SAN FRANCISCO BAY SALINITY: OBSERVATIONS, NUMERICAL SIMULATION, AND STATISTICAL MODELS

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Understanding the variability of salinity in San Francisco Bay is a key to defining the bay's physics, chemistry, and biology. This paper is in part a literature review and in part uses decades of observations supported by results from statistical-dynamical and numerical models to describe salinity variability in San Francisco Bay. Findings include the following: (1) Freshwater delta flow (DF) is the master control on mean-monthly salinity in the Bay, (2) Salinity fluctuations are reasonably well modeled on mean monthly and daily time scales, (3) Hysteresis is observed in both data and models, (4) Coastal ocean processes affect salinity in the Bay and vice versa, (5) statistical dynamical models driven by variations in hourly sea surface height near the mouth can estimate about 80% of the hourly salinity variance near mid- estuary at tidal time scales during low relatively uniform delta flow, and *(6)* Climate (small effect) as well as freshwater diversions (large effect) control long-term (decadal) salinity variations.

Knowledge of the salinity field is fundamental to many estuarine studies. To a large degree, how clearly we understand the details of salinity variability in the San Francisco Bay measures how well we understand the entire estuarine system. Beyond this are the aspects of societal interests. Approximately 20 million people depend on the fresh water supply of the bay's delta, a supply vulnerable to sea-salt contamination especially in times of drought. For these reasons salinity is a key element in estuarine research and is often proposed as a water quality standard for estuarine resource management.

This paper describes the nature and causes of salinity variability in San Francisco Bay focusing on time scales from day's to years. We know that tidal forces dominate the short time scales of salinity variability (hours to days) when the fresh water flow is low, and winds contribute small amounts ofvariance. At intermediate time scales, days to fortnights, salinity variability must include both tidal and fresh-water flow effects (and wind effects, which are considered beyond the scope of this paper). We also know that over the longer periods, the months, seasons, and years, the primary cause of salinity variability is related to changes in the discharge of the major source of fresh water, the Sacramento-San Joaquin River (Peterson *et al.* 1989). Hereafter this flow is referred to as delta flow (DF; see Fig. 1).

In reviewing previous work, one soon learns that California has a rich history of interest in the salinity of San Francisco Bay's waters. However, much of that literature, perhaps even hundreds of documents, are in the limited distribution category, including in-house reports of various agencies and are difficult to access. For a descriptive overview of the hydrography and salinity of the Bay, see Conomos

(1979) and Cloern & Nichols (1985). Only major issues on salinity variability in the bay are summarized here.

One of the earliest salinity studies was concerned with the effects of drought, upland fresh water consumption, and river and bay channelization on increasing salinity. The study was initiated because increased salinity led to invasion of boring organisms that devastated the bay's pier facilities (Hill & Kofoid 1927). Similarly, a comprehensive compilation on salinity was motivated in the 1920s and early 1930s by droughts which caused low DF and, in response high salinity threatened to contaminate the fresh water in the delta (California, 1931).

These early studies showed that salinity problems in the bay are clearly linked to delta flow. Hence, there was increased interest in determining a more quantitative estimate of delta flow. In the 1950s a lively discussion was focused on the difficult problem of how you estimate fresh water flow under tidal conditions when a large fresh water reservoir existed in the system (Todd & Lau 1956, 1957; Pritchard 1957, 1958). Estimating the actual DF was even more difficult because local consumption was very poorly known. Thus the inverse problem of using the salt field to better estimate delta flows (rather than the delta flow to estimate the salinity) was considered. This information was then used to refine the estimates of local delta consumption in the water budget to the Bay (Glover 1955).

Probably one of the most controversial papers inferred that delta flow had a major influence even on the South Bay salt field (McCulloch & others 1970). This apparently radical view was followed up by bay-wide surveys that included a more holistic analysis of the bay as a system, including the two books noted above. These more recent surveys suggest that evaporation and local stream flow can be important to the salinity cycle in South Bay and must be considered when interpreting the annual variability in nutrient patterns there (Hager & Schemel, this volume).

Much of the work in the 1980's involved field observations and numerical analysis of mechanisms of salinity variability including tidal and spring-neap variations, gravitational circulation and floods (*e.g.*, Ford, Wang & Cheng 1990; Smith & Cheng 1987; Smith & Cheng 1991; Walters & Gartner 1985). Uncles & Peterson (in press and 1995) provide a review of some of the topics in these papers. In essence, San Francisco Bay, like other estuaries, responds to variations in the above forcing. Vertical mixing strengthens during spring tidal regimes. Salinity stratification, and apparently gravitational circulation, strengthen during neap tides; the latter strengthening is particularly noticeable in deeper channels. Salinity stratification is also enhanced during river floods.

