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Spatial and Temporal Variability in South San Francisco Bay (USA). I. Horizontal Distributions of Salinity, Suspended Sediments, and Phytoplankton Biomass and Productivity

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The horizontal pattern of mesoscale (1 4 km) variability in salinity was a poor predictor of mesoscale patterns in chlorophyll *a*, suspended particulate matter, and daily primary productivity in the South San Francisco Bay estuary during spring 1987. The tidally-averaged salinity distribution varied over weekly time scales, reflecting inputs of freshwater as well as transport processes. Spatial distributions of the other quantities also varied weekly, but not in concert with the salt field. Spatial patterns of phytoplankton biomass (chlorophyll *a*) deviated from the salinity patterns, largely reflecting *in situ* production of phytoplankton biomass during the spring bloom. The tidally-averaged distribution of suspended particulate matter (SPM) was highly dynamic and responded to (1) the riverine input of suspended sediment during a freshet, (2) neap-spring variations in tidally-driven resuspension, and (3) resuspension in shallows following a period of wind mixing. Two-dimensional distributions of primary productivity P', derived from maps of biomass and turbidity (SPM), also varied weekly, but the spatial variability of P' was only about half that of SPM and chlorophyll. Since the magnitude and patterns of spatial variability differ among nonconservative quantities, at least in part because of local sources and sinks, we conclude that the spatial distributions of nonconservative quantities cannot be predicted from distributions of conservative tracers, such as salinity.

Introduction and background

Spatial patterns of estuarine quantities change with time. The distribution of conserved quantities may reflect differences in tidal advection (Dyer & Ramanoorthy, 1969), the influence of bathymetry (Ingram, 1976), meteorological events (Elliot & Wang, 1978), varying freshwater flows (Garvine, 1975), or other dynamic effects (Smith, 1978, 1980). In addition, for nonconservative properties, local *in situ* sources and sinks may contribute to

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the observed distributions (Ulanowicz & Flemer, 1978). Previous measurements of the patterns of physical parameters in estuaries, such as spatial variability in the salinity and velocity fields, have been conducted with the aim of evaluating the longitudinal salt flux (Dronkers & van de Kreeke, 1986), or the dynamic balance (Pritchard, 1952,1956; Dyer, 1973). Accordingly, they have focused on vertical variability, along and across the estuary.

Other investigators have measured two-dimensional surface distributions of salt, i.e. Meade (1966)—Connecticut River; Dyer (1973)—Southampton Water; and de Silva Samarasinghe and Lennon (1987)—Gulf St Vincent. However, none of these studies present simultaneous information on the distribution of non-conservative quantities, such as chlorophyll a or suspended sediments. Other two-dimensional studies give data on such non-conservative parameters. Cadee and Hegeman (1974) present temporal series of chlorophyll a and potential primary productivity in the Dutch Wadden Sea over monthly time scales. Harrison *et* al. (1983) review data on chlorophyll a, turbidity, and primary production (and many other biological quantities) for the Strait of Georgia, though few of the investigations overlap one another or other physical/hydrographic studies. Several works compare conservative (e.g. physical) and nonconservative properties, but do not attempt to present a full two-dimensional pattern. Seliger *et* al. (1981) and Malone *et* al. (1986) give accounts of the connection between some physical phenomena and biological quantities, including chlorophll a, in different regions of the Chesapeake Bay. Similar investigations in Narragansett Bay (Farmer *et* al., 1982), the Bay of Concepción (Arcos & Wilson, 1984), and Bahia San Quintin (Millan-Nuñez *et* al., 1982) correlate temporal or spatial series of physical quantities, like salinity or temperature, with those for chlorophyll a or primary productivity. Duedall *et* al. (1977) present a particularly complete account of variations for a large number of quantities over a wide band of time scales—tidal and seasonal—along a single transect line near the Hudson River mouth. From studies over a year at six stations in St Margaret's Bay, Therriault and Platt (1978) concluded that variations in physical quantities, like salinity, were uncorrelated with biological and chemical variability.

In this, the first of two papers, we present detailed information about two-dimensional surface patterns of salinity and three non-conservative quantities, chlorophyll a, suspended particulate matter (SPM), and derived primary productivity, over the neap-spring time scale in South San Francisco Bay. A companion (following) contribution (Cloern *et* al., 1989) emhasizes changes over the tidal time scale. Here we focus on spatial scales of approximately 1-4 km; Powell *et* al. (1986) have discussed aspects of spatial variability over smaller and larger scales solely in the channel of this estuary. We chose salinity as a conservative quantity that can be used to indirectly trace patterns of water circulation. Emphasis was placed on chlorophyll a and turbidity (SPM) distributions for two reasons. First, these quantities indicate abundance of the important biogenic (phytoplankton) and abiotic (sediment) particles in the water column. These two seston components presumably have different mechanisms of spatio-temporal variability and, perhaps, different scales of variability. Second, they represent two important components of variability in the distribution of primary productivity in estuaries (e.g. Cole & Cloern, 1987). Accordingly, from the distributions of phytoplankton biomass (chlorophyll a) and SPM, the regression model of Cole and Cloern (1987) can be used to estimate the variability of primary productivity in two dimensions over the time and space scales considered here.

