Decadal and Shorter Period Variability of Surf Zone Water Quality at Huntington Beach, California

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The concentration of fecal indicator bacteria in the surf zone at Huntington Beach, CA, varies over time scales that span at least 7 orders of magnitude, from minutes to decades. Sources of this variability include historical changes in the treatment and disposal of wastewater and dry weather runoff, El Niño events, seasonal variations in rainfall, spring-neap tidal cycles, sunlight-induced mortality of bacteria, and nearshore mixing. On average, total coliform concentrations have decreased over the past 43 years, although point sources of shoreline contamination (storm drains, river outlets, and submarine outfalls) continue to cause transiently poor water quality. These transient point sources typically persist for 5−8 yr and are modulated by the phase of the moon, reflecting the influence of tides on the sourcing and transport of pollutants in the coastal ocean. Indicator bacteria are very sensitive to sunlight; therefore, the time of day when samples are collected can influence the outcome of water quality testing. These results demonstrate that coastal water quality is forced by a complex combination of local and external processes and raise questions about the efficacy of existing marine bathing water monitoring and reporting programs.

Introduction

Huntington Beach made national news in the summer of 1999 when a large section of beach, at one point encompassing 20 km, was closed to the public. Over 1 million people visit this stretch of beach in a typical summer; therefore, the closures impacted the local economy and contributed to public concern that surf water quality in California is getting progressively worse (*1*). Nationally, the number of beach advisories and closures nearly doubled from 1999 to 2000, primarily due to changes in the state and local regulations governing surf monitoring and reporting (*2*). In this study, we utilize a 43-yr-long time series of monitoring data and several short-term high-frequency sampling studies to characterize the decadal and shorter period variability of surf water quality at Huntington Beach. These data shed light on how (i) physical and biological phenomena modulate the impact of coastal pollution on surf water quality, (ii) water quality at this site has evolved over time and in response to infrastructure improvements, and (iii) monitoring and reporting of coastal water quality and identification of specific sources of coastal pollution can be improved.

Methods

Historical Data: Regulatory Bacteriological Monitoring. Marine bathing water regulations in California, and throughout most of the world, are based on the concentration of coliform and/or enterococci bacteria in the surf zone where bather contact is most likely to occur. Since June 1958, the Orange County Sanitation District (OCSD) and the Orange County Health Care Agency have measured total coliform (TC) concentrations at a minimum of six surf zone stations in Huntington Beach (Figure 1). The sampling and laboratory methodologies employed in this monitoring effort have remained static, but the number of sites sampled and the sampling frequency at each site have changed over time. Prior to 1998, surf zone water was assayed for TC only. Briefly, 100 mL of ocean water is collected from an incoming wave at ankle depth in a sterile container, put on ice, and returned to the laboratory within 6 h where 1.0 mL, 0.1, and 0.01 mL are analyzed according to standard method (SM) 9221B. Beginning in July 1998, the analyses were expanded to include assays for fecal coliform (FC) and enterococci (ENT). Analyses for FC are conducted on 1.0 mL, 0.1 mL, and 0.01 mL of surf zone water using SM 9221E; 10−50 mL of sample is assayed for ENT using EPA Method 1600. From 1958 to 1970, water samples were collected daily from five locations within the beach boundaries: stations 0, 3N, 6N, 9N, 12N, and 15N (Figure 1). In 1970, stations 21N and 27N were incorporated into the monitoring program, and the sampling frequency was decreased to 3−5 times per week. During 1981 and 1982, samples were collected only once per week.

Historical Data: Rainfall. Local rainfall data is archived on the Orange County Public Facilities and Resource Department Web site (*3*). We utilized data recorded at the Huntington Beach fire station from 1958 through 1999. Because the fire station rainfall gauge was not maintained after 1999, we utilized data recorded at nearby Costa Mesa Water District for 2000 and 2001. Dates and strengths of El Niño events were retrieved from the National Atmospheric and Oceanic Organization Web site (*4*).

Historical Data: Analysis. All of the TC and rainfall data collected in a given year were divided into a winter period (January−February−March, JFM) and a summer period (June−July−August, JJA). We then calculated the geometric means and 95% confidence intervals for TC during JFM and JJA using data collected at all sites in the study area. The total amount of rainfall recorded during JJA and JFM of each year was also computed.

The summertime pollution signal was divided into four periods of time (events) based on the presence of unique TC sources that impaired beach water quality for multiple years. During each of the events, water quality in the entire surf zone, or at a subset of surf zone stations, was analyzed for