Several biological consequences of changes in salinity stratification and the salinity field are especially worth noting. First, salinity stratification changes the normal growth patterns for phytoplankton in the South Bay. These changes are most noticeable in spring during periods when the smallest neap tides occur (Cloern 1991, 1984; Koseff *et al.* 1993) . A second biological affect is that benthic filter feeders invade northern San Francisco Bay in times of drought and persistent high salinity farther inland (*e.g.*, 1976-1977, 1981, 1985, 1987, Nichols 1985; Carlton *et al.* 1990; Nichols, Thompson, & Schemel 1990). At the other extreme, floods on the rivers can alter benthic community patterns. Partly because salinity plays such an important role in community structure, the distance **(X)** of the 2 psu near-bottom isohaline from the Golden Gate, defined as **X2,** is proposed as a quantitative parameter for purposes of managing the bay's salinity field (Kimmerer & Monismith 1993; Denton, R.A. 1993).

In the 1990s the issue of the changing salinity field in San Francisco Bay has broadened to include: (1) the effects of climate control on fresh water flow into the bay (Cayan & Peterson 1993; Dettinger & Cayan 1995); (2) the exchange between the coastal ocean and the bay (Largier, this volume); and (3) paleo-salinity (Ingram & Sloan 1991, and Ingram & Ingle, this volume). But much of the core research focuses on more standard, long-standing issues as salt penetration with discharge (Harder 1977; Winkler 1985; Denton, R.A. 1993). This research includes investigations of how changes in magnitude and phase of estuarine elevation, velocity, salinity, river flow and geometry are linked to processes occurring in intratidal and tidal deltas (*e.g.*, Burau, Monismith & Stacey, this volume; Simpson, Sharples & Rippeth 1991; Friedrichs & Aubrey 1994; Uncles & Jordan 1980). High resolution numerical models are also used to explore these processes (Cheng, Casulli & Gartner 1993). In the following, we will review the aspects of the above processes that involve changes in the salinity field at subtidal and tidal frequencies, discuss some new results from numerical models, and touch briefly on the relationship between large-scale atmospheric patterns and salinity patterns in the bay.

DATA AND MODELS

The salinity observations used in this paper were obtained from a variety of sources (Table 1, Fig. 1). The original data were sampled at several different rates, spanning periods from 15 minute to daily. Tidal frequencies were removed from the data sampled at hourly rates or less with a low-pass Godin filter (supplied by Lawrence Smith 1992). Gaps in daily salinity observations were filled using spline methods (de Boor 1990).

The relations between mean-monthly delta flow (input) and salinity (response) has previously been studied using linear statistical dynamical methods (Peterson ***et al.*** 1989). These methods were also used to study the relations between tidal forcing (estimated sea surface elevation) and salinity at tidal time scales. Sea surface elevation near the Golden Gate was estimated using the method given by Cheng & Gartner (1984). In both instances, the model structure and parameter values were identified and estimated using an instrumental variable method (Ljung 1987, 1988). **A** limitation with this method is that this statistical dynamical method only estimates deviations from a mean salinity in response to deviations from mean delta flow; the mean is not estimated. However, a "steady-state" approximation of the relation between salinity and delta flow including the mean is represented by an exponential equation.

In this paper, we also use a numerical model to simulate salinity in response to delta flow. The numerical model estimates a mean as well as the fluctuating response. In brief, the numerical model is a two-layer box model with the boxes defined in Fig. 1. The model includes external forcing from delta flow and tidal currents averaged over one day. Physically-based vertical and horizontal eddy diffisivities are increased or decreased by a parameter greater or less than one. In most instances the physically based estimates underestimated the horizontal and overestimated the vertical eddy diffusivities used in this paper as well as in the earlier efforts cited. **A** more detailed description of the model is described by (Uncles & Peterson, in press and 1995).