South San Francisco Bay (Figure 1) is a shallow, lagoon-type estuary characterized by extensive shoals bordering a deep (10–15 m) longitudinal channel. The tidal regime is mixed diurnal and semidiurnal; and tidal currents approximate a standing wave

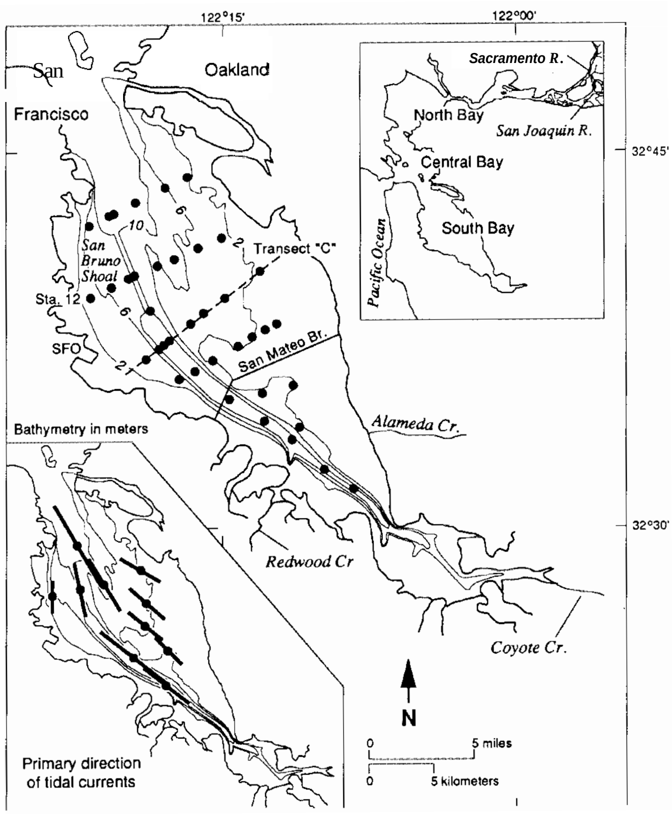

Figure 1. Map of South San Francisco Bay showing locations of sampling sites. SFO is San Francisco International Airport. Lower inset indicates mean tidal current speed and direction based on previous current meter measurements (Cheng & Gartner, 1985).

(Conomos, 1979; Walters et *al* ., 1985). Both current meter measurements (Cheng & Gartner, 1985) and numerical models (Cheng & Casulli, 1982) indicate that tidal circulation is strongly influenced by the bathymetry. Near the channel and north of the San Mateo Bridge (Figure 1), tidal streamlines lie parallel to isobaths, and the mean speed scales with depth. Hence, the tidal excursion is large (approximately 10 km) and aligned with the deep channel. However, across the shoals the tidal excursion is smaller and oblique to the isobaths (and the channel).

The seasonal change in riverine flows affects the salinity as well as turbidity and vertical density stratification, which, along with surface irradiance, are the major determinants of primary productivity (Cloern, 1984; Cole & Cloern, 1987). During the summer–autumn period of low river discharge, the salinity of South Bay is uniformly greater than 30 and, more importantly, the water column is well mixed. Phytoplankton biomass is usually low when the water column is unstratified. However, following winter or spring inputs of freshwater from the Sacramento–San Joaquin Rivers and/or from local streams, the channel can become density stratified. The degree of stratification is proportional to river flow, and it is strongly influenced by variations in tidal current speed over the neap-spring cycle (Cloern, 1984). During periods of persistent stratification, usually following a prolonged neap tide in March or April, phytoplankton biomass increases rapidly in the surface layer (Cloern, 1984; Cloern *et* al., 1985).

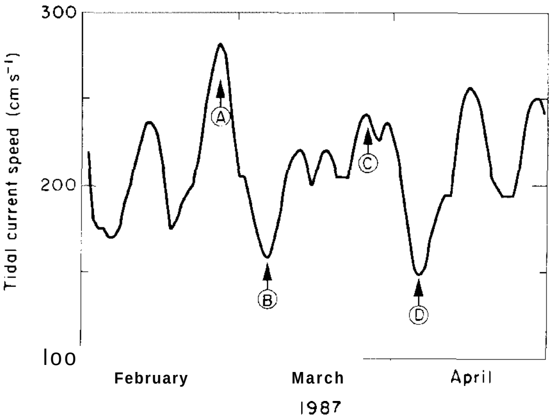

Figure 2. Predicted maximum daily current speed (NOAA Tidal Current Tables, 1987) at the entrance to San Francisco Bay, February–April 1987.

