Title
Observation of Physical Fluxes Between an Estuary and the Ocean

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Final Report
"Observation of physical fluxes between an estuary and the ocean"
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SUMMARY

The work funded under California Sea Grant R/CZ-170 has been focused on observations of ocean-estuary exchange at the mouth of San Francisco Bay. The observational program consisted of 6 transect experiments, each capturing a complete 24-hour tidal day (with 2 exceptions due to instrument failures), spanning various seasons and tidal conditions. Using repeated transects of water velocity, conductivity, temperature, optical backscatter, and chlorophyll fluorescence, we have made great strides in developing a clear, quantitative understanding of ocean-estuary exchange in San Francisco Bay. The work has produced two manuscripts that are in review at the Journal of Physical Oceanography (see references below). The first focuses on the mechanisms of residual flow creation; the second analyzes the net salt flux between the ocean and the estuary and defines which flux mechanisms are most important. A third manuscript that examines Chlorophyll exchanges is currently in preparation. In the remainder of this report, we document our achievements in more detail; the figures are taken from the manuscripts referenced at the end of this report.

INTRODUCTION

The exchange of nutrients and biota between the ocean and an estuary is critical to both ecosystems. The importance of this exchange cuts across species: some use the estuary as a nursery grounds, others move to the coastal ocean to mature and return to the estuary as adults. Even those species that spend their entire lifecycle in one body of water are dependent upon the exchange to determine the local salinity and the supply of nutrients. In this report, we describe results from a study to examine the physical processes that govern ocean-estuary exchange and some impacts of this exchange on biological processes in the estuary.

The net exchange between the coastal ocean and estuaries is a result of the interaction between three mechanisms: oceanic conditions, tidal forcing, and freshwater inflow. These mechanisms also interact with the local bathymetry and the resulting exchange flows will be characterized by distinct spatial and temporal structure. Understanding the mechanisms responsible for ocean-estuary exchange is critical to predicting and managing the local aquatic ecosystems; this study has been developed to address the physical mechanisms of exchange.

The study was designed to answer four important questions at the interface between San Francisco Bay and the coastal ocean: (1) What are the net fluxes between the estuary and the ocean? (2) What mechanisms are responsible for these fluxes? (3) How do the responsible mechanisms vary with tidal and oceanic conditions? (4) What role does the coastal ocean play in the productivity of the estuary (and vice versa)? The first three questions are primarily physical in nature: what are the exchanges and how are they created? The fourth question links these physical observations with the ecosystem of the San Francisco estuary, and addresses an important issue in the analysis of the estuarine ecosystem: the boundary condition with the ocean.

OBSERVATIONS

We have completed all of the proposed experiments. The first was during the winter/spring season of 2002; the second was in the fall of 2002; the third and final experiment was during the summer of 2003. In each season, the experiment was repeated during spring and neap tides. During the summer and fall experiments, the studies were of 25-hour duration – spanning a complete tidal day; during the spring experiment, the navigation equipment was not appropriate for overnight work, so a series of daylight cruises were performed instead.

In each experiment, transects just to the east of the Golden Gate Bridge (Figure 1) were repeated on approximately a 12 minute interval. Deployed from the vessel (the R/V Turning Tide from the U.S. Geological Survey) was a boat-mounted 300 kHz acoustic Doppler current profiler (ADCP) measuring water velocities and a towed, undulating vehicle that carried a SeaBird conductivity-temperature-depth sensor (CTD) along with an optical backscatter sensor (OBS) and a fluorometer (SCUFA) for measuring chlorophyll fluorescence. The undulating vehicle was flown in a sawtooth pattern to within 5-10 meters of the surface and bed along the transect path.