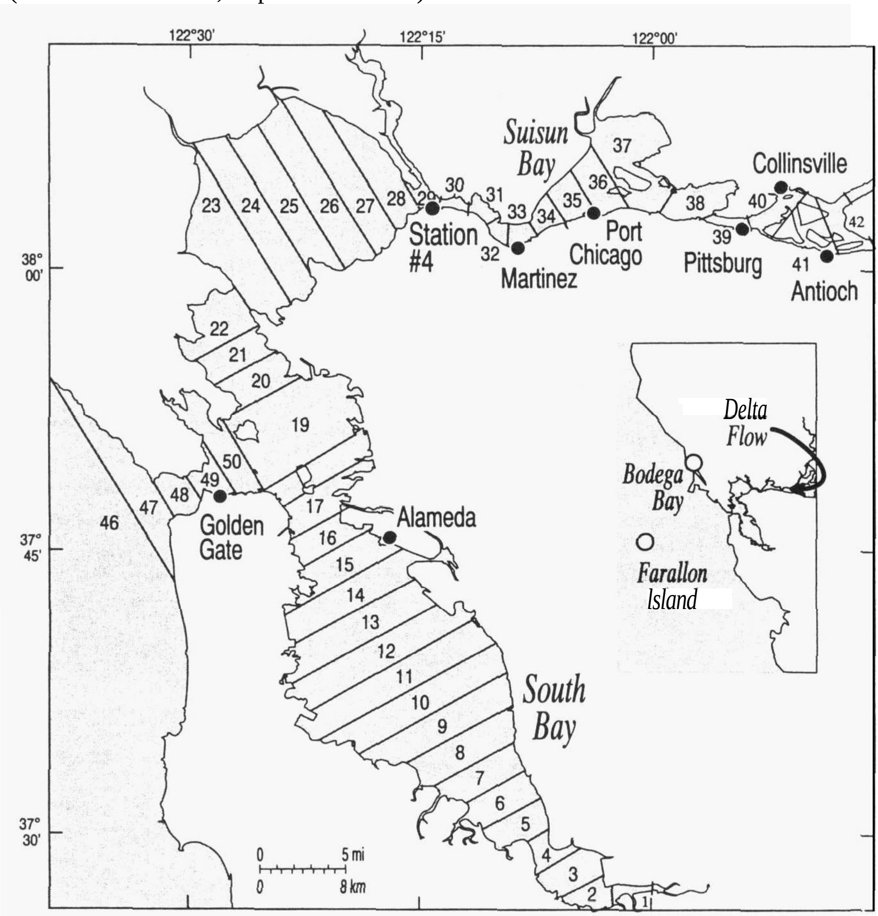

FIGURE 1. San Francisco Bay region and locations of observations in this study and the distribution of segments used in a numerical model of San Francisco Bay salinity (modified from Uncles & Peterson 1995).

EFFECTS OF SUBTIDAL FLUCTUATIONS IN DELTA FLOW

In the past a key issue in San Francisco Bay estuarine research, and we expect for years to come, is to more fully understand the effects of variations in delta flow on the bay. In this section, we will concentrate on how changes in mean-monthly DF modify salinity patterns in the bay. We will also discuss the link between

TABLE 1. Description of data, location and source parameter.

Parameter	*Period of Record (WaferYear)*	*Location*	*Remarks/Source*
Delta Flow	1955-1992	Confluence of Sacramento-San Joaquin Rivers	Daily estimates, Sheila Greene California Dept. of Water Resources, unpublished
Salinity	1958-1992	Farallon Island	Daily grab samples, Patricia Walker Scripps Institution of Oceanography, unpublished
Salinity	1976-1992	Bodega Bay	Daily observations, Patricia Walker Scripps Institution of Oceanography, unpublished
Salinity	1922-1992	Fort Point	Daily grab samples, National Ocean Service, unpublished
Salinity	1941-1942	Alameda	Same as above
Salinity	1928-1956	Point Orient	Mean-monthly values from daily grab samples at maximum tide height (supplied by Phyllis Fox)
Salinity	1968-1988	Martinez	Mean-daily, Sheryl Baughman and Muriel Ferris, US Bureau of Reclamation, unpublished
Salinity	1968-1986	Port Chicago	Same as above
Salinity	1968-1988	Pittsburg	Same as above
Salinity	1968-1988	Collinsville	Same as above
Salinity	1968-1988	Antioch	Same as above
Salinity	1992	Station #4	15 minute near-surface and near-bottom, Larry Smith, **U.S.** Geological Survey, unpublished

salinity fluctuations in the coastal ocean and in the bay. Mean-monthly DF is used here because mean-daily delta flow is not measured directly. It is calculated via a series of source – sink terms, some involving highly managed water resources (California 1986). Mean-monthly estimates of DF are considered more reliable than daily estimates, presumably because some of the errors in daily estimates cancel.

San Francisco Bay Salinity

This first section on the Bay's salinity presents a simple relation between mean-monthly near-surface salinity as a decreasing exponential function of delta flow. This is followed by a section that studies bay-wide mean-daily (and mean-monthly) salinity using a numerical box model (NBM) largely forced by delta flow and tidal variations (Uncles & Peterson, in press and 1995).