Previous studies have shown differences in salinity, SPM, chlorophyll a concentration, and primary productivity between the shoals and the channel (Cloern et al., 1985). Similar lateral variations have been observed in the Chesapeake Bay (Malone et al., 1986). Prior measurements in South San Francisco Bay were collected without regard to tidal phase, so more extensive sampling was needed to assess the extent to which the observed spatial variability was a response to tidal redistribution or longer-term processes, including local in *situ* growth and losses, and riverine inputs.

Our primary objective in this study was to characterize spatial patterns of the selected constituents, and to determine stability of the patterns over two time scales (weekly, hourly). A second objective was to determine the importance of purely physical forcing (i.e. transport) relative to local source/sink terms (e.g. growth, resuspension) on the major constituents of particulate matter in estuaries—phytoplankton and sediment. Our sampling spanned a discrete inflow event and thus allows us to assess the impact that an inflowing pulse of riverine freshwater makes on the distribution of salinity, chlorophyll a, SPM, and primary productivity. At certain times and locations 'the physics' alone appears to determine spatial and temporal patterns. At other times and places the local sources and sinks are clearly important. Further, these conclusions depend critically upon the time and space scales under consideration.

Sampling design and methods

In this study repeated measurements of surface salinity, chlorophyll a, and SPM were made within a grid of 38 fixed locations, over a 12 h period (0600 h–1800 h) on four dates in 1987. Sampling dates (Figure 2) were chosen to coincide with extreme spring tides (26 February, 27 March) and neap tides (9 March, 7 April) around the anticipated period of the spring phytoplankton bloom (Cloern, 1984). Sampling stations were spaced at about 1-4 km intervals in the main body of the South Bay (Figure 1), and were chosen to represent spatial variability along the deep channel as well as transverse to the channel across the subtidal shallows (to the 2 m isobath). Sampling was done continuously from three (26 February, 9 March) or four (27 March, 7 April) vessels that occupied each site every 2 hours. At each station, depth profiles of conductivity and temperature were

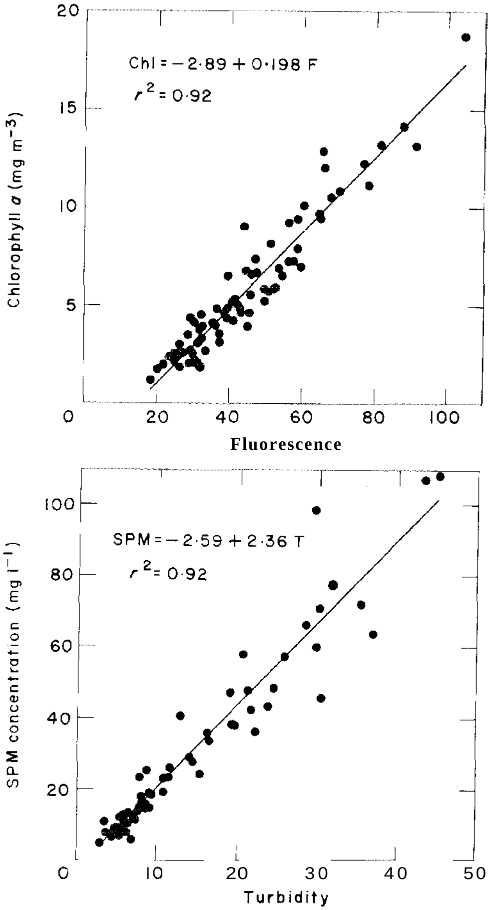

Figure 3. Calibrations of the fluorometer and nephelometer for measuring chlorophyll *a* and SPM concentrations.

obtained with Seabird CTD's (model number SBE 9/11), and surface water samples were collected with a bucket. Aliquots were later analyzed to determine concentrations of chlorophyll *a* from in *vivo* fluorescence (using a Turner Designs Model 10) and suspended particulate matter (SPM) from nephelometry (using a Turner Designs Model 40).