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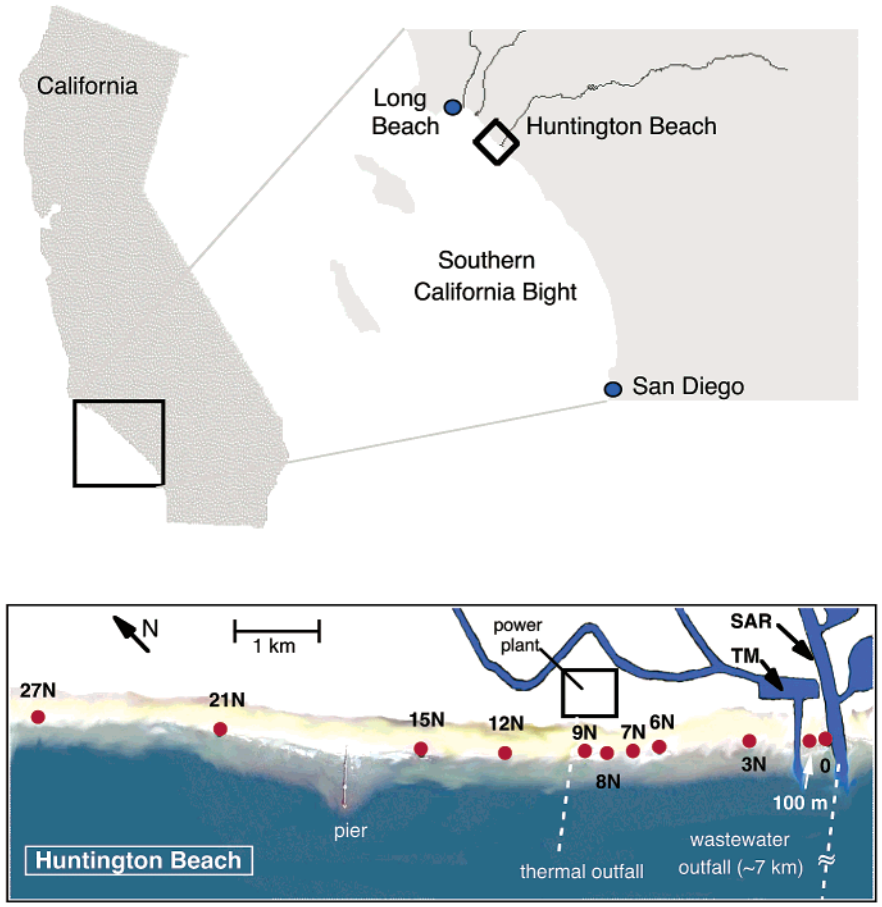

FIGURE 1. Map of the study area. Red circles represent monitoring stations. Only stations 0, 3N, 6N, 9N, 12N, 15N, 21N, and 27N have been sampled regularly over the last 43 years. TM and SAR are the Talbert Marsh and Santa Ana River, respectively.

lunar periodicity as follows. The data were binned according to when a sample was collected in the lunar calendar (day 0 is the full moon). The geometric mean and 95% confidence intervals of TC were then calculated for each day of the lunar calendar.

Short-Term Studies: Twice Daily Sampling. Between November 1963 and March 1965, surf zone water sampling was conducted twice daily at stations 0, 3N, 6N, 9N, 12N, and 15N, once between 8:00 and 9:00 and again around 14:00. Samples were collected and analyzed for TC using the same standard methods described above for regulatory monitoring. The geometric means of TC in the morning and afternoon samples were computed.

Short-Term Studies: Hourly Sampling. TC, FC, and ENT were measured hourly at four surf zone stations for 2 weeks from May 2 to May 16, 2000. 1-L samples were collected at ankle and waist depth on an incoming wave in sterile bottles at stations 0, 3N, 100m, and 9N (Figure 1). Within 6 h of collection, samples were analyzed for TC (SM 9221B), FC (SM 9221E), and ENT (EPA Method 1600). In addition, solar irradiance was recorded every 30 min with a thermopile radiometer (Kipp & Zonen, CM3 Thermopile Radiometer, The Netherlands) located at the San Joaquin Marsh, 6 km west of Huntington Beach.

Data collected during the 2-week study were binned according to the hour of day when they were collected, and the geometric means and 95% confidence intervals of indicator bacteria, and average and standard deviation of solar irradiance measurements were calculated for each hour. Concentrations below the detection limit were set equal to the lower limit of detection (10 most probable number (mpn)/100 mL). We also calculated the percent of samples collected each hour that contained bacteria levels above the detection limit.

Short-Term Studies: Mesocosms. The effect of sunlight on the survival of TC, FC, and ENT was investigated with two mesocosm studies on October 20 and 27, 2001. Water was collected from the surf zone at station 9N (Figure 1) at midnight and placed into four 60-L aquariums. Aquariums were placed in a large water bath and maintained between 18 and 19 °C, which is within the temperature range measured in the surf zone. Of the four aquariums, two were exposed to sunlight and two were covered with a black tarp. 225-mL aliquots were removed from each aquarium hourly between 4:00 and 23:00 and analyzed for indicator bacteria. The indicator bacteria in the mesocosms were present in the surf zone water at the time of collection (i.e., the aquariums were not seeded with bacteria). On October 27, samples were analyzed for TC using Colilert-18 (IDEXX, Westbrook, MN). On October 20, samples were assayed for FC using SM 9222D and ENT using both EPA Method 1600 and Enterolert (IDEXX, Westbrook, MN). Colilert-18 and Enterolert are defined substrate tests implemented in a 97-well quanti-tray. Detection limits were 10 mpn/100 mL for IDEXX methods and 1 mpn/100 mL for others. On both days, UV intensity was recorded hourly with a UV Minder handheld radiometer (Apprise Technologies, Duluth, MN). On October 20, peroxide levels were monitored in both light and dark aquariums utilizing an enzyme-mediated fluorescence decay method with horseradish peroxidase and scopoletin (*5*).