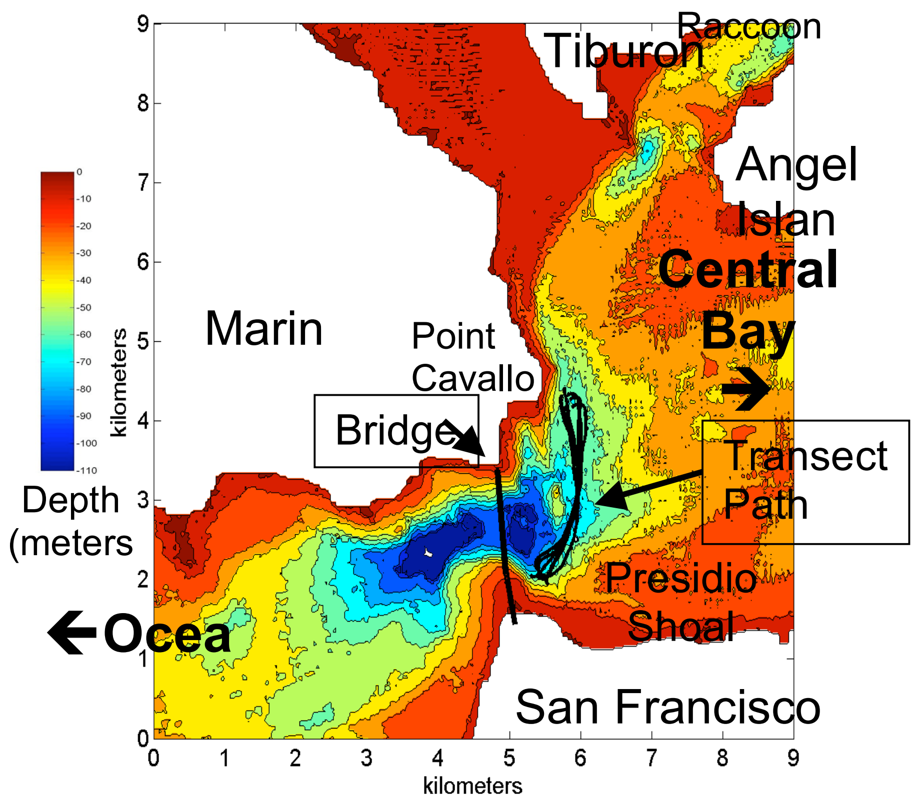

Figure 1: Bathymetry in vicinity of the Golden Gate and transect path for studies

The velocity measurements that resulted from this sampling were complete across the cross-section, and needed only some error checking before being used in other calculations. The scalar measurements, however, did not span the entire cross-section (due to the sawtooth pattern) and required interpolation and extrapolation to extend the data to the boundaries. The interpolation of the data within the sawtooth pattern was done with ordinary kriging. The extrapolation to the surface and bottom required specification of the top and bottom boundary conditions. For salt, a no-flux condition was established; for sediment and phytoplankton, we are continuing to explore appropriate extrapolations. The resulting scalar fields span the entire cross-section on the same grid as the velocity fields.

RESIDUAL FLOW ANALYSIS

The high temporal resolution (every 12 minutes) and complete cross-sectional coverage has allowed us to consider the residual flow through the ocean-estuary interface in great detail. A straight averaging of the data, however, would not provide reliable estimates of the net flow, however, due to subtle tidal asymmetries and variations from day-to-day. Instead, we have turned to principal components analysis to separate the primary barotropic tidal flow component from the smaller magnitude flow structures that create residual flow.

A summary figure of residual flow through the cross-section (with the barotropic tidal component removed) is presented in Figure 2. Instead of the classic estuarine exchange (out of the estuary at the surface, in at the bottom), there is significant lateral variability in the residual flow, including a significant north-south component. Further, the magnitude of the exchange flow is considerably larger than would be expected for a density-driven flow.