From selected bucket samples, aliquots were filtered onto pre-weighed 47 mm silver filters (Selas Plotronics FM-47) then air-dried for approximately a month and reweighed to determine seston weight. SPM concentration was calculated after correcting for the salt content retained in the filters (Hager & Harmon, 1984). Separate aliquots for chlorophyll *a* measurement were filtered onto 47 mm glass fiber filters (Gelman G F A/E) then frozen until analyzed in the laboratory. These filters were ground with 90% acetone, and chlorophyll *a* concentration determined spectrophotometrically using the method of Strickland and Parsons (1972) and Lorenzen's (1967) equations to correct for phaeopigments. The measured SPM concentrations from all four cruises (n = 80) were regressed against relative turbidity measured with a nephelometer (Figure 3). This highly significant linear regression ($r^2 = 0{\cdot}92$) provided a simple method for estimating SPM concentration from nephelometer readings of water samples taken at all sites on all sampling circuits. The standard error of the estimate for SPM was 6.7 mg l-'. Similarly, the measured chlorophyll a values from the four cruises were pooled and chlorophyll a concentration regressed against *in vivo* fluorescence (Figure 3). This regression was also highly significant ($r^2 = 0{\cdot}92$), allowing estimation of chlorophyll a concentration at all stations and circuits from measured *in vivo* fluorescence. The standard error of the estimated chlorophyll a concentration was 1.0 mg m^{-3}.

From measured chlorophyll a and SPM concentrations at each site, we estimated a potential daily primary productivity, P', from the empirical function of Cole and Cloern (1987) based on historical measures of primary productivity with the ^{14}C method:

$$P' = 150 + 0{\cdot}73[BZ_pI_o]. \tag{1}$$

Here, P' is productivity in the photic zone (mg C $m^{-2}\,d^{-1}$), B is chlorophyll a concentration (mg m^{-3}), Z_p is photic depth estimated from SPM concentration (mg l^{-1}), and I, is surface irradiance (Einst $m^{-2}\,d^{-1}$) measured at Redwood Creek (Figure 1) with a LiCor 190S quantum sensor, and averaged over the seven-day period preceding each sampling date. Photic depth Z_p (m) was calculated as $4{\cdot}61/k_t$ (i.e. depth of 1% surface irradiance), where the light attenuation coefficient, k_t (m^{-1}), is a function of SPM concentration (Cloern, 1987):

$$k_t = 0{\cdot}77 + 0{\cdot}06(\mathrm{SPM}). \tag{2}$$

Results and discussion

Figure 4b shows the four sampling dates relative to freshwater discharge from the Sacrament—San Joaquin River system into the northern reach of San Francisco Bay (North Bay, Figure 1). The first sampling date (A) occurred before a month-long period of heightened flow. The final sampling date (D) occurred at the end of this river flow event. In northern California 1987 was a dry year with only 60% of normal rainfall (U.S. Bureau of Reclamation). In a normal or wet year a series of large freshwater pulses is common from about December through April. Thus, the results we present here (a single-pulse study) characterize one element of a more complex seasonal process consisting of several pulses. However, because the sampling period completely bracketed a discrete flow event in a dry year, it also represents a model of the annual cycle of river-driven variability—from the low discharge period of late autumn, through the winter–spring period of high inflow, and then returning to the low flow period of summer–autumn.

As observed in earlier studies (Walters *et* al., 1985), the salinity minimum in the South Bay channel (Figure 4a) was seen about ten days after the peak in river discharge. The maximum chlorophyll concentration seen in the South Bay channel (Figure 4a) also occurred following this period of high freshwater inflow, in agreement with observations in other years (Cloern, 1984). Figure 4c shows an earlier, and smaller, pulse of freshwater into the South Bay from local sources on the east and south shores at Alameda and Coyote Creeks (Figure 1). Flow from these local sources was negligible during the four-cruise sampling period.

Figure 5 shows the patterns of tidally-averaged surface salinity on the four sampling dates. The average was calculated from the six sampling circuits taken during each day, i.e. over a 12 h tidal cycle (stations below the San Mateo Bridge were sampled only on the last two dates). Note the similarity between cruises A and B, when the isohalines in the eastern

