

Episodic changes in lateral transport and phytoplankton distribution in South San Francisco Bay

Abstract—Observations in South San Francisco Bay during 1982 showed that substantial cross-channel, nontidal flows accompanied episodic increases in the longitudinal, nontidal flows. Along the channel the nontidal circulation was enhanced during the monthly minima in tidal energy or as a result of wind forcing, producing up-estuary flows 2–3 times greater than normal. These longitudinal pulses modified the horizontal and vertical salinity distributions and generated cross-channel flows of up to 0.07 m s^{-1} that persisted for several days. The increased lateral flows were directed to the west and may explain the large fluctuations in phytoplankton biomass observed over the broad eastern shoal during spring.

Estuaries are environments of extreme spatial variability. This variability has been well characterized along the longitudinal axis due to the importance of river-ocean mixing in the distribution of dissolved and particulate constituents. In broad coastal plain estuaries and embayments having sharp bathymetric transitions, however, variability transverse to the longitudinal axis can equal that in the longitudinal dimension (e.g. Malone et al. 1986). Hence, in these systems the characterization of spatial variability requires sampling in all three dimensions and, more importantly, requires knowledge of processes that generate spatial patterns in three dimensions. Spatial distributions of nonconservative constituents, such as phytoplankton, result from the balance between local kinetics (rates of production and consumption) and transport processes. Here we present observations made in the South San Francisco Bay estuary during spring 1982, when the circulation pattern (transport) changed markedly over short times. Epi-

sodic departures from the near circulation coincided with large-scale redistributions of phytoplankton biomass, suggesting a mechanism through which physical processes can determine spatial distributions in estuaries.

The southern section of San Francisco Bay (South Bay) is a wide coastal plain estuary. There is a broad, deep basin at the entrance, but to the south a single deep channel (10–15-m depth) runs the length of the estuary (Fig. 1). The transverse San Bruno Shoal forms a sill in the channel between the northern and central parts of the estuary. Bordering the channel are extensive shoals (<3-m depth) that occupy 40% of the area of South Bay. Tidal currents are predominantly semidiurnal and have typical speeds of 0.5 m s^{-1} along the channel, increasing to $>1.0 \text{ m s}^{-1}$ at spring tides; across the shoals these speeds are reduced (Cheng and Gartner 1985). Although little is known of the nontidal circulation across the shoals, flows along the channel are highly variable in both magnitude and direction as a result of hydrologic, tidal, and meteorological forcings (Walters 1982; Walters et al. 1985). Phytoplankton biomass is greatest during spring (Cloern et al. 1985). In the channel, blooms occur in response to increased stratification, which usually occurs during prolonged neap tides in March or April. Phytoplankton biomass also increases over the lateral shoals where the water column remains vertically well mixed, but connections between the channel and shoal blooms are poorly understood.

Throughout 1982, data were collected at a series of stations located along the main channel and across the broad eastern shoal (see Fig. 1) to characterize horizontal and vertical distributions of salinity and phytoplankton biomass. Sampling occurred every 3–7 d from mid-January to the end of June, and about every 2 weeks thereafter. Separate vessels were used to sample concurrently along the channel and across the shoal. Data collection took ~4–5 h each day

Acknowledgments

We thank Ralph Cheng and Jeff Gartner for providing current-meter data, Andrea Alpine, Brian Cole, Fred Nichols, and Jan Thompson for field assistance, Sally Wienke for laboratory analyses, and the crew of the RV *Polaris*, Byron Richards and Scott Conard. David Jones drafted the figures, and Marlene Noble and Stephen Monismith provided manuscript reviews.

and occurred at varying phases of the tide. Intratidal variability was measured on 16 April (neap tide) and 27 April (spring tide), when each station was sampled repeatedly over the tidal cycle.

At each station in the channel, measurements of salinity, temperature, and *in vivo* fluorescence were made at the surface, bottom, and at selected intermediate depths. Water was pumped from depth to an inductive salinometer (Schemel and Dedini 1979) and Turner Designs model 10 fluorometer. Over the shoals, salinity and temperature were measured with a handheld Beckman RS35 inductive salinometer. Salinity values were calibrated with bottle samples that were taken randomly along the salinity gradient and analyzed in the laboratory with a Beckman RS7-B salinometer. Surface and near-bottom water samples were collected at all shoal stations for determination of *in vivo* fluorescence. The fluorometers were calibrated on each cruise by measuring Chl *a* concentration in selected water samples with the methods of Strickland and Parsons (1972) and Riemann (1978).