Short-Term Studies: Ten-Minute Sampling. TC, *Escherichia coli* (EC, a subset of FC), and ENT levels were measured every 10 min at shoreline stations 0, 3N, 6N, 7N, 8N, 9N, and 12N (Figure 1) for 12 h from 21:00 September 14 to 9:00

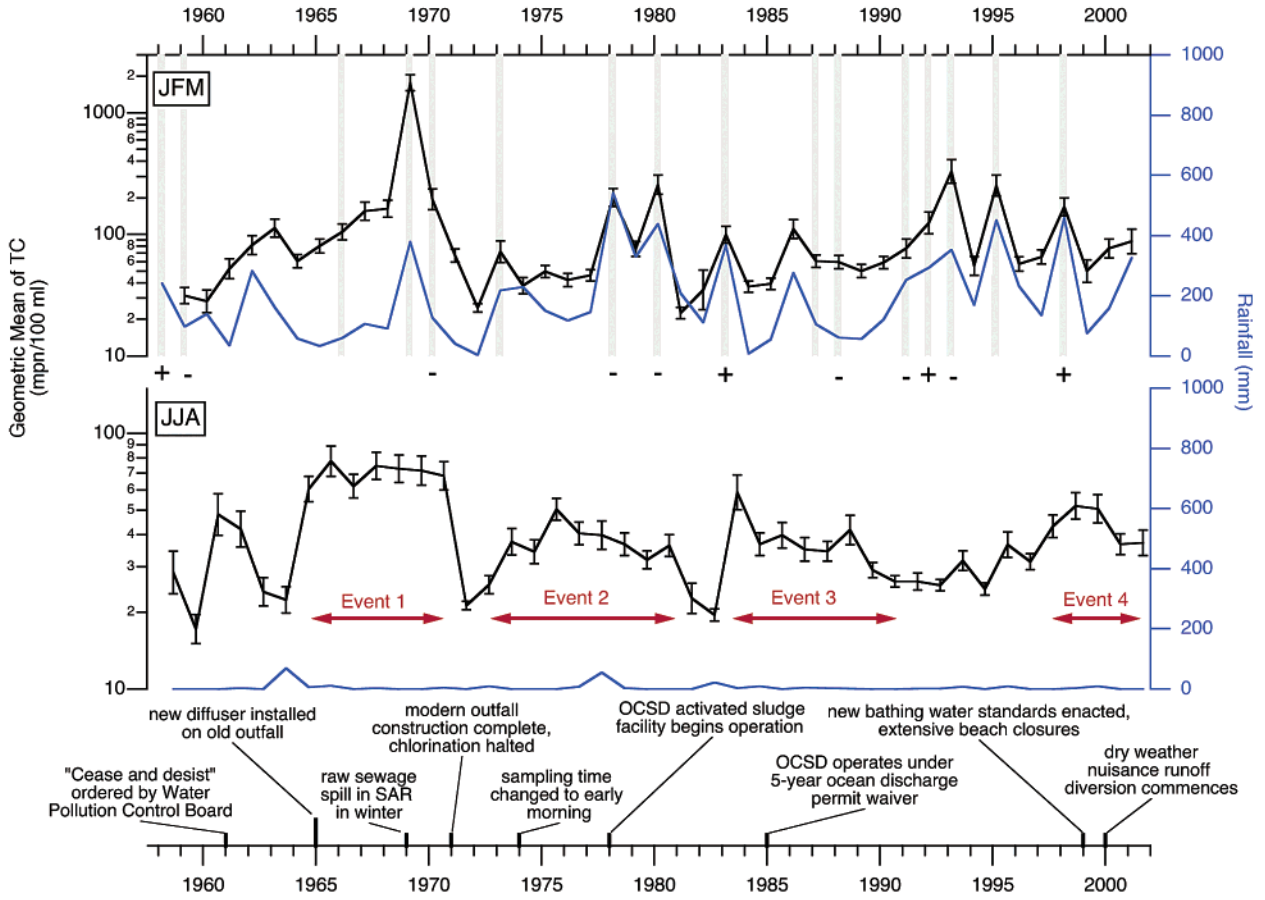

FIGURE 2. The 43-yr history of water quality at Huntington Beach, CA. The geometric means and 95% confidence intervals of total coliform (TC) bacteria during January−February−March (JFM) (top panel) and June−July−August (JJA) (bottom panel) calculated using all samples collected within study site. Total rainfall is shown in blue. El Niño events are designated by gray bars; strong and weak events are labeled (+) and (−), respectively, while average events are not labeled. A time line of important events is shown beneath the graph. Red lines in bottom panel delineate specific contamination events in the JJA signal and are discussed in the text. SAR and OCSD are acronyms for the Santa Ana River and the Orange County Sanitation District. This graph summarizes 33 910 TC (approximately 400 per GM) and 743 rainfall measurements.

September 15, 2001. Samples were collected from ankle depth on an incoming wave in a sterile bottle every 10 min and immediately stored on ice. Samples were transported to the laboratory within 6 h and assayed for TC, EC, and ENT using Colilert-18 and Enterolert (IDEXX).

Results and Discussion

Historical Data: Infrastructure Changes and Seasonal Variability. Forty-three years of historical monitoring data at Huntington Beach is summarized in Figure 2. The top and bottom panels show the geometric means and 95% confidence intervals of TC (black) and total rainfall (blue) during winters (JFM) and summers (JJA), respectively. On average, the geometric mean of TC during JFM is three times greater than the geometric mean of TC during JJA. Furthermore, during JFM the log mean of TC is correlated with rainfall ($r^2 = 0.6$), and the peak TC values align with El Niño events (gray bars in top panel of Figure 2). While TC events appear to coincide with El Niño events, the converse is not true; i.e., not all El Niño events coincide with elevated TC in the surf zone. Hence, the relationship between El Niño events, local rainfall, and coastal pollution is not straightforward. This region of southern California has separate storm and sanitary sewer systems, and both can contribute to surf zone pollution during storms (*6*, *7*). During the winter of 1969, for example, OCSD records indicate that upstream sewage treatment plants discharged raw sewage into the Santa Ana River during storms in February. The raw sewage flowed into the ocean from the Santa Ana River and caused some of the highest TC levels ever recorded at Huntington Beach (compare TC levels in top panel to historical time line at bottom of Figure 2). Little rain falls in the study area during the summer, and consequently, TC and rainfall do not correlate during JJA ($r^2 = -0.15$).