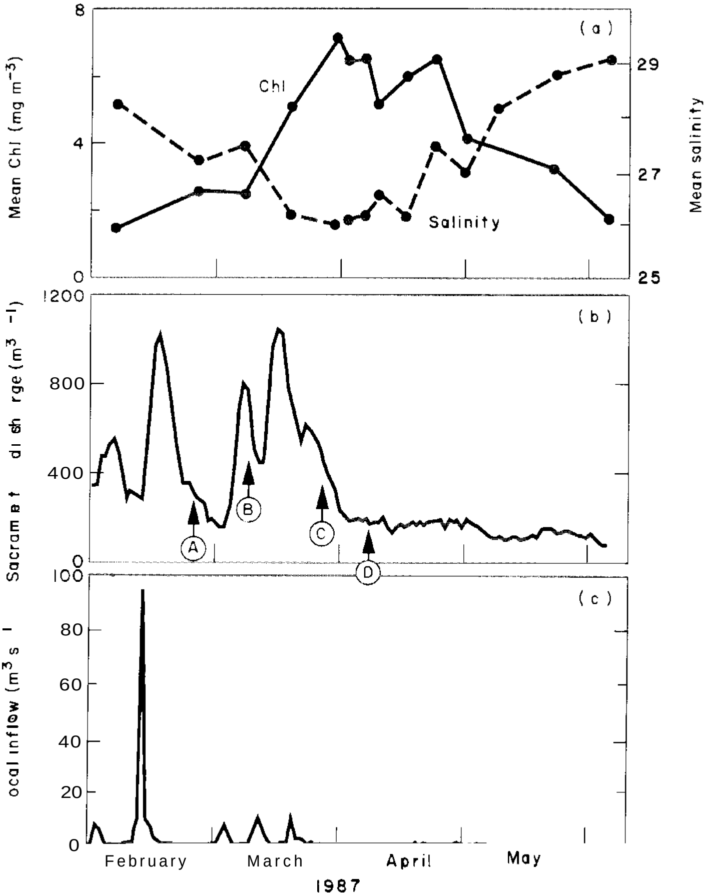

Figure 4. (a) Mean values for surface chlorophyll *a* and surface salinity measured at all channel sites in South San Francisco Bay, north of San Mateo Bridge (see Figure 1), from February through May 1987. (b) Daily discharge into San Francisco Bay from the Sacramento–San Joaquin River system (California Department of Water Resources, unpublished data). (c) Daily discharge from Alameda Creek+ Coyote Creek into South San Francisco Bay (U.S. Geological Survey, unpublished data). Sampling dates are noted with arrows.

portion of the bay paralleled the longitudinal axis of the estuary, approximately northwest to southeast. Salinity distributions from these first two cruises differed substantially from the last two, when the longitudinal isohalines were absent. The third cruise, C, occurred during the several-week-long period of strongest inflow when peak discharge (approximately 1100 $m^3 s^{-1}$) was sufficiently strong to drive freshwater into the central South Bay (Imberger *et* al., 1977). Thus, the longitudinal gradient in salinity was reversed at the (northern) mouth of the South Bay, leading to a salinity maximum in the mid-portion of the estuary for cruise C. Only the last cruise, D, was significantly affected by wind. Figure 6 shows daily averaged wind speeds from nearby San Francisco International Airport during the sampling period. Adopting the viewpoint of exploratory data analysis (Tukey, 1977), we consider wind speeds to be significant if they lie in the upper quartile for the sampling period. Speeds on 7 April fell on the upper quartile boundary;

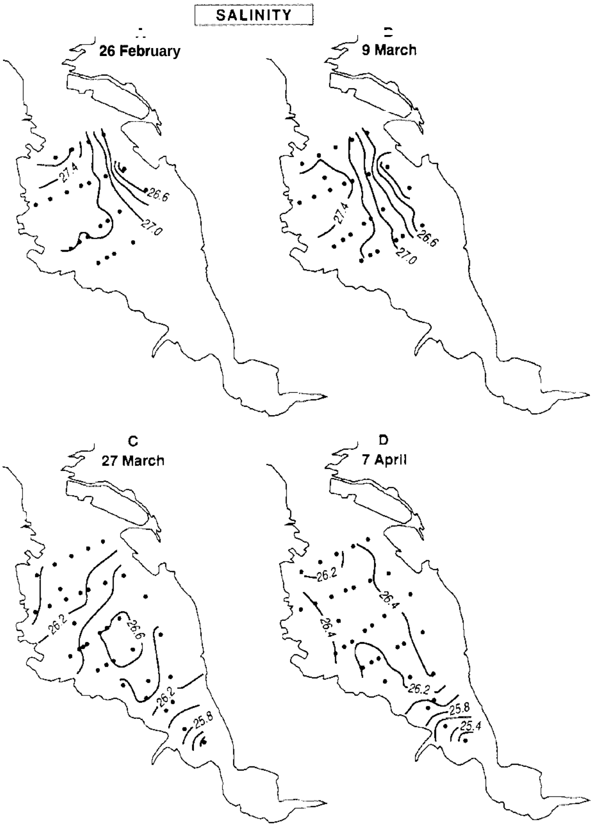

Figure 5. Contour maps of near-surface salinity in South San Francisco Bay on the four sampling dates. Contoured values are tidally-averaged means of 5–6 salinity measurements taken at each station over 12 h periods.