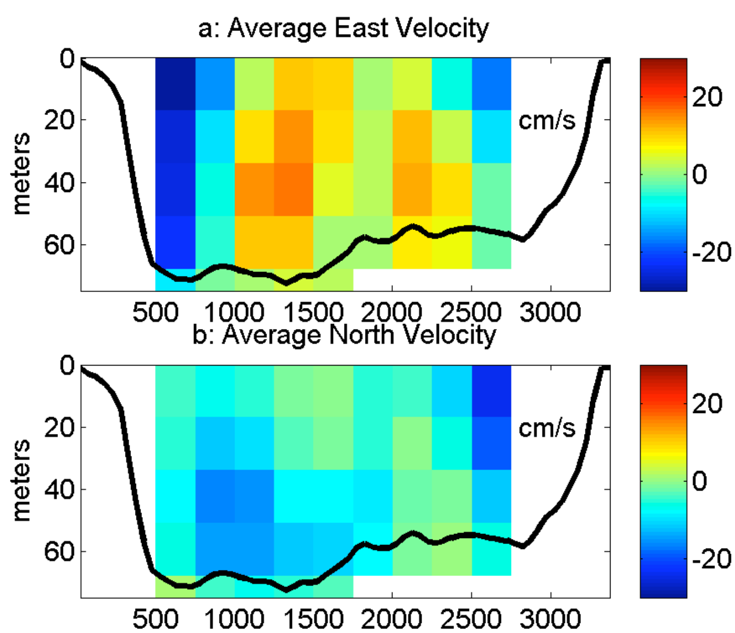

Figure 2: Residual flow across all seasons (cm/s). (a): east-west component; (b) north-south component.

These results suggest that other mechanisms must be acting to create residual flow in addition to density-driven exchange. Our observations have allowed us to identify two of these mechanisms (see Fram et al., Part I for a more detailed discussion). First, the lateral structure of the residual flow is strongly influenced by an eddy formed on the flood tide behind Point Cavallo (on the north end of our transect see Figure 1). This eddy is trapped behind the headland during the flood tide, but during the transition to ebb is advected out into the main channel of the Golden Gate, and modifies the net (tidally-averaged) circulation.

The second mechanism involves the strengthening of the vertical phase lag of the flow as it transitions from ebb to flood, which creates a stronger vertical exchange flow than would be predicted by traditional estuarine scaling. During the ebb tide, a lateral density gradient is created due to the advection of north bay (fresh) waters into the north side of the channel and south bay (more saline) waters into the south side of the channel. At the end of the ebb tide, this lateral density gradient relaxes, and produces vertical stratification at the beginning of the flood tide. This density stratification inhibits mixing and delays the transition to flood tide in the upper water column. The result is an exchange flow that has the same structure as the expected estuarine residual but is larger in magnitude.

Taken together, we conclude that tidal forcing is largely responsible for the residual flow structures observed at the mouth of San Francisco Bay. In one case (the tidally-produced eddy), tidal flows produce a net circulation due to their interaction with the local bathymetry. In the other case, the tides interact with the local density field, which is different between North and South Bay, to define the residual flow.

SALT FLUX ANALYSIS

The primary goal of the research pursued under this funding was to quantify ocean-estuary exchange, including its seasonal variability. Initially, we have focused our attention on salt, because we have the most complete data for this scalar, including measurements from the interior of the estuary with which we can evaluate the accuracy of our flux estimates.

In order to calculate the net flux of salt (or other scalar), we need to perform a temporal averaging that removes the tidal fluctuations. With the short datasets collected, a straight temporal average would have significant errors, due to asymmetries and variability from one tidal cycle to the next. Instead, we have pursued a harmonics-based analysis that first fits the velocity and scalar measurements to the expected tidal harmonics; we then integrate the resulting sinusoids to define the net flux.

The result of the harmonic analysis is the salt flux estimates contained in Table 1. Here we find that the net flux of salt is into the estuary during all seasons, but is considerably larger during the spring and summer seasons. As was noted above, the summer experiment had abnormally high freshwater influence due to a series of late storms that year, so the spring and summer experiments had fluxes of similar magnitude. Comparing these dispersive fluxes to the advective flux produced by river flow (Table 1), we see that values of these fluxes are of the magnitude and sign expected. Further, using observations of salinity variation in the interior of Central Bay and a "Box Model" analysis (presented in lower half of Table 1), we see that the net flux (i.e., advective flux out minus dispersive flux in) is consistent with the rate of change of the bay salinity (based on the volume required for the box model to balance; see Fram et al. Part II for a complete discussion).