An exponential model.

As a first-order approximation, the mean-monthly salinity in northern San Francisco Bay is defined as an exponential function of delta flow (Peterson *et al.* 1989):

$$S(x) = S_o + S_1 e^{-\beta(x)Q} \qquad (1)$$

$S(x)$ is the mean-monthly near surface salinity at a site, **x**, where x is the distance inland from the Golden Gate. It is a function of the mean-monthly delta flow Q (cubic meters per second) and the exponential coefficient, $\beta(x)$. S_o, an offset independent of the first-order model, and S_1, the apparent salinity at $Q = 0$, are coefficients of the empirical relation (note estuaries are not at steady state).

The exponential model predicts near-surface salinity reasonably well at locations in northern San Francisco Bay. The parameter $\beta(x)$ increases inland along the longitudinal axis of the estuary (Table 2) reflecting that the salinity response to delta flow increases from the mouth to the head of the estuary (*e.g.*, at some distance offshore there is no response). The parameters S_o and S_1 are reasonably consistent except for S_o at two stations, Point Orient and Martinez; we suspect this is partly from a problem with the sampling scheme at those stations as well as the simplistic nature of the model.

TABLE **2.** Parameters of the exponential equation (1) for near-surface salinity in northern **San** Francisco Bay as a function of Delta flow.

Location	S_o	S_1	β
	(PSU)		*(seconds per cubic meter)*
Fort Point	**0.15**	**33.5**	**0.000133**
Point Orient	**9**[1]	**23**	**0.00057**
Martinez	**0.5**[2]	**21**	**0.0018**
Port Chicago	**0.15**	**18**	**0.0033**
Pittsburg	**0.15**	**13**	**0.0082**
Collinsville	**0.15**	**13**	**0.012**
Antioch	**0.15**	**10**	**0.0119**

[1] **The mean-monthly values are based only on high-tide observations and may account, in part, for this disparate value.**
[2] **A possible artifact of the sampling location near the highest longitudinal salinity gradients.**

One difficulty in using this model to represent the bay's salinity field is that we do not know quantitatively how the bay-wide mean-monthly salinity near the bottom compares with surface values throughout the bay. The difference is commonly estimated to be small at low salinities. For example, Kimmerer & Monismith (1993) assumed a surface salinity of 1.7 psu was equivalent to a near-bottom salinity of 2 psu when they calculated the location of the 2 psu at a height of one meter above the bottom (called X_2) as a function of varying levels in delta flow. It is reassuring that the location of the 2 psu value at the surface, calculated using equation (I), is close to the independently derived positions of the 2 psu value measured near the bed, at least in the interior estuary (Table 3).

Numerical Box Model

Although the above exponential relation between salinity and flow is useful, much of the detail remains obscure. The two-layer box model provides added insight into relationships between delta flow and salinity. The NBM results are

TABLE **3.** Delta flow associated with salinity **of 2** PSU at 1 meter above the bottom (X_2), northern San Francisco Bay Estuary.

X_2 Distance from Golden Gate (km) or, Location	*Delta Flow (cubic meters per second)*	*Reference*
60	**1,200**	**K&M[1] 1993**
Port **Chicago**	**750**	**Table 2[2]**
65	**790**	**K&M[1] 1993**
70	**430**	**K&M[1] 1993**
75	**340**	**K&M[1] 1993**
Pittsburg	**260**	**Table 2[2]**
80	**210**	**K&M[1] 1993**
Collinsville	**210**	**Glover 1955[3]**
Collinsville	**190**	**Table 2'**
85	**I40**	**K&M[1] 1993**
Antioch	**160**	**Table 2[2]**
90	**88**	**K&M[1] 1993**

[1] **Kimmerer and Monismith, 1993.**
[2] **Table 2 in this paper, assuming a surface salinity of 1.7 PSU is equivalent to a near-bottom salinity of 2 PSU (Kimmerer & Monismith 1993).**
[3] **Difficult to estimate because of variable flow, Fig. 3, p. 647, Glover, 1955.**

tuned by time-series observations of salinity in the bay and the model skill is evaluated by subsequently comparing the simulated salinity to the observations. Model results serve several purposes: to develop a better understanding of salinity/DF interactions, to fill in large data gaps at specific measurement sites, and to predict salinities at sites where few observations have been taken.