Here we consider only data collected during the highly dynamic spring period (February–May). During that time, as part of an ongoing study to examine tidal and residual flows, current meters (Endeco 174) were deployed for varying intervals at two stations in the main channel (Fig. 1). Meters were positioned at 2.0 and 5.4 m below MLLW at station GS27 (mean water depth, 8 m) and at 3.0 and 6.3 m below MLLW at station GS28 (mean water depth, 9 m). These instruments record average speed and instantaneous values of direction every 2 min (Cartner and Walters 1986). The current-meter records were vector averaged to obtain hourly values, decomposed into their along- and across-channel directions, and low-pass filtered (Godin 1972).

Despite discontinuities in the current-meter records, the along-channel, or longitudinal, component of the nontidal flow indicates that a weak gravitational circulation occurred throughout spring, with mean speeds of $\sim 0.05 \text{ m s}^{-1}$ (Fig. 2a,b). On three occasions, however, there were large departures from this mean flow pattern. For a period of ~ 1 week starting on 13 February,

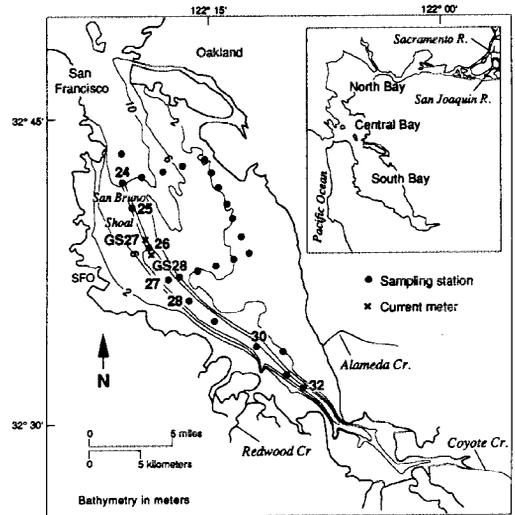


Fig. 1. Map of South San Francisco Bay (South Bay) showing the hydrographic and current-meter stations, February–May 1982. SFO—San Francisco Airport.

up-estuary flow, with speeds of up to 0.12 m s^{-1} , was recorded at all the current meters, disrupting the normal two-layered circulation. It was followed by a period of down-estuary flow. Similar up-estuary flow pulses occurred on 16–18 March (at GS27) and on 4–11 April (at GS28). Commencing on 14 April there was very strong down-estuary flow, which attained speeds of 0.20 m s^{-1} on 18 April.

These departures from the mean nontidal circulation in February and March occurred at the time of the monthly minima in tidal energy (Fig. 2d). The magnitude of density-driven, nontidal circulation is inversely proportional to the vertical eddy viscosity and is therefore greatest during neap tides (Officer 1976). In South Bay, near the equinox, this effect is amplified by the coincidence of tropic and neap tides, resulting in a large diurnal inequality and thus a prolonged period of low tidal velocities. Similar large increases in the gravitational circulation at neap tides occur in Puget Sound (Geyer and Cannon 1982).

During April the tidally driven flow patterns were disrupted by strong northerly directed winds. As Weisberg (1976) showed in the Providence River, a compensating

