log-transformed EC and ENT measurements at these two sites (Table 2); for comparison the RPD values calculated for replicate samples are also included in this table. The average buoyancy frequency calculated from CTD measurements of salinity and temperature ($0.013 \pm 0.006\ s^{-1}$) is well below the threshold indicative of a stratified water column (>0.1 $s^{-1}$), consistent with the idea that the water column is relatively well-mixed over the vertical[21] (raw salinity and temperature profile data presented in Figure S32). The steep cross-shore gradient in FIB concentration, coupled with shoreward directed currents generated by anthropogenic activities in Avalon Bay, give rise to a cross-shore advection term that is, on the whole, larger in magnitude than the die-off term in the advection—diffusion equation (compare panels A and C (EC) and B and D (ENT) in Figure 4). Both the advection and die-off terms are approximately log-normally distributed, with geometric means of 52 and 7 MPN/100 mL $h^{-1}$ (EC) and 5 and 1.8 MPN/100 mL $h^{-1}$ (ENT). If sustained, the larger values for the cross-shore advection term are sufficient to cause, within a single hour, a drop in the FIB concentration at the shoreline on par with California's marine bathing water single-sample criteria for EC (400 MPN/100 mL) and ENT (104 MPN/100 mL). Given the probability distributions presented in Figure 4, anthoropogenically forced currents appear to influence shoreline water quality as much as, or more than, light and dark die-off, and could certainly account for at least a portion of the diurnal water quality signal previously observed in Avalon Bay. Studies are presently underway to evaluate the effect of anthropogenic currents on bottom shear stress, particle resuspension, and vertical flux of FIB in the nearshore waters at this field site.

## ■ ASSOCIATED CONTENT

**Supporting Information.** Procedures for data processing and figures. This material is available free of charge via the Internet at http://pubs.acs.org.

## ■ AUTHOR INFORMATION


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