The mean-monthly time series provide a start for comparing observed and simulated salinity near the two estuarine boundaries, the head, Collinsville, and mouth, Fort Point. One problem with the observational data, as stated above, is that we do not have a long record of daily-mean salinity observations at the mouth of the bay. In addition, the records of once-daily observations at the mouth are aliased with tidal noise. At the head, better data are available and we selected near-surface salinity sites located on both sides of the confluence of the Sacramento-San Joaquin River, one site slightly upstream from the other (Pittsburg and Collinsville, Fig. **1).**

For the upper-estuary location, the simulated salinities are lower than the observed salinities for periods when salinity values are near zero (Fig. 2, Collinsville not shown). This disparity is partly due to the low values for river salinity specified in the model (Uncles & Peterson, in press and 1995). It is also possible that there is some uncertainty in the measured salinities because they are derived from the same linear transformation over the entire range of electrical conductivities and the signal to noise ratio probably decreases at very low conductivities. These small differences are of minor significance for this study; the basic salinity fluctuations are simulated reasonably well. The standard deviation in the residual salinity at Pittsburg was ± 0.45 psu and at Collinsville ± 0.44 psu. These residuals are low for this part of the bay partly because the mean salinity is low. Notice, however, that even though the model results are reasonable, the model skill is less

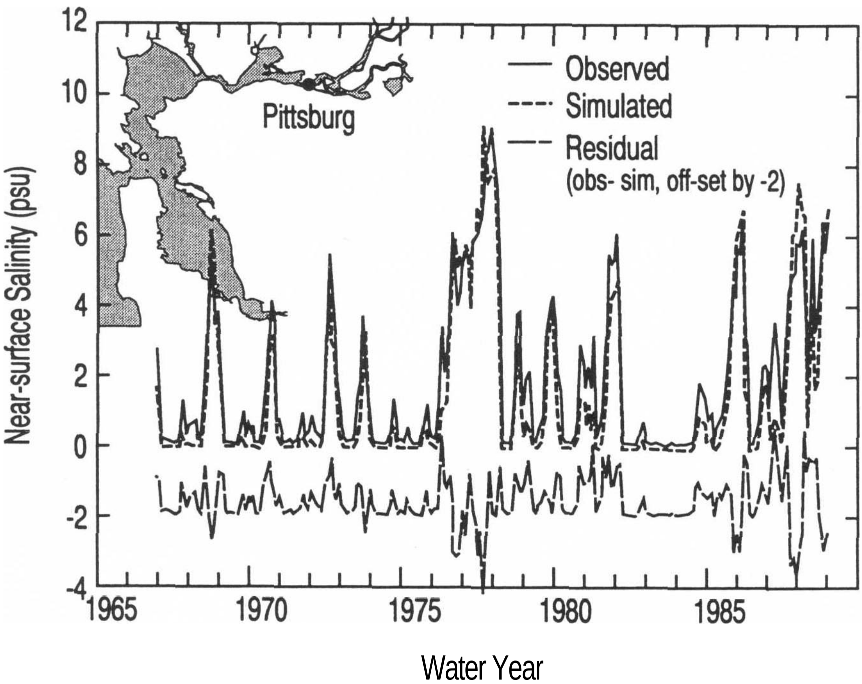

FIGURE 2. Observed and simulated mean-monthly near-surface salinity, Pittsburg; residual is the observed minus simulated value. Simulated values are from the numerical box model.

than the apparent accuracy in the observations (as is indicated by R = 0.82 in their residual cross-correlation). In other words, these data may be useful in guiding future model refinements.

Near the mouth of the estuary, at Fort Point and Alameda, the simulated salinities match observations fairly well (Figs. 3 and 4). The standard deviation of the residual at Fort Point is ± 1.39 psu and at Alameda ± 1.64 psu. This is much less than the standard deviation of the measured salinities, 3.5 and 4.7 respectively. The residual salinities between these two stations are not correlated (R = 0.06). Nor are they correlated with residual salinities near the head of the bay (R = -0.15 at zero lag). Hence, it may be difficult to use these data to further refine model predictions.

One application of the numerical model is to study time variations in residuals (observed minus simulated salinity). For example, visual inspection of the residual values for Fort Point (Fig. 3) suggests that the 1970s were less accurately simulated than the 1980s. One possible explanation is that the observations were of nonuniform quality; in fact the original field notes from the 1920s to present do show significant variations in completeness and in uniformity of sampling. In general the observations appear to be more complete in the early decades. The NBM results support the suggestion that data quality problems increased in the 1970s. But further, and perhaps even more convincing, in a separate unpublished study (J. Slack, pers. commun. 1988) simulated salinities from a regression model based on