To determine how water quality at Huntington Beach has changed over time, we performed linear regressions between the seasonal (JFM or JJA) geometric mean of TC and the year. The regression slopes indicate that water quality at Huntington Beach has improved over the past 43 years (slopes and 95% confidence intervals of $m = -2 \pm 6$ and -0.3 ± 0.4 mpn/100 mL each year for JFM and JJA, respectively). However, this overall improvement is biased by the dramatic improvement in water quality that resulted from the construction of the new wastewater outfall in 1971 (see discussion below). If we regress only data collected after the outfall's construction, the results suggest that TC concentrations have been slowly rising over time ($m = 2 \pm 3$ and 0.2 ± 0.4 mpn/100 mL each year for JFM and JJA, respectively).

The summertime TC signal at Huntington Beach is characterized by a series of contamination events that persist for 5−8 years (red arrows in JJA panel of Figure 2). The probable causes of these events were reconstructed from written records maintained by OCSD and from interviews with their staff. From 1954 until 1971, OCSD discharged a

mixture of primary and secondary treated sewage that was intermittently chlorinated into the ocean through a 2.1 km long outfall that terminated directly offshore of Huntington Beach. On the basis of evidence that the original outfall was impacting the beach (e.g., the frequent sighting of grease), the local Water Pollution Control Board issued a cease and desist order that required OCSD to improve sewage treatment and disposal in 1961. In 1965 a new diffuser was installed on the end of the outfall pipe to increase the near-field mixing of the sewage field. Instead of improving local surf zone water quality, however, the concentration of TC during JJA increased abruptly and remained high until the short outfall was replaced with a longer (7.5 km) outfall in 1971 (event 1 in Figure 2). The construction of the new outfall was supported by a grant from the Federal Clean Water Act program, and hence this appears to be a case where federal investment in point source control led to measurable improvement in receiving water quality. The improvement in JJA water quality that occurred after construction of the new outfall is probably more dramatic than appears in Figure 2 because the time of day when surf zone samples were collected shifted from early afternoon (before 1971) to early morning (after 1974). In the twice daily sampling experiments conducted at Huntington Beach from 1963 to 1965, OCSD personnel found that, on average, surf zone samples collected early in the morning had TC concentrations twice that of samples collected in the early afternoon. (The geometric means of TC measured in the morning and afternoon samples were 250 mpn/100 mL and 100 mpn/100 mL ($n = 294$), respectively.) As will be documented later in the paper, at least part of this time-of-day sampling effect is due to sunlight-induced mortality of indicator bacteria.

The next two JJA contamination events in Figure 2 appear to have been caused by dry weather flows from a storm drain at the northeast end of the study area near station 21N (event 2) and from the mouth of the Santa Ana River (event 3). Presently, contamination at Huntington Beach is centered between surf zone stations 6N and 9N (event 4). All four JJA contamination events are discussed in more detail below.

Historical Data: Lunar Variability. Lunar variability in surf zone water quality may arise if the loading and/or nearshore transport of contamination is modulated by the tides. Possible examples include the tidal flushing of estuaries and storm channels (*8*, *9*), tidally modulated nearshore circulation patterns (*10*, *11*), foreshore washing of contaminated beach sand by wave action, exfiltration of sewage-contaminated groundwater by tidal pumping (*12*), and horizontal and vertical movement of offshore wastewater fields by internal tides (*13*, *14*). To determine if the pollution events at Huntington Beach exhibit lunar variability, geometric means and 95% confidence intervals of indicator bacteria were plotted against the day since the full moon (Figure 3A,B) following an approach used by Pineda (*15*) to examine tidally forced nearshore upwelling. TC concentrations in the surf zone were higher during the neap tide after the new moon (around day 20) from 1964 to 1970 when the source was discharge from the short outfall (event 1); there is no obvious lunar pattern at station 21N from 1972 to 1981 when the source was dry weather runoff from a storm drain (event 2); and TC levels at station 0 were highest during spring tides (around days 0 and 15) from 1983 to 1990 when the source was outflow from the Santa Ana River (event 3). The lunar pattern for event 1 might reflect less overall dilution of the sanitation district sewage field during neap tides, for example, because of less energetic tidal-band nearshore currents. The absence of a clear lunar pattern for event 2 is consistent with a more or less steady input of dry weather runoff from a storm drain. The spring tide lunar pattern evident for event 3 can be explained by increased transport of contaminants out of the Santa Ana River during spring tides when the tidal prism extends farther inland and greater volumes of water are exchanged with the ocean (*8*, *9*). The recent dry weather contamination at Huntington Beach (event 4), which appeared abruptly in 1997, has a lunar pattern that is unlike events 1−3 (compare lunar patterns in Figure 3, panels A and B). TC, FC, and ENT levels all peak a couple days before the new moon spring tide and again around the full moon spring tide (Figure 3B). The center of the recent contamination is located 2−3 km north of the Santa Ana River mouth (around 6N and 9N, see Figure 3C) and shoreward of a short (700 m) thermal outfall operated by a 872 MW power generating station. Investigations are currently underway to determine if the thermal outfall is a source of fecal indicator bacteria. The fact that each pollution event is characterized by a unique lunar signature raises the intriguing possibility that sources of coastal pollution might be identifiable based on their lunar patterns. For example, the contamination of a surf zone by sewage released from an offshore outfall might be characterized by elevated concentrations during neap tides (event 1).