The level of detail in the observations allows us to also consider the physical mechanisms that are acting to produce these net fluxes. We have concluded that the dominant mechanism for ocean-estuary exchange is tidal pumping across all seasons, and is responsible for approximately 75% of the net flux. The vertical steady exchange, which includes both the baroclinic exchange and the tidal phasing described above, is responsible for only about 10% of the net exchange. The remainder of the flux is primarily due to steady exchange with a lateral structure, which likely includes some contribution from tidal pumping as well due to the transect location (see Fram et al., Part II for details).

	Spring ’02	Summer ’03	Fall ’02
Advective (DWR)	-18490	-12170	-4450
Dispersive	28620	23110	3510
% Difference	40%	46%	27%
fluxes in (Salinity*m3/s)			
	BOX MODEL		
dS/dt (Salinity/day) (USGS)	0.21	0.14	-0.005
Characteristic Volume	4100	6600	16200
MSL Central Bay (USGS)	4386		
Entire Bay (Mm3)	8446		

Table 1: Flux results for each season. Advective and dispersive fluxes given in units of psum^3/s. Box model results indicate that difference between advective and dispersive fluxes is of the right magnitude and sign.*

CHLOROPHYLL FLUX ANALYSIS

The extension of the salt flux analysis to biological scalars is not trivial due to the challenges involved with extrapolating the biological data to the boundaries. Whereas for salt boundary conditions at the surface, bottom and lateral boundaries are well known, for phytoplankton, the possibility of settling, growth, and perhaps even buoyancy effects, makes it difficult to extend our chlorophyll data beyond the measurement domain.

Nonetheless, we can consider the variability of chlorophyll relative to that of salt within the domain of the measurements. In Figures 3 and 4, we present timeseries of block-averaged salinity, suspended sediment concentration, and chlorophyll. Of particular interest is the phasing of chlorophyll relative to that of the other scalars. During the spring and fall periods (fall experiment shown, Figure 3), the chlorophyll concentration is in phase with that of sediment, and out of phase with salt. As established in the previous section, the net tidal flux of salt is into the estuary – we conclude that the tidal pumping mechanism is carrying chlorophyll and sediment out of the estuary during these two seasons.

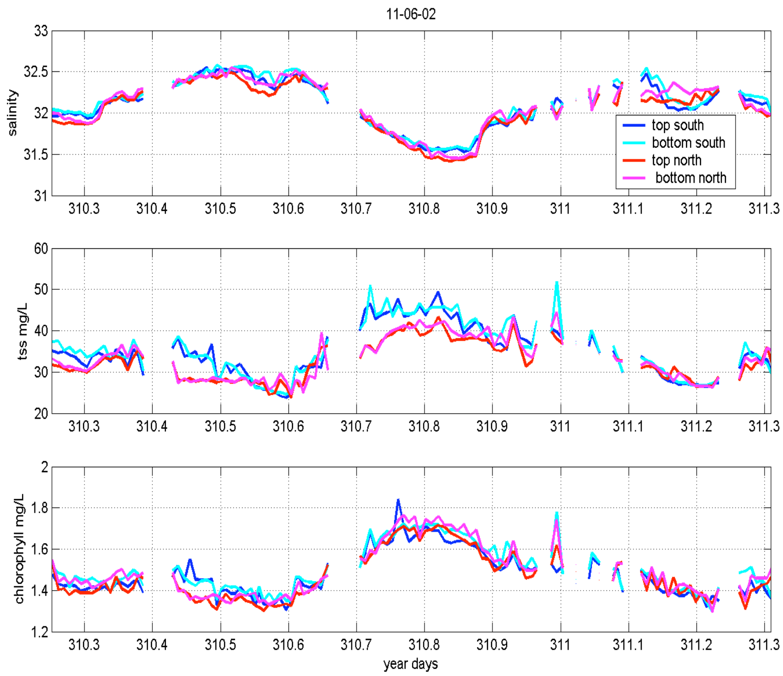

Figure 3: Tidal variability of scalars during fall experiment. (a) Salinity; (b) Total suspended solids; (c) Chlorophyll. Both chlorophyll and suspended solids are out of phase with salinity.