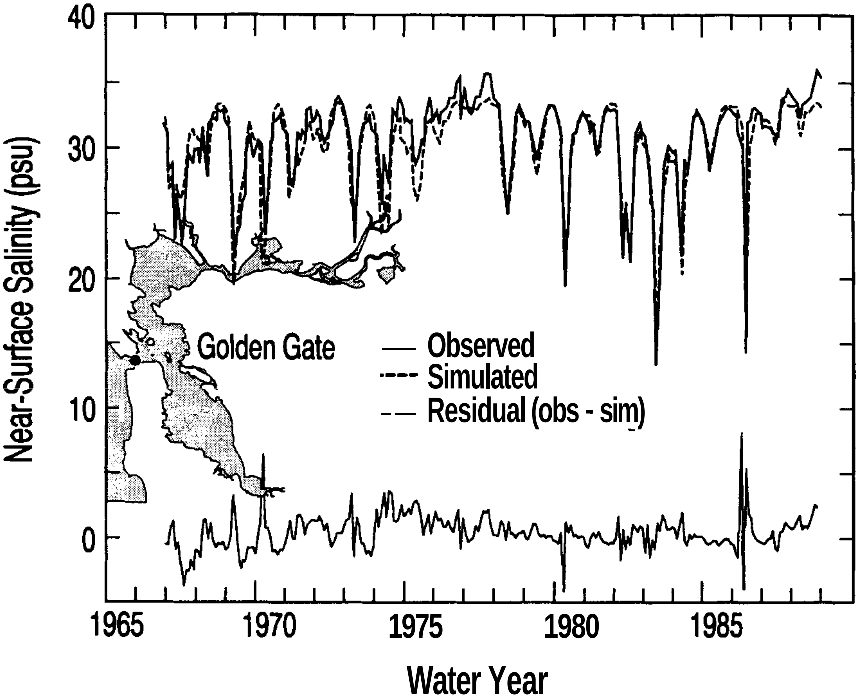

FIGURE 3. Observed and simulated mean-monthly near-surface salinity, Fort Point; residual is the observed minus simulated value. Simulated values are from the numerical box model.

observed salinity data from 1920 through 1940 represented the observed data in the 1970s and 1980s better than a similar model based on the 1970s and 1980s data alone (suggesting a lower signal-to-noise ratio in the 1970s and 1980s data compared to earlier data). The above suggests that during periods of sporadic observations, NBM may provide a better estimate of the actual values than the observations near the estuary mouth.

Another use of NBM is to provide a bay-wide frame-of-reference of the simulated salt field to compare with sparsely located observations. The mean residual salinity at Alameda is -2 psu (Fig. 4). This offset is significant and could be due to the east-side location of the observations. The model predicts salinity from an average across an entire segment. In this particular example, higher salinities may be expected on the relatively deep west side near the Golden Gate relative to the more distant and shallow east side location from coastal high salinities (see salinities for Hunters Point in Fig. 2, p. A4, McCulloch et *al.* 1970 compared to Alameda). Hence, the segment-averaged salinity could be slightly higher than the salinity observed on the east (but not necessarily 2 psu higher). Again, the model points out the complex spatial patterns for salinity in the estuary and a direction for possible future research.

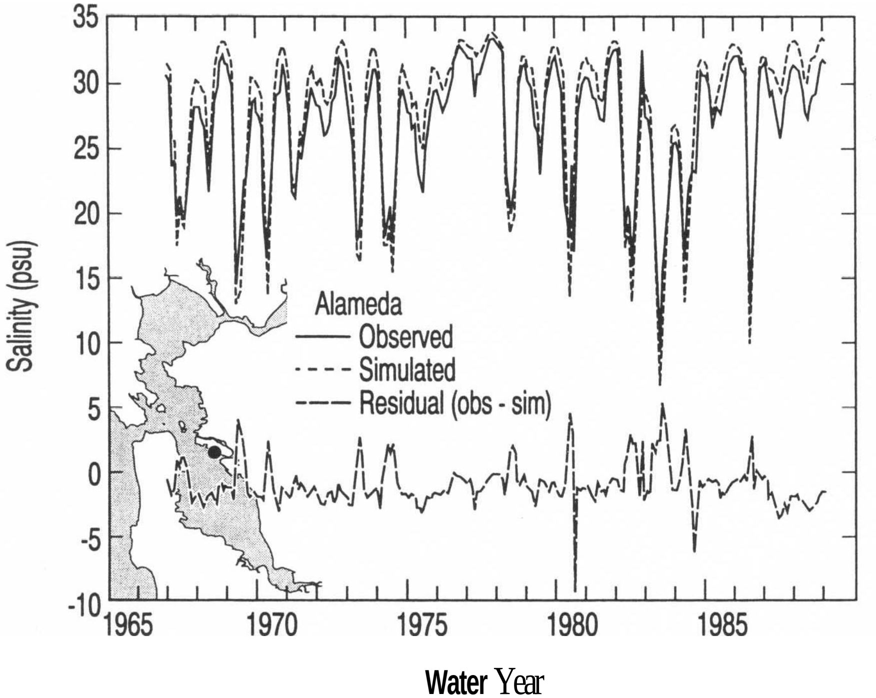

FIGURE 4. Observed and simulated mean-monthly near-surface salinity, Alameda; residual is the observed minus simulated value. Simulated values are from the numerical box model.