Short-Term Studies: Hourly Variability. Concentrations of indicator bacteria in the surf zone at Huntington Beach exhibit diurnal variability based on a study in which TC, FC, and ENT were measured hourly at four shoreline stations for 2 weeks during May 2000. Figure 4A shows the geometric means and 95% confidence intervals for all samples collected each hour of the day (bottom panel), the percent of samples collected each hour that were above the detection limit of 10 mpn/100 mL (middle panel), and the average solar radiation each hour (top panel). The concentration of indicator bacteria and the percentage of samples that tested positive for indicator bacteria are both highest in the middle of the night; as solar radiation peaks at midday, the concentration of indicator bacteria falls to levels near or below the detection limit.

The diurnal trend noted above is due, at least in part, to sunlight-induced bacterial die-off or injury. In a set of unseeded mesocosm experiments (Figure 4B), the concentrations of ENT, FC, and TC in isolated samples of surf zone water exposed to sunlight dropped below detectable levels by noon (open symbols) but remained elevated throughout the day in samples of the same water kept in the dark (closed symbols). Photolysis of organic material in the sunlight-exposed surf zone water caused peroxide levels to increase to 400 nM (blue open circles in top panel in Figure 4B) (*16*). These data confirm earlier reports that sunlight accelerates the die-off and injury of indicator bacteria in marine waters (*17*−*19*) and raise the possibility that peroxide and other photochemically produced oxidants may play a role in this process, as has been suggested previously for coliform die-off in sewage fields (*19*).

The data presented in Figure 4A raise an equally important question: Why is the surf zone so rapidly resupplied with indicator bacteria after the sun goes down? There are several possible explanations. (i) During daylight hours a substantial fraction of indicator bacteria in the surf zone are injured, and these organisms are resuscitated by photoreactivation and/or dark-repair mechanisms (*20*, *21*). (ii) Indicator bacteria are rapidly growing in the surf zone, and after dark their growth outpaces their removal by die-off and bacteriovory. (iii) There is a more or less continuous supply of indicator bacteria to the surf zone from onshore or offshore sources of pollution. (iv) There is a large reservoir of indicator bacteria in the foreshore and nearshore sediments that are continuously resuspended by wave action.

In the mesocosm experiments described above, we found that the concentration of indicator bacteria declined after isolated samples of surf zone water from Huntington Beach were exposed to sunlight. Importantly, the concentration of indicator bacteria in the mesocosms did not rebound after