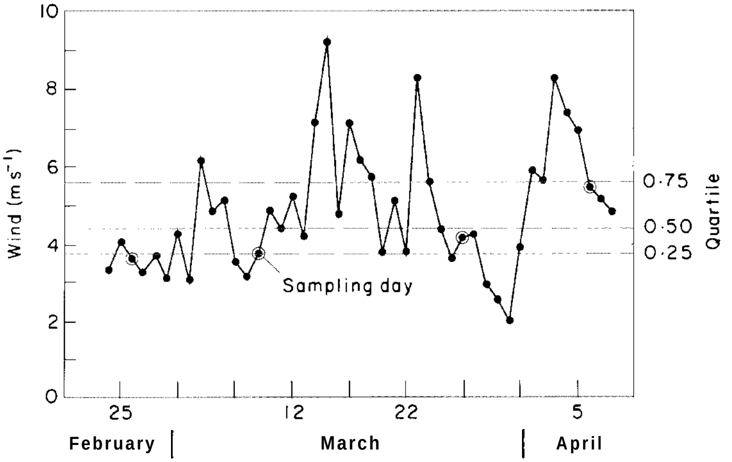

Figure 6. Mean daily wind speed at San Francisco International Airport (SFO in Figure 1) during the sampling period (from Bay Area Air Pollution Control District). Dashed lines show quartiles (e.g. 25% of all values fall below the 0.25-quartile line).

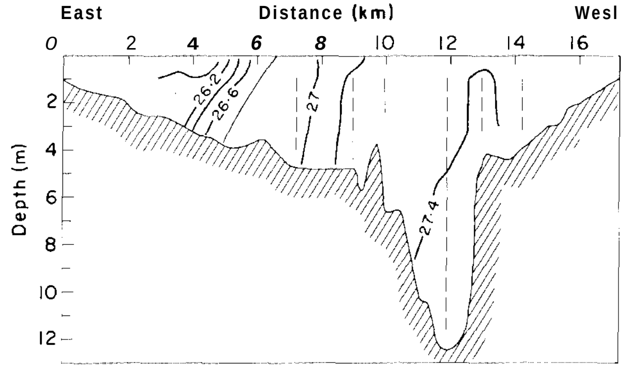

Figure 7. Representative vertical section of salinity during the sampling period. These data were collected along transect ' C ' in mid-South Bay (see Figure 1) on 9 March 1987.

moreover, cruise D followed three days of heavy winds. On that date strong winds arose in the early afternoon in the central section of South Bay, mixing that portion of the estuary (and forcing early cessation of sampling). Accordingly, surface isohalines for cruise D showed little structure, except south of the San Mateo Bridge. Note also that for this dry year, the estuary was well-mixed in the vertical (e.g. Figure 7).

The sequence of maps in Figure 5 shows that salinity distribution in this estuary largely reflects the freshwater inputs. On the first two cruises the salinity structure indicated that the dominant inputs were the local sources at the south and east shores of the South Bay (Coyote and Alameda Creeks, Figure 4c), hence, the freshwater over the eastern shoals. However, between the second and third cruises a larger pulse of freshwater entered the northwest end of the estuary from North Bay, thus reversing the transverse density (and pressure) gradient. We speculate that this freshet relaxed a dynamical " barrier " that had enhanced retention of less saline water against the eastern shore (compare Figures 5b and 5c). Further investigation of lateral transport is in preparation (Huzzey *et* al., 1988). Finally, wind effects, as seen on the last sampling date, mixed the entire central portion of the estuary (Figure 5d).

Figure 8 shows the tidally-averaged maps of surface chlorophyll on the four sampling days. On the first two dates the longitudinal isopleths of chlorophyll a resembled the isohalines (Figure 5), especially in the eastern portion of South Bay (we have removed one point at Station 12 from Figure 8, cruise B, because chlorophyll concentrations may have been contaminated from a nearby, accidental sewage discharge into San Francisco Bay on 7 March). However, on the last two sampling dates, the chlorophyll isopleths did not resemble the simultaneous isohalines. A distinct trend for chlorophyll to be highest in the south, lowest to the north, is apparent on cruises C and D, especially D. This north–south gradient, commonly observed in South San Francisco Bay (Cloern *et* al., 1985), persisted from cruise C to D, despite the fact that little pattern in salinity was apparent. Correlations between chlorophyll and salinity on each of the sampling dates confirm this picture. Figure 9 shows that for the first two dates mean chlorophyll concentration was highly correlated with mean salinity; however for the last two dates chlorophyll and salinity were only weakly correlated or not correlated at all (for consistency, the data in Figure 9 only include measurements from those stations that were sampled every cruise).