Hysteresis in the Salinity Response

In this subsection on the Bay's salinity we use linear statistical-dynamical models to study both time series observations and NBM results. As background, the annual cycle of mean-monthly salinity as a function of delta flow exhibits hysteresis (Fig. 5, and Peterson ***et al.*** 1989). Salinity is higher per unit discharge when delta flow is rising, lower per unit discharge when delta flow is declining. This is because the net discharge over the preceding months had changed the average salinity field in the bay. The bay is freshest after the highest discharge period.

There are also spatial differences in the effects of antecedent discharge. Salinity near the mouth of the estuary tends to be influenced most by past winter conditions because winter is the period of highest salinity variance. Salinity near the head of the estuary, where summer is the period of highest salinity variance, tends to be influenced most by past summer conditions.

These spatial and temporal patterns provide another test of the effectiveness of bay models. They also help identify where particular types of models work best. The response of salinity to discharge is near-linear at the mouth (over the observed range in discharge) and, therefore, linear models have a straight-forward applica-

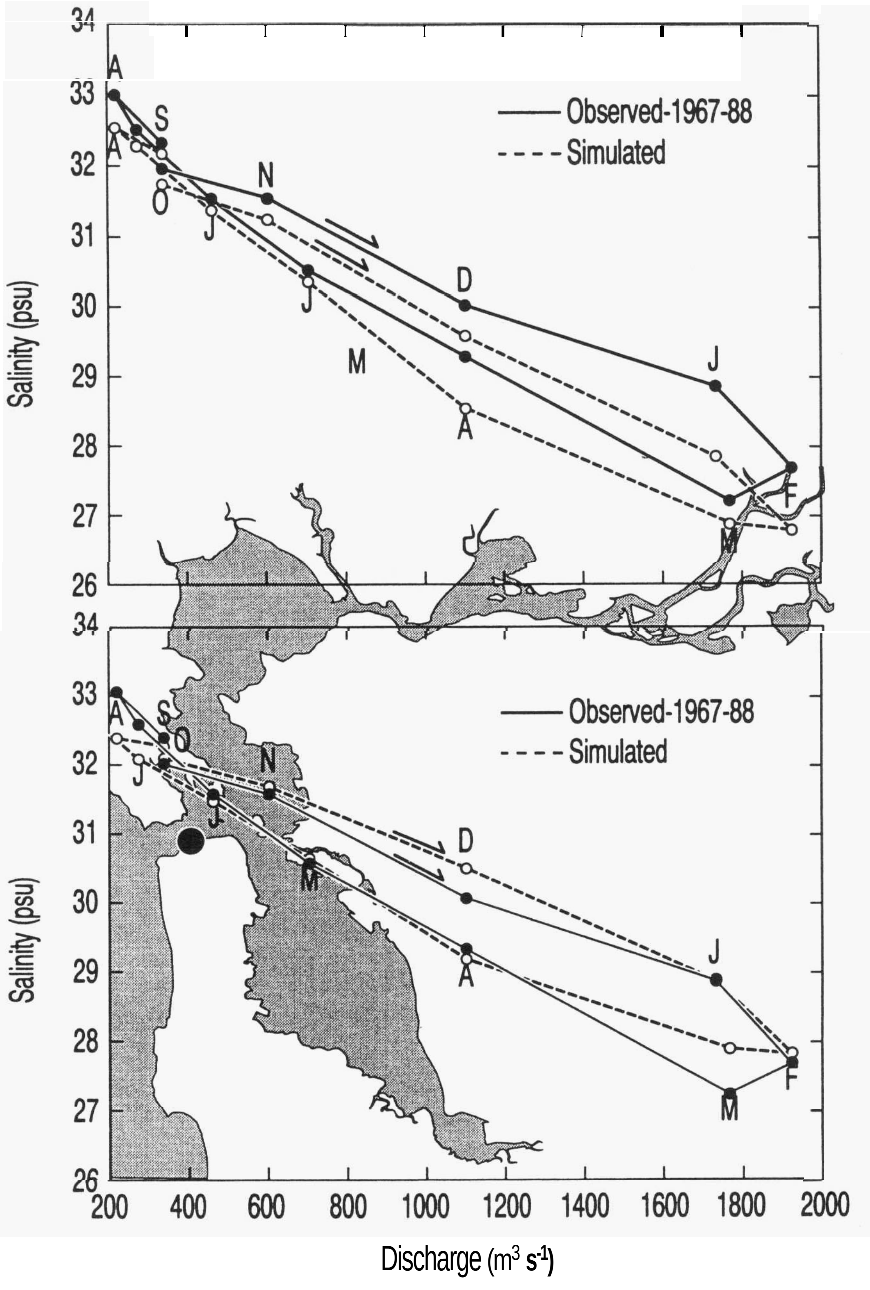

FIGURE 5. Upper Panel, mean annual cycle of salinity versus delta flow at Golden Gate from observations (1967-1988 at Fort Point) and numerical box model simulation (near surface segment # 49 in Fig. 1, 1967-1988). Lower Panel, mean annual cycle of salinity versus delta discharge at Golden Gate from observations (1967-1988) at Fort Point and from a statistical-dynamical model of salinity driven by delta flow using the observed salinity to estimate the response coefficients.