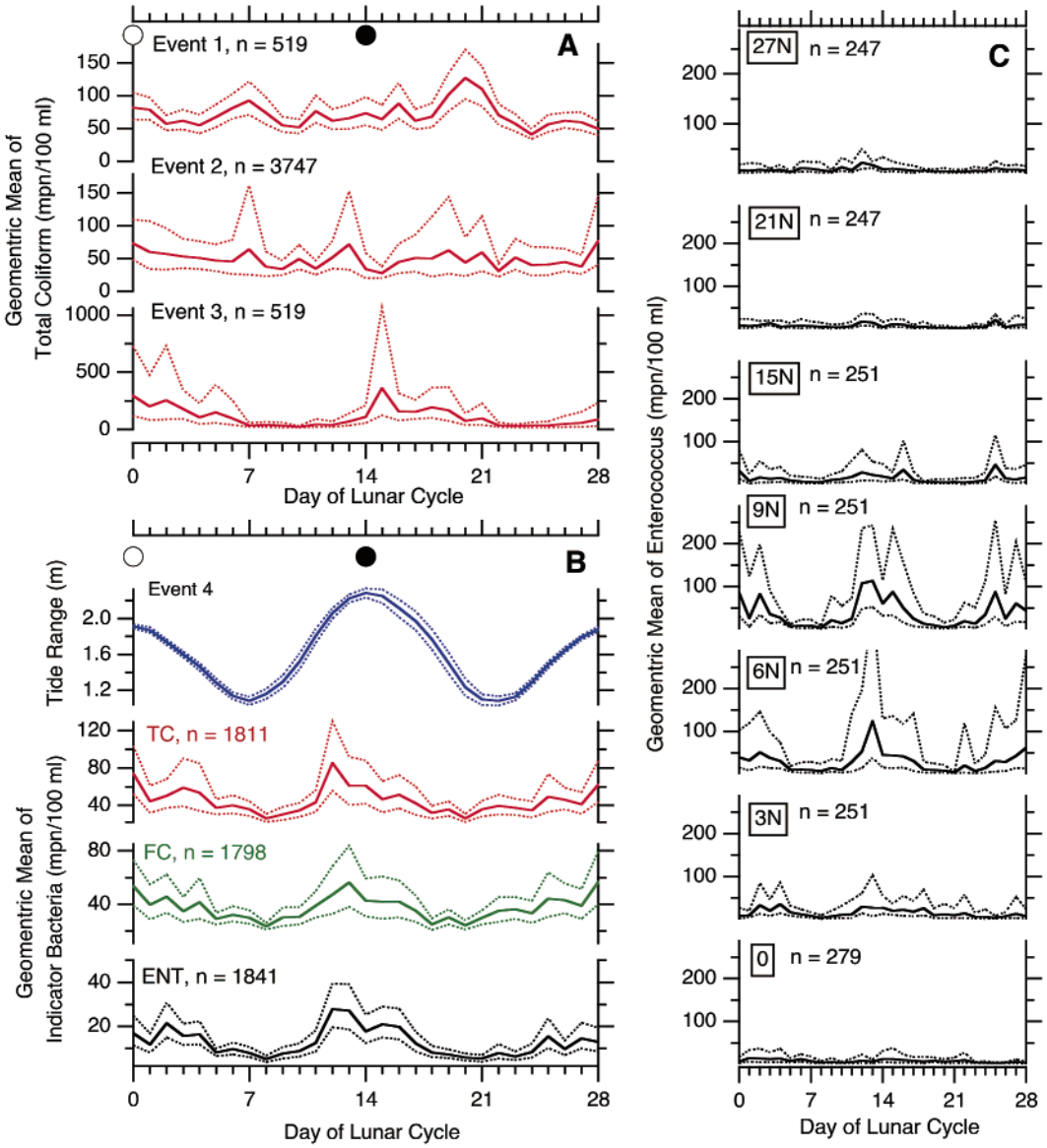

FIGURE 3. (A) Geometric means (GM) (solid lines) and 95% confidence intervals (dashed lines) of TC as a function of day in the lunar cycle measured during JJA from 1964 to 1970 (event 1) at monitoring stations 0, 3N, 6N, 9N, 12N, and 15N (21N and 27N were not utilized during this period) (top panel), from 1972 to 1981 (event 2) at station 21N (middle panel), and from 1983 to 1990 (event 3) at station 0 (bottom panel). The lunar phase is indicated at the top of the graph (○ and ● are full and new moons, respectively). (B) GMs and 95% confidence intervals of TC (red), FC (green), and ENT (black) during JJA from 1998 to 2001 (event 4) at monitoring stations 0, 3N, 6N, 9N, 15N, 21N, and 27N as a function of day in the lunar cycle. The average tide range (defined as the daily difference between the high−high and the low−low tide) and standard errors are shown in blue. (C) The spatial distribution of the lunar signal at Huntington Beach during JJA from 1998 to 2001 (event 4). The number of data points used to calculate each lunar plot is indicated next to the curves.

sunset. This result does not support the idea that bacterial reactivation and/or growth is the cause of surf zone replenishment (hypotheses i and ii above). The possibility that indicator bacteria are continuously entrained in the surf zone from onshore and offshore sources (hypothesis iii) seems likely given what is already known about this system (*8*, *9*, *14*). Foreshore sediments, on the other hand, appear to have relatively low concentrations of fecal indicator bacteria (*8*), and hence particle resuspension is probably not responsible for the rebound of bacteria after sunset (hypothesis iv).

Short-Term Studies: Ten-Minute Variability. The variability of surf zone water quality extends to time scales shorter than 1 h based on results of a study in which surf zone samples were collected every 10 min for 12 h at six shoreline sites (Figure 5). Coherent pulses of ENT are evident in these time series, although they are quite short-lived (<80 min); similar high frequency variability is evident in the TC and EC signals (data not shown). Between 6N and 9N an ENT pulse appears to propagate in a northeast direction at approximately 0.3 m/s (dashed line in the figure), consistent with an earlier measurement of littoral drift velocities at Huntington Beach during similar wave conditions (*8*). Assuming a littoral drift velocity of 0.3 m/s and a maximum pulse duration of 80 min, we estimate that individual pulses of ENT in the surf zone are less than 1.4 km in length. The results of a dye study (*8*) indicate that one rip cell in Huntington Beach is approximately 800 m in length, and thus, the pulse size is on the order of the distance between rip cells. This observation is consistent with the idea that pulses of indicator bacteria originate when contamination from intermittent onshore or offshore sources is mixed into the surf zone by rip cell currents (*8*, *22*). If this is the case, then high-frequency variability should not be unique to Huntington Beach as rip currents are a universal characteristic