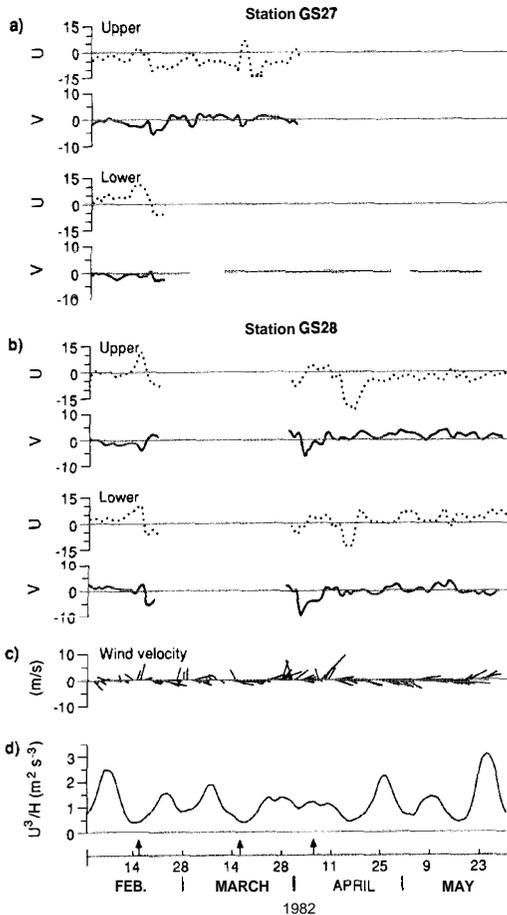


Fig. 2. a,b. Low-pass filtered, along-channel (U , positive up-estuary) and across-channel (V , positive to the east) velocities at stations GS27 and GS28 between February and May 1982. Station locations shown in Fig. 1. All speeds in $cm\ s^{-1}$. Arrows mark periods of increased up-estuary and westerly flows. c. Daily mean winds at San Francisco Airport. Directions rotated to oceanographic convention. d. Tidal energy calculated with predicted maximal tidal speed, U , at the Golden Gate (NOAA Tide Tables) and depth $H \approx 10\ m$.

bottom return flow will occur in response to axial winds. For the period February through May 1982, strong (i.e. $>5.1\ m\ s^{-1}$, and thus in the upper quartile for the sampling period; Tukey 1977) northerly directed winds occurred on 15 February and between 30 March and 2 April (Fig. 2c). Thus we infer that the up-estuary (i.e. southerly) flow in early April was wind forced. The large down-estuary flow between 14 and 19 April followed a very high freshwater dis-

charge from the Sacramento–San Joaquin Rivers into the mainstem of San Francisco Bay on 13 April ($6,500\ m^3\ s^{-1}$; mean spring discharge for 1982 was $3,000\ m^3\ s^{-1}$).

The lateral, nontidal flows showed similar episodic variations in magnitude and direction. Mean speed of the cross-channel flows was $0.015\ m\ s^{-1}$, and they were generally directed to the east. On several occasions, however, there were strong pulses of westerly flow, with speeds between 0.05 and $0.10\ m\ s^{-1}$ —3–6 times greater than the mean (Fig. 2a,b). Utilizing the techniques of exploratory data analysis (Tukey 1977), we consider that flows are significant if they lie in the upper quartile for the sampling period. Analysis of the current-meter records showed that periods of significant ($>0.02\ m\ s^{-1}$) westerly flows occurred between 15 and 21 February (GS27 and GS28), 16 and 17 March (GS27), and 3 and 10 April (GS28). These flow events closely corresponded to the enhanced up-estuary flows. The down-estuary flow event in mid-April, despite its magnitude, did not affect the lateral flows at station GS28.

On time scales of a week or less, there was marked variation in the degree of stratification along the channel and the strength of the horizontal salinity gradient across the eastern shoal. Although our hydrographic data were collected at varying phases of the tide, results of tidal cycle studies during 1987 (Cloern et al. 1989) and 1982 demonstrate that these differences in salinity distribution were not the result of intratidal variability. The strongest stratification along the channel recurred monthly—on 19 February, 19 March, and 19 April, several days after the monthly minima in tidal energy (Fig. 2d). In February, March, and early April, stratification increased rapidly in conjunction with the enhanced up-estuary, nontidal flows (Fig. 3). During winter and spring, when the Sacramento–San Joaquin River flow is large, low-salinity water may enter the mouth of South Bay and reverse the surface salinity gradient down-estuary from the San Bruno Shoal. During 1982 this reversal was evident on 19 February, 19 March, and 16 April (Fig. 3). On all occasions the stratification decayed within 5 d.