These patterns demonstrate the non-conservative nature of phytoplankton biomass (chlorophyll) over the observed time scales during this period. Local growth processes,

Figure 8. Contour maps of near-surface chlorophyll *a* (mg m^{-3}) in South San Francisco Bay on the four sampling dates. Contoured values are tidally-averaged means of 5–6 measurements taken at each station over 12 h periods.

i.e. net production through a spring bloom, became apparent halfway through the four-cruise sampling period. Moreover, a simple explanation of the high chlorophyll concentrations to the south and east, and low chlorophyll to the north and west need consider only two coupled effects--one due to in *situ* effects (the east–west gradient), the other transport (the north–south gradient). The former arises since the mean phytoplankton growth rate in the channel (toward the western edge of the estuary) is about five times lower than in the shoals, because of extreme light limitation in the deep, well-mixed channel (Cloern *et* al., 1985). The latter occurs because low-chlorophyll waters, originating both from the coastal ocean and the Sacramento–San Joaquin river system, dominate the northern end of the South Bay.

Figure 10 shows the patterns of surface turbidity (tidally-averaged SPM concentration) on the four sampling dates. Note that on each date, a unique distribution of SPM concentration was observed. Further, none of these patterns matched closely the corresponding spatial pattern of either salinity or chlorophyll. Comparison of cruise A (a spring tide) with cruise B (a neap tide) shows that the average near-surface SPM concentration was more than three times greater on the spring tide sampling date (Table 1). Comparison of SPM concentrations during the two neap tide cruises, B and D, demonstrates the effect of

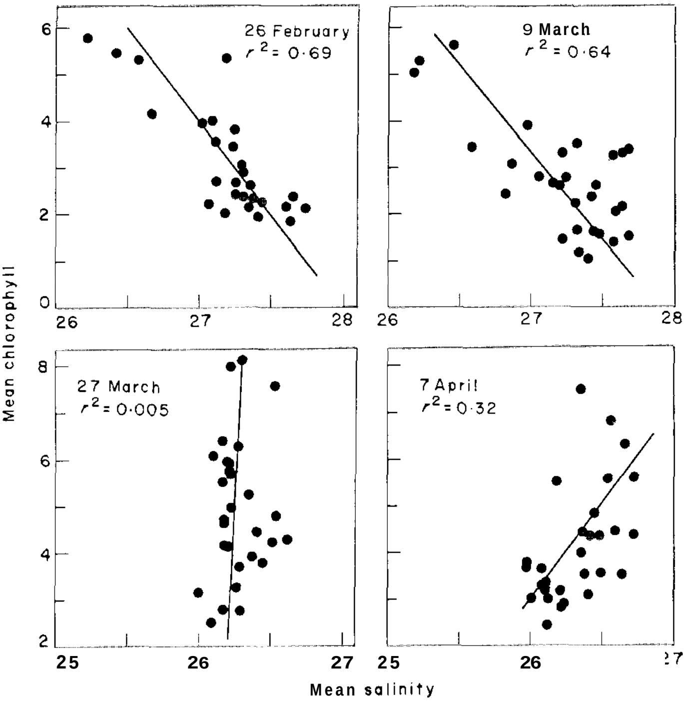

Figure 9. Tidally-averaged chlorophyll a concentration vs. tidally-averaged salinity, measured at all locations north of San Mateo Bridge (Figure 1), on the four sampling dates.

wind-driven resuspension: mean SPM concentration was nearly threefold higher on cruise D (Table 1), following a 6-day period of strong winds. Effects of wind-driven resuspension were most evident across the broad eastern shallows where mean SPM concentration exceeded 50 mg l^{-1} (Figure 10d). Sampling on cruise C followed closely the season's largest intrusion of high-turbidity, low-salinity river water (Figure 5). Highest SPM concentrations were found then in the deep northwest basin of the South Bay, where the effect of the freshwater inflow was felt most strongly.

The maps in Figure 10 demonstrate that spatial patterns of SPM concentration can vary markedly over the time scale of weeks. Moreover, the four different patterns apparently arose from those mechanisms most often thought to increase suspended sediment concentration in estuaries: high tidal activity, i.e. spring tides; resuspension due to high winds; and riverine inputs of turbid water (e.g. Pejrup, 1986; Demers *et* al., 1987). It is therefore not surprising that the resulting turbidity patterns bear little relation to the salinity or chlorophyll distributions because they generally result from different mechanisms.

Figure 11 shows a map of the daily primary productivity, P', derived from equation 1 and averaged over the tidal cycle for each sampling date. Mean productivity was higher on the last two sampling dates (the bloom period; Table 1). However, the spatial distribution of productivity showed no consistent relation to the distribution of biomass (chlorophyll a). At times, variations in P' reflect the negative correlation with SPM concentration (e.g. the local P' minimum over the eastern shoals in association with the very high SPM