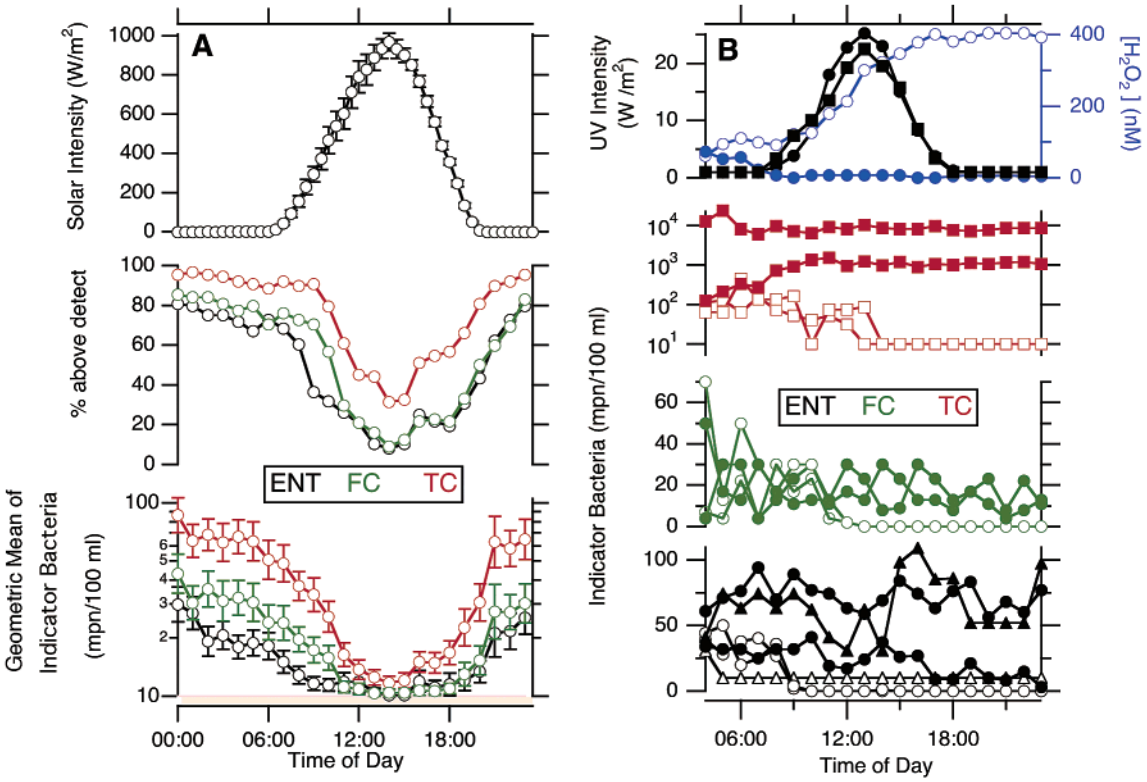

FIGURE 4. (A) Results from the hourly 2-week sampling program from May 2−16, 2000. A total of 6336 TC, FC, and ENT measurements were sorted according to the time of day they were collected. Shown are the percent of samples above the detection limit of 10 mpn/100 mL (middle panel), and the geometric mean and 95% confidence intervals of indicator bacteria (bottom panel). The average solar irradiance and standard error for each hour are shown in the top panel. (B) Results from mesocosm experiments on October 20 (circles and triangles) and 27 (squares), 2001. TC, FC, and ENT concentrations as a function of time in aquariums exposed to sunlight (open symbols) and covered with a black tarp (closed symbols) are shown in the second, third, and fourth panel from top, respectively. For ENT, concentrations determined using EPA Method 1600 and Enterolert are designated by circles and triangles, respectively. In the top panel, UV intensity on both days (black) is shown along with the concentration of H_2O_2 (blue) measured in one light (open circles) and one dark (solid circles) aquarium on October 20.

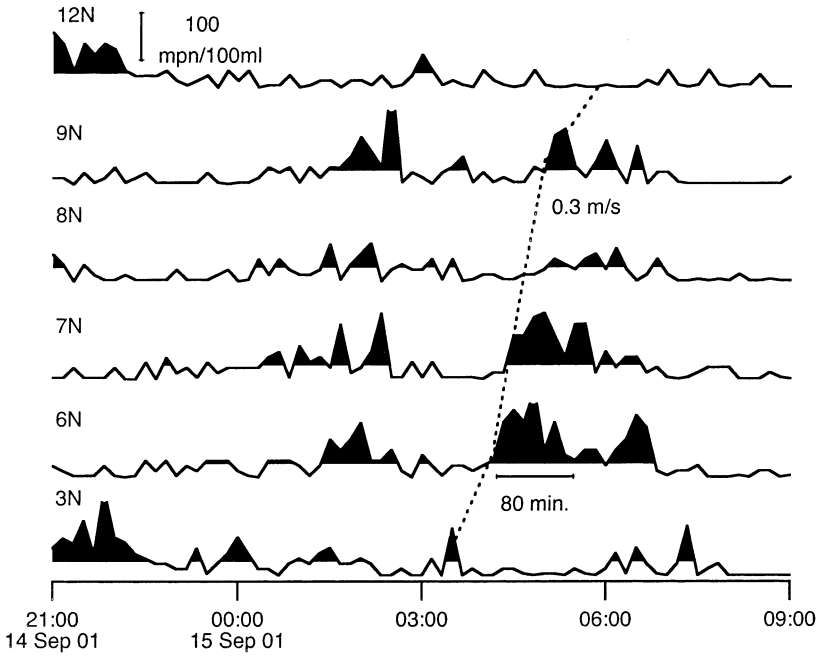

FIGURE 5. ENT concentrations measured during 10-min sampling from 21:00 on September 14, 2001, to 9:00 on September 15, 2001, at six surfzone stations. Concentrations in excess of 35 mpn/100 mL are indicated by filled portions of the curves. This plot summarizes a total of 584 ENT measurements.