Surface salinities in South Bay ranged be-

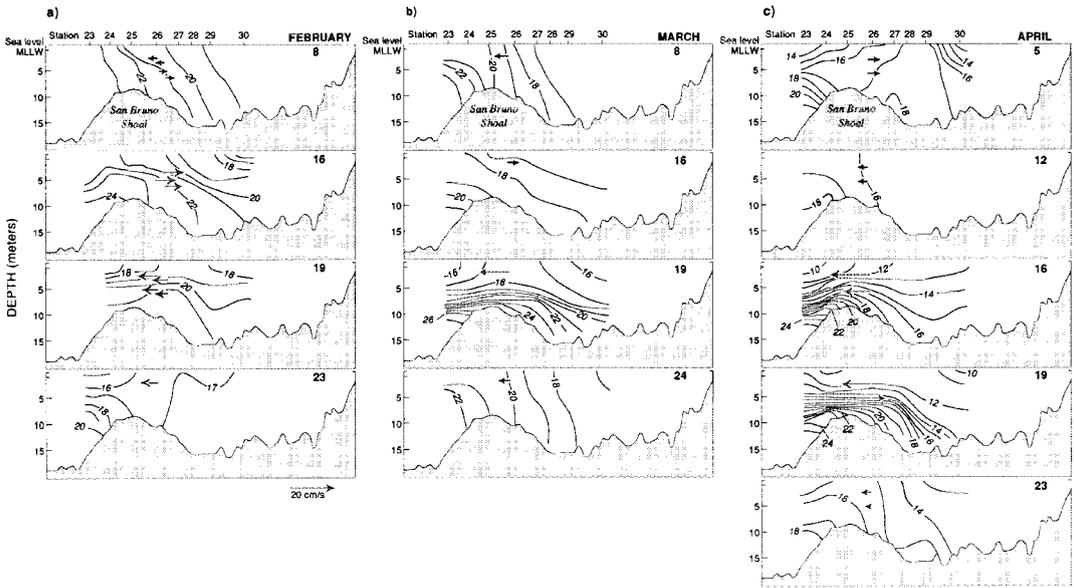


Fig. 3. Changes in the salinity distribution along the channel in South Bay during February, March, and April 1982. Arrows represent the direction and magnitude of nontidal flows on each date.

tween 11 and 23‰, with minimal salinities to the south and east (Fig. 4). This salinity distribution is typical (Conomos et al. 1985; Powell et al. 1989) and reflects the local sources of freshwater (Alameda and Coyote Creeks, Fig. 1). Note that at the time of the very large freshwater intrusion at the estuary mouth (16 April), the horizontal salinity gradient across the eastern shoal was completely reversed, with more dense water trapped against the eastern shore; within 1 week however, the lateral gradient had returned to normal (Fig. 4). Horizontal gradients in the lateral direction were frequently as great as in the longitudinal. Isohalines were usually aligned oblique to the channel, but they rotated to a more northerly, or along-estuary, orientation during the up-estuary flow events of 16 February, 16 March, and 5–12 April (Fig. 4). This change in orientation suggests a down-estuary flow along the eastern shoal in response to the up-estuary flow in the channel.

The distribution of phytoplankton biomass (measured as Chl *a*; see Wienke and Cloern 1987) was highly dynamic during this period. In the channel, Chl *a* concentration was $<5 \text{ mg m}^{-3}$ until the onset of

the annual bloom in mid-April, when chlorophyll concentration in the surface layer was $10\text{--}15 \text{ mg m}^{-3}$. Chlorophyll concentrations over the eastern shoals were consistently higher than in the channel, attaining values up to 60 mg m^{-3} and exhibiting large-amplitude variations over 1–2 weeks. Four distinct "events" (three of which are shown in Fig. 5) were evident over the eastern shoal, each characterized by a rapid increase in biomass followed by an abrupt decline. Large redistributions of phytoplankton biomass occurred during each event. Phytoplankton biomass on 8 February was high across the eastern shoal with a strong horizontal gradient in chlorophyll between the shoals and the channel (Fig. 5). Between 8 and 16 February, however, biomass declined over the shoals, and by 23 February biomass was uniformly low ($<10 \text{ mg m}^{-3}$ Chl *a*) across the sampling grid. Remarkably similar sequences occurred from 2 to 16 March and from 26 March to 5 April.