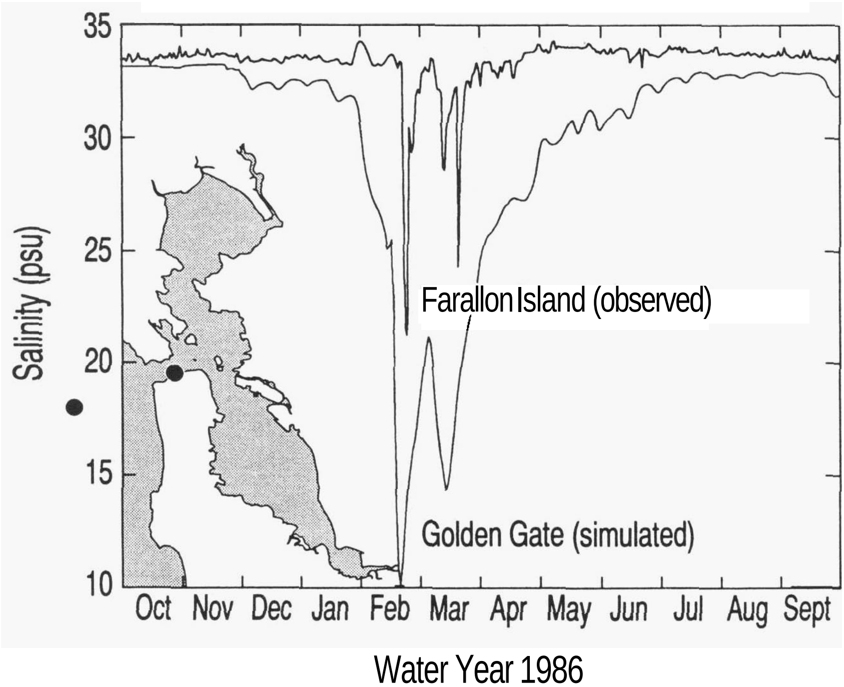

FIGURE 6. Daily near-surface salinity at Farallon Island and simulated daily salinity at Golden Gate, 1986. Simulated values are from the numerical box model.

tion. To illustrate observed and modeled hysteresis, we select results near the mouth (linear response) rather than near the head (nonlinear response).

The observed and modeled annual cycles illustrate a subtle difference in model behavior (Fig. 5). Both the NBM and statistical–dynamical models show the observed hysteresis in the salinity response to delta flow amplitudes. The width of the hysteresis loop is about the same as is measured, though the difference in salinity values just after a peak flow is less than measured. Also, the observed salinity appears more linear in response to falling delta flow. It is not yet clear how much these differences are due to a model parameter "tuning" problem rather than characteristics of the models themselves.

THE COASTAL OCEAN SALINITY

As discussed above, numerical simulations provide a reasonable description of the variations in salinity as a function of delta flow on mean-monthly time scales. However, in using mean-monthly anomalies, it is difficult to identify how changes in salinity in the coastal ocean affect salinity in the bay and vice versa (Peterson *et* al. 1989; Cayan & Peterson 1993).

To investigate this problem, we compare the NBM's daily estimates of salinity at Golden Gate with the observed daily salinity fluctuations at Farallon Island,