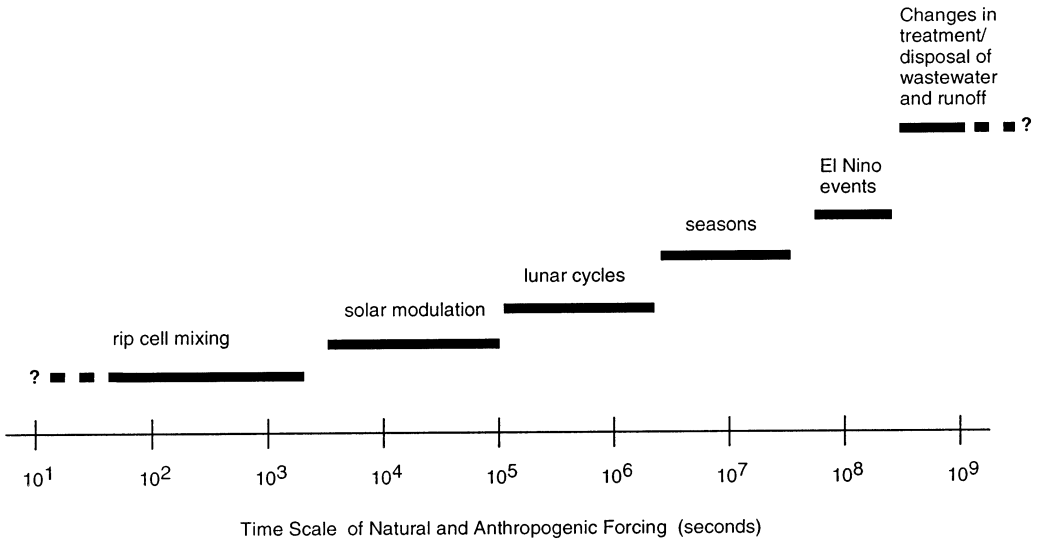

FIGURE 6. Surf zone water quality at Huntington Beach varies over time scales that span at least 7 orders of magnitude, from minutes to decades.

of wave-dominated beaches (*22*). It should be noted that resuspension of sediments by wave-driven turbulence and precision limits associated with biological assays might also contribute to the intermittent character of the bacterial signal.

Implications. The results presented above can be understood within the conceptual framework illustrated in Figure 6. At the finest scale, the pollution signal in the surf zone consists of individual contamination pulses that last on the order of 100 min or less. These pulses may be generated when intermittent sources of pollution (e.g., ebb flow from rivers and estuaries or cross-shelf transport of offshore wastewater fields) are mixed into the surf zone by rip cells. The frequency with which bacterial pulses appear in the surf zone and their magnitude are modulated by a number of different processes operating over many time scales including the rise and fall of the sun, phase of the moon, change of season (JJA vs JFM), El Niño events, and changes in the treatment and disposal of wastewater and dry weather runoff. The lunar variability patterns are interesting because they suggest an underlying mechanism for the delivery and mixing of pollutants in the coastal ocean and may may also prove useful for fingerprinting specific types of point and nonpoint sources of coastal pollution.

The variability documented in this paper has immediate practical implications for the monitoring and mitigation of coastal pollution:

(i) Decisions to post or close a beach should not be based on the concentration of indicator bacteria in a single grab sample. In many coastal areas of the United States, warning signs are posted on public beaches if the concentration of indicator bacteria in a single sample exceeds a set of single-sample standards. For example, in California, the single-sample standards for ENT, FC, and TC are respectively 104, 400, and 10 0000 mpn or colony forming units (cfu) per 100 mL; a lower single-sample standard for TC of 1000 mpn or cfu per 100 mL applies when the TC/FC ratio falls below 10. There is generally a 24−96-h delay between when a sample is taken and when the testing results are known. Hence, if a surf zone sample exceeds one of the single-sample standards, it is likely that the pollution event that caused the exceedence will have passed by the time a sign is posted. Indeed, a study of Los Angeles daily monitoring data found that 70% of single-sample exceedences lasted 1 day or less (*23*), and similar results were reported for beaches along Lake Michigan (*24*). This problem cannot be resolved solely by developing more rapid methods of detecting indicator bacteria. On the basis of all the measurements made during the hourly and 10-min sampling programs conducted as part of this study, we calculate that at least 70% of the single-sample exceedences last less than 1 h ($n = 86$) and at least 40% last less than 10 min ($n = 28$). Even if indicator bacteria could be detected instantaneously, the high-frequency character of the bacterial signal in the surf zone would result in the untenable situation where beach postings would have to be updated on a minute-by-minute basis.

(ii) The geometric mean standard, in which the geometric mean of multiple samples collected over a specified window of time is used to make decisions about beach postings or closures, may represent a better way of assessing beach water quality as compared to the single-sample standard. Future research should focus on refining marine bathing water standards to determine the optimal number of samples and days over which to calculate the mean. Currently, California's geometric mean standards (35, 200, and 1000 mpn or cfu/100 mL for ENT, FC, and TC, respectively) are based on a 30-day averaging window.

(iii) Fecal indicator bacteria in the surf zone are strongly affected by sunlight and possibly its secondary effects (e.g., photochemically produced oxidants). Hence, the time a sample is collected can dramatically influence the concentration of indicator bacteria detected. This observation has several important implications. First, routine water quality monitoring programs should, at a minimum, collect samples at the same time every day, ideally early in the morning before sunlight has had a chance to reduce bacterial concentrations. Early morning sampling is justified both because it represents a conservative approach (i.e., the concentration of bacteria in the morning is likely to be higher than at mid-day) and because human viruses, which can also be associated with sewage-contaminated coastal waters, are more resistant than bacteria to sunlight (*25*). Second, spatial surveys intended to isolate sources of coastal pollution should carefully take into account potential artifacts associated with collecting samples at different times of the day. For example, apparent spatial gradients in the concentration of fecal indicator bacteria may, in fact, reflect when during the day different samples were collected.

(iv) Despite public perceptions to the contrary (*1*), beach water quality has actually improved over time. The record at Huntington Beach indicates that large-scale investment in waste treatment and disposal infrastructure has had a positive effect on coastal water quality over time. It is also

interesting to note that it takes, on average, 5−8 yr to identify and mitigate small-scale point sources of shoreline pollution, for example, storm drains. Perhaps better coordination between governmental agencies responsible for monitoring, regulating, and mitigating coastal pollution would reduce this overall response time.

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