Data presented here show that during spring 1982 there were episodic increases in the nontidal flows both along and across the channel. In February and March the up-estuary flow pulses reflected an increase in

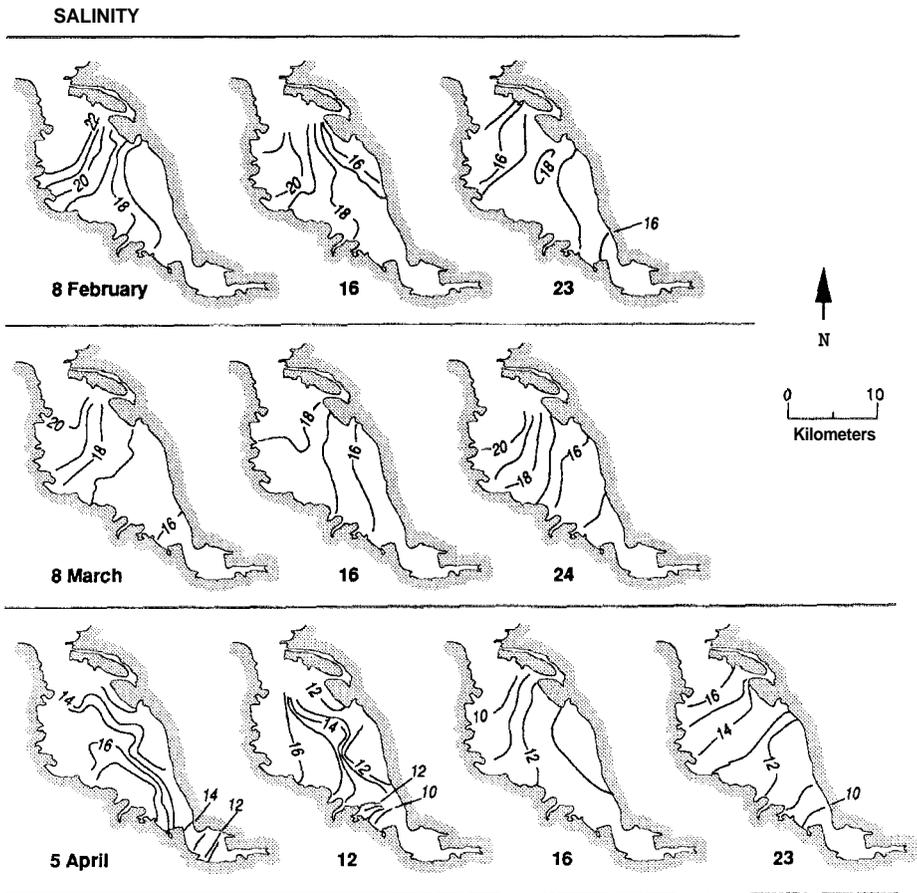


Fig. 4. Changes in the horizontal distribution of near-surface salinity in South Bay during February, March, and April 1982.

the gravitational circulation at neap tides, whereas in April the up-estuary flow was driven by winds and then followed by a large down-estuary flow associated with extreme rainfall. Studies of variability in the nontidal currents of other estuaries have focused on these longitudinal flows. In South Bay, however, changes in the direction and magnitude of the lateral, or cross-channel, flows accompanied changes in the longitudinal flow. Nontidal, lateral transports in estuaries can be the result of geomorphological variability such as channel bends, varying bathymetry or tributary rivers (Dyer 1977), persistent lateral density gradients (Doyle and Wilson 1978), or cross-estuary winds (Boicourt 1982). Abrupt temporal changes in cross-channel flows can be induced by

changes in the cross-estuary wind forcing or the lateral density gradient. As neither of these conditions pertain to the events observed in South Bay, the generation mechanism of these lateral flow pulses is uncertain. These events clearly demonstrate nonetheless the three-dimensional nature of estuarine flows and the magnitude of event-scale departures from the mean circulation.

The potential for episodic changes in the lateral, as well as longitudinal, nontidal flows has implications for the distribution of suspended and dissolved materials across an estuary. In South Bay during 1982, the three periods of rapid phytoplankton depletion over the shoals coincided with the periods of increased up-estuary and westerly directed cross-channel flows. This coinci-