In the summer, however, the phasing of the chlorophyll is shifted to be in phase with salt, but out of phase with sediment (Figure 4), which suggests a net tidal flux of chlorophyll into the estuary. Thus, during the summer upwelling season, when oceanic productivity is highest, it appears that the net flux of chlorophyll is into the estuary; during the spring and fall (and, arguably, the rest of the year), the tidal flux of chlorophyll is out of the estuary.

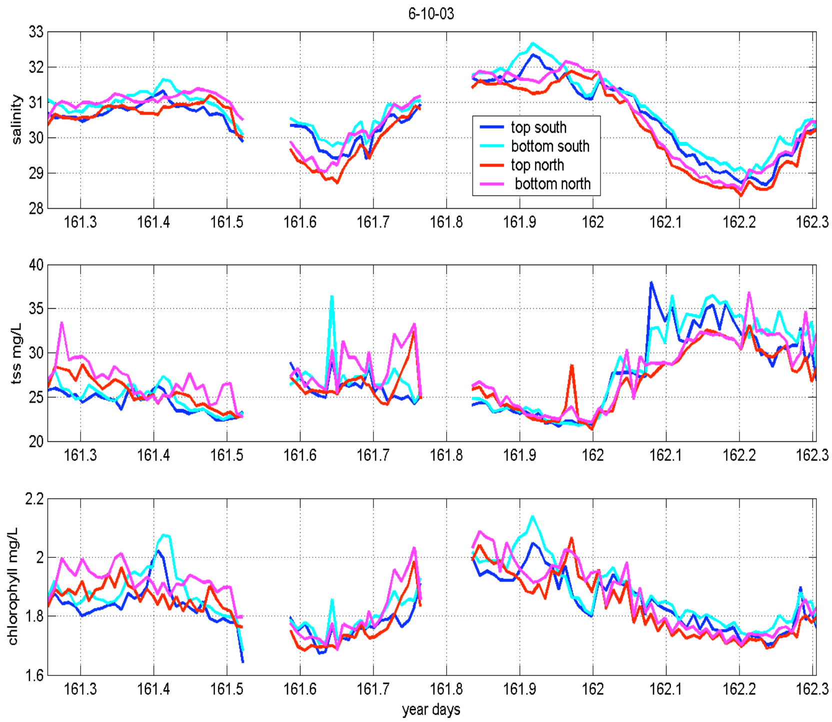

Figure 4: Tidal variability of scalars during summer experiment. (a) Salinity; (b) Total suspended solids; (c) Chlorophyll. During this season, chlorophyll is in phase with salinity while suspended solids remain out of phase.

CONCLUSIONS

Taken as a whole, this series of studies provides arguably the most complete set of observations of ocean-estuary exchange collected to date. The analysis of this data is proving to be exceptionally successful, including the evaluation of residual flows and net salt fluxes, along with a delineation of the important mechanisms driving them, and even a first estimate of the net tidal flux of biological scalars.

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Introduction

Phytoplankton are the base of the food web in San Francisco Bay, and require light and nutrients for photosynthesis and growth. Primary production is limited by respiration, low light, low nutrients, grazing and transport. Within San Francisco Bay, primary production is less than most estuaries because growth is limited by light availability (Alpine and Cloern 1988) and intense benthic grazing (Cloern 1982). In contrast, the coastal ocean off Northern California is considered one of the most productive parts of the Pacific Ocean. As a consequence of relatively low autochthonous (generated within) and an unknown contribution of allochthonous (generated externally) primary productivity, higher trophic levels within San Francisco Bay (zooplankton, shrimp, etc) are usually food limited (Cloern 1996).

While the mechanisms and dynamics of estuarine and coastal blooms may be relatively well understood in isolation, little is known about how the two interact. Understanding the connectivity of North Bay, South Bay and coastal waters provides a management tool to determine how altering one will affect the others. In the north the Delta levee system is changing and sunken lakes are being restored. In the south, the Cargill salt flats will be restored to tidal marshes. These projects may change freshwater flows and sediment transport dynamics which in turn could drastically alter the phytoplankton dynamics of the entire ecosystem. One of the greatest unknowns in understanding the estuary-scale impacts of these restoration efforts is the ecological link between the estuary and the coastal ocean, the research conducted under SeaGrant project # R/CZ-170 begins to address this need.