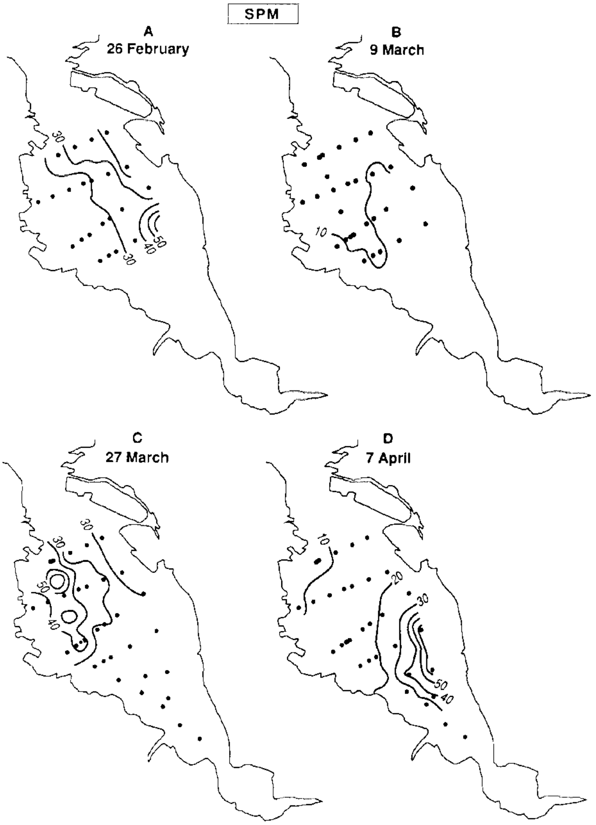

Figure 10. Contour maps of near-surface SPM concentration (mg l^{-1}) in South San Francisco Bay on the four sampling dates. Contoured values are tidally-averaged means of 5–6 measurements taken at each station over 12 h periods.

TABLE 1. Mean values of chlorophyll a, SPM, and derived productivity P' for each sampling date in 1987. Mean values were calculated from individual measurements at n sampling sites over m phases of the tide (sampling circuits). Also shown for each quantity is the coefficient of spatial variation (CV = mean, for m tidal phases, of $100[\mathrm{SD}_j/\overline{x}_j]$, where SD, =standard deviation among sites for circuit j and $\overline{x}_j$ = spatial mean for circuit j).

Cruise date	A 26 Feb	B 9 March	C 27 March	D 7 April
Number of sampling stations	29	29	38	38
Number of sampling circuits	6	6	6	5
Mean chlorophyll (mg m^{-3})	3 1	3 0	5 0	5 9
CV	50%	69%	48%	42%
Mean SPM (mg l^{-1})	28 6	9 3	31 3	25 6
CV	54%	45%	49%	66%
Mean P' (mg C m^{-2} d^{-1})	210	260	360	470
CV	19%	30%	33%	21%

Figure 11. Contour maps of mean photic-zone productivity P' (mg C m^{-2} d^{-1}), derived from mean chlorophyll a concentration, SPM concentration, daily insolation, and the regression model of equation 1.

concentration there on 7 April). At other times this influence was not readily apparent. On any one sampling date, the spatial variability of P' was considerably less than that for chlorophyll a concentration. Consider the last cruise, for example. From Figure 8, chlorophyll varied between 3 and 10 mg m^{-3} (a factor of 3·3), while P' varied between 400 and 650 (a factor of 1.6). Similarly, the spatial variability of P' was much less than that of SPM concentration. In general, the coefficient of variation for P' was approximately half that of either chlorophyll a or SPM (Table 1). This occurs because of an approximate cancellation of the effects of SPM and biomass in equation 1, such that P' is similar in the (low biomass–low turbidity) channel and (high biomass–high turbidity) shallows. Measurement of productivity is labour intensive, and difficult to do synoptically over a grid of sampling locations. Hence, there are few estimates of the two-dimensional distribution of production in estuaries. However, spatial patterns in the distribution of P' suggest that phytoplankton productivity is relatively uniform across the larger gradients of biomass and turbidity in this estuary.

Conclusions

Results of this study demonstrate that the two-dimensional distributions of conservative and non-conservative quantities can vary significantly over the weekly time scale in coastal plain estuaries such as South San Francisco Bay. It is further apparent that different quantities vary in response to different forcings. For example, the horizontal distribution of salinity responds to local and far-field inputs of freshwater and transport processes. Redistributions of phytoplankton biomass (chlorophyll) can result from these same processes as well as from local sources or sinks (e.g. net production of biomass during the spring bloom as observed here). Similarly, local sources (tide- or wind-induced resuspension) as well as riverine inputs play an important role in the horizontal distribution of suspended sediments, and variability in the strength of these sources is obvious over the neap-spring cycle and with wind events. Primary productivity, as derived from equation 1, shows significantly less variability in space than salinity, chlorophyll, or SPM. And finally, because of the importance of *in situ* processes, the spatial distribution of salinity is, in general, a poor predictor of surface patterns in SPM concentration, phytoplankton biomass, or productivity.

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