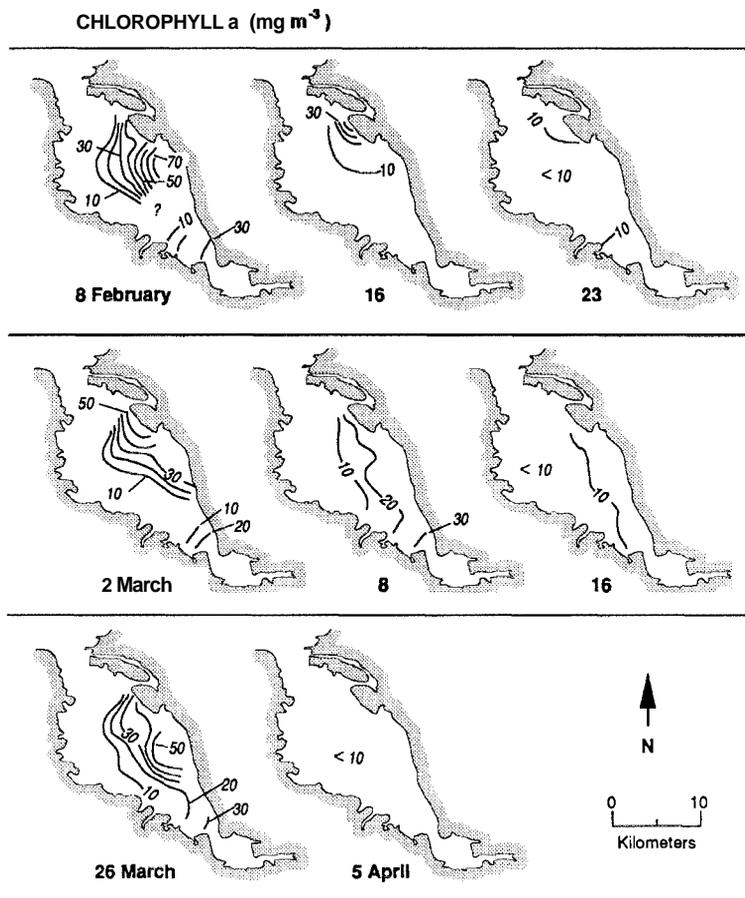


Fig. 5. Changes in the horizontal distribution of phytoplankton biomass (near-surface Chl *a* concentration, mg m^{-3}) in South Bay around the times of the longitudinal and lateral pulsed flow events. Near-surface and near-bottom Chl concentrations were similar over the eastern shallows.

dence suggests that when nontidal circulation is weak and directed to the east, phytoplankton biomass can accumulate over the eastern shallows (Powell et al. 1988 propose an alternative explanation). During the episodic pulses, cross-channel flows reverse and accelerate (to speeds of 0.07 m s^{-1}), and down-estuary flows may be induced along the shoals. Both these flows can transport phytoplankton biomass off the shallows into the deeper channel, either to the west or north, at rates faster than population growth ($0.3\text{--}1 \text{ d}^{-1}$) can resupply (Alpine and Cloern 1988).

These observations from South San Francisco Bay suggest several conclusions that may apply to other coastal plain estuaries.

First, a background pattern of weak, nontidal circulation can be disrupted, at the event scale, by tidal, meteorological, or hydrologic forcings. Such events may be characterized by strong coherence between enhanced flows in longitudinal and lateral directions. Second, these episodes of enhanced flow can be associated with rapid redistributions of phytoplankton biomass. Thus local biological processes (growth, grazing) can dominate distributions (and create large lateral gradients) during periods of weak circulation, but advective transport can dominate during episodes of enhanced circulation. Malone et al. (1986) demonstrated similar connections between lateral transports and phytoplankton distribution

across upper Chesapeake Bay. Finally, these conclusions apply to other constituents, such as planktonic larvae, nutrients, or suspended sediments, which also can have large horizontal gradients in estuaries.

As a final comment, we note that 1982 was a year of extremely high precipitation and river flow. The sequence of events presented here (e.g. pulsed nontidal flows, large redistributions of phytoplankton biomass) did not occur during 1987, a year of extremely low precipitation and river flow when vertical and horizontal density gradients were small (Powell et al. 1989).