Methods

During the past two years we measured scalar fluxes, including salinity, sediment and chlorophyll (chl-a) at the mouth of San Francisco Bay just east of the Golden Gate

Bridge (Figure1).

Figure 1 Location of data collection. Red line is approximately boat transect.

Data were collected during each of three seasons: winter/spring runoff, summer upwelling, and fall relaxation. Within each season, 12 minute transects across the channel were repeated continuously for 25 hours for two days, one during spring tide and one during neap tide. Velocity was measured from a boat-mounted acoustic Doppler profiler (RDI ADCP), and scalar concentrations were obtained from a tow-yo profiler (SeaSciences Acrobat) as well as a boat-mounted CTD (RBR). The tow-yo package includes instruments measuring temperature, salinity, depth, optical backscatter (OBS), and UV-A chlorophyll fluorescence (SCUFA).

To calculate chlorophyll fluxes between estuary and ocean collected data were extrapolated to fill the entire cross sectional area and averaged. Depending on the averaging method, flux results differ. Subsequent results are reported for averaging horizontally first. For a full description of the methods please see Fram et.al.(in review) Fluxes were calculated by fitting harmonics to scalar and velocity data. Where velocity is $U = u_0 + \sum_{i}^{5} A_i^Q \sin(\omega_i^Q t + \theta_i^Q)$ and similarly chlorophyll is

$C = c_0 + \sum_{i}^{5} A_i^C \sin(\omega_i^C t + \theta_i^C)$. The subscripts correspond to the different harmonic frequencies (ωi = M2, K1, S2, M4) and the superscripts indicate flow (Q) or chlorophyll (C). The remaining variables are fit using a least squares algorithm. The total flux, $\frac{1}{T}\int_0^T UCdt$ is comprised of an advective, $u_0 c_0$ and dispersive flux. Although the advective flux from harmonic analysis is $u_0 c_0$, we choose to use the measured (Delta outflow gauge) river outflow and measured mean chlorophyll instead.

The dispersive flux is the sum of the remaining harmonics and can be further decomposed into physical processes. First, the cross-section temporal mean is separated from overall velocity, u.

$$\mathrm{u}_0 = \left\langle \overline{\overline{\mathrm{u}}} \right\rangle, \quad \mathrm{u}_1 = \mathrm{u} - \mathrm{u}_0$$

Next we extract cross-section averaged velocity (u1barbar) and steady shear (u_3), leaving unsteady shear fluctuations (u_4).

$$\mathrm{u}_2 = \mathrm{u}_1 - \overline{\overline{\mathrm{u}_1}}$$

$$\mathrm{u}_2 = \langle \mathrm{u}_2 \rangle + (\mathrm{u}_2 - \langle \mathrm{u}_2 \rangle) = \mathrm{u}_3 + \mathrm{u}_4$$

$$\mathrm{u}(\mathrm{y},\mathrm{z},\mathrm{t}) = \mathrm{u}_0 + \overline{\overline{\mathrm{u}_1(\mathrm{t})}} + \mathrm{u}_3(\mathrm{y},\mathrm{z}) + \mathrm{u}_4(\mathrm{y},\mathrm{z},\mathrm{t})$$

Fischer (1974) averages horizontally first to find baroclinic flow and unsteady vertical shear, with the remainders becoming horizontal steady and unsteady shears.

$$\mathrm{u}_3 = \overline{\mathrm{u}_3}^{\mathrm{h}} + \left(\mathrm{u}_3 - \overline{\mathrm{u}_3}^{\mathrm{h}} \right) = \mathrm{u}_5(\mathrm{z}) + \mathrm{u}_6(\mathrm{y},\mathrm{z})$$

$$\mathrm{u}_4 = \overline{\mathrm{u}_4}^{\mathrm{h}} + \left(\mathrm{u}_4 - \overline{\mathrm{u}_4}^{\mathrm{h}} \right) = \mathrm{u}_7(\mathrm{z}) + \mathrm{u}_8(\mathrm{y},\mathrm{z})$$

$$\mathrm{u}_3 = \overline{\mathrm{u}_3}^{\mathrm{v}} + \left(\mathrm{u}_3 - \overline{\mathrm{u}_3}^{\mathrm{v}} \right) = \mathrm{u}_{5\mathrm{H}}(\mathrm{h}) + \mathrm{u}_{6\mathrm{H}}(\mathrm{y},\mathrm{z})$$

$$\mathrm{u}_4 = \overline{\mathrm{u}_4}^{\mathrm{v}} + \left(\mathrm{u}_4 - \overline{\mathrm{u}_4}^{\mathrm{v}} \right) = \mathrm{u}_{7\mathrm{H}}(\mathrm{h}) + \mathrm{u}_{8\mathrm{H}}(\mathrm{y},\mathrm{z})$$

Multiplying flow by salinity and averaging over the cross-section and time gives the flux of salt through the channel. The processes associated with the scalar flux terms are advection from river flow and dispersive flux (a), which includes tidal pumping (b), steady baroclinic exchange (c), steady lateral exchange from tidal pumping (d), and unsteady vertical and horizontal shear exchanges from frictional phasing and tidal trapping (e&f).

$$\textit{Total Flux} \quad = \underbrace{u_0 s_0}_{A} + \underbrace{\left\langle \overline{\overline{u_1 s_1}} \right\rangle}_{B} + \underbrace{\overline{u_5 s_5}^{\,v}}_{C} + \underbrace{\overline{\overline{u_6 s_6}}}_{D} + \underbrace{\overline{\langle u_7 s_7 \rangle}^{\,v}}_{E} + \underbrace{\overline{\overline{\langle u_8 s_8 \rangle}}}_{F}$$

Results

During spring and fall the net flux of chlorophyll-a is out of the estuary. The sign of the dispersive flux changes during the summer, resulting in a net flux of chlorophyll-a into the estuary (Table 1). Advective flux is largest during the spring, -1443 mg/s, and smallest during fall, -229 mg/s. Dispersive flux is largest during the summer, +1996 mg/s, and smallest during fall, -309 mg/s.

Table 1 Flux of chlorophyll-a between San Francisco Bay and Pacific Ocean. Values have already been multiplied by cross sectional area.

	Advective Flux (mg/s)	Dispersive Flux (mg/s)	Net Flux (mg/s)
Spring 2002	-1443	-1251	-2694
Fall 2002	-229	-309	-538
Summer 2003	-731	+1996	1265

Decomposition of dispersive flux into physical mechanisms indicates that phytoplankton flux is dominated by tidal pumping during summer and steady horizontal shear in fall. Spring results are the least certain and the dominant physical mechanism is not reported. The magnitude of the flux results is reasonable but values are not exact because of incomplete vertical coverage and short duration.

Conclusion

The flux of chlorophyll does change seasonally and in a way that is consistent with the current qualitative understanding of the system dynamics. Within each season the order of magnitude of advective and dispersive flux are the same, however, the order of magnitude changes between seasons. There is a net flux of chlorophyll-a out of the estuary during the spring and fall. The direction of the spring flux is expected as the river flows are highest during the spring, meaning a large advective velocity and large density driven velocity, and estuarine phytoplankton bloom during that season, meaning a large mean chlorophyll concentration. The fall advective fluxes should be smallest as river flows and density driven circulation are smallest. During coastal upwelling there is a net flux of chlorophyll-a into San Francisco Bay. Net transport in summer is largely due tidal pumping which is dependent on the concentration differences between estuary and ocean. Coastal phytoplankton bloom during upwelling, meaning there is a higher concentration of chlorophyll outside the estuary than inside, leading to a net transport of chlorophyll into estuary. These results indicate coastal blooms may be a seasonally important food source for higher trophic levels in the estuary, especially during the period between spring and autumn estuarine blooms.

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