*Linda M. Huzzey
James E. Cloern*

U.S. Geological Survey (MS 496)
345 Middlefield Rd.
Menlo Park, California 94025

Thomas M. Powell

Division of Environmental Studies
University of California
Davis 95616

References

- ALPINE, A. E., AND J. E. CLOERN. 1988. Phytoplankton growth rates in a light-limited environment, San Francisco Bay. *Mar. Ecol. Prog. Ser.* **44**: 167-173.
- BOICOURT, W. C. 1982. The detection and analysis of the lateral circulation in the Potomac River estuary. *Chesapeake Bay Inst. Rep.* 204 p.
- CHENG, R. T., AND J. W. GARTNER. 1985. Harmonic analysis of tides and tidal currents in South San Francisco Bay, California. *Estuarine Coastal Shelf Sci.* **21**: 57-74.
- CLOERN, J. E., B. E. COLE, R. L. J. WONG, AND A. E. ALPINE. 1985. Temporal dynamics of estuarine phytoplankton: A case study of San Francisco Bay. *Hydrobiologia* **129**: 153-176.
- , T. M. POWELL, AND L. M. HUZZEY. 1989. Spatial and temporal variability in South San Francisco Bay (USA). 2. Temporal changes in the salinity, suspended sediments, and phytoplankton biomass and productivity over tidal time scales. *Estuarine Coastal Shelf Sci.* **28**: 599-613.
- CONOMOS, T. J., R. E. SMITH, AND J. W. GARINER. 1985. Environmental setting of San Francisco Bay. *Hydrobiologia* **129**: 1-12.
- DOYLE, B. E., AND R. E. WILSON. 1978. Lateral dynamic balance in the Sandy Hook to Rockaway Point transect. *Estuarine Coastal Mar. Sci.* **6**: 165-174.
- DYER, K. R. 1977. Lateral circulation effects in estuaries, p. 22-29. *In* Estuaries, geophysics and the environment. *Natl. Acad. Sci.*
- GARTNER, J. W., AND R. A. WALTERS. 1986. Tidal and residual currents in South San Francisco Bay, California. Results of measurements, 1981-1983. U.S. Geol. Surv. Water Res. Invest. Rep. 86-4024. 148 p.
- GEYER, W. R., AND G. A. CANNON. 1982. Sill processes related to deep-water renewal in a fjord. *J. Geophys. Res.* **87**: 7985-7996.
- GODIN, G. 1972. The analysis of tides. Univ. Toronto.
- MALONE, T. C., AND OTHERS. 1986. Lateral variation in the production and fate of phytoplankton in a partially stratified estuary. *Mar. Ecol. Prog. Ser.* **32**: 149-160.
- OFFICER, C. B. 1976. Physical oceanography of estuaries. Wiley.
- POWELL, T. M., J. E. CLOERN, AND L. M. HUZZEY. 1989. Spatial and temporal variability in South San Francisco Bay (USA). 1. Horizontal distributions of salinity, suspended sediments, and phytoplankton biomass and productivity. *Estuarine Coastal Shelf Sci.* **28**: 583-597.
- , S. WILLMOT, J. D. MURRAY, V. S. MANORANJAN, AND J. E. CLOERN. 1988. Transient spatial patterns in plankton communities: Blooms and travelling waves of phytoplankton in estuaries, p. 236-257. *In* Proc. Trieste Conf. Math. Ecol.
- RIEMANN, B. 1978. Carotenoid interference in the spectrophotometric determination of chlorophyll degradation products from natural populations of phytoplankton. *Limnol. Oceanogr.* **23**: 1059-1066.
- SCHEMEL, L. E., AND L. A. DEDINI. 1979. A continuous water sampling and multiparameter system for estuaries. U.S. Geol. Surv. Open-File Rep. 79-273.
- STRICKLAND, J. D. H., AND T. R. PARSONS. 1972. A practical handbook of seawater analysis, 2nd ed. *Bull. Fish. Res. Bd. Can.* 167.
- TUKEY, J. W. 1977. Exploratory data analysis. Addison-Wesley.
- WALTERS, R. A. 1982. Low frequency variations in sea level and currents in South San Francisco Bay. *J. Phys. Oceanogr.* **12**: 658-668.
- , R. T. CHENG, AND T. J. CONOMOS. 1985. Time scales of circulation and mixing processes of San Francisco Bay waters. *Hydrobiologia* **129**: 13-36.
- WEISBERG, R. H. 1976. The nontidal flow in the Providence River of Narragansett Bay: A stochastic approach to estuarine circulation. *J. Phys. Oceanogr.* **6**: 721-734.
- WIENKE, S. M., AND J. E. CLOERN. 1987. The phytoplankton component of seston in San Francisco Bay. *Neth. J. Sea Res.* **21**: 25-33.

*Submitted: 7 June 1989
Accepted: 11 October 1989
Revised: 2 November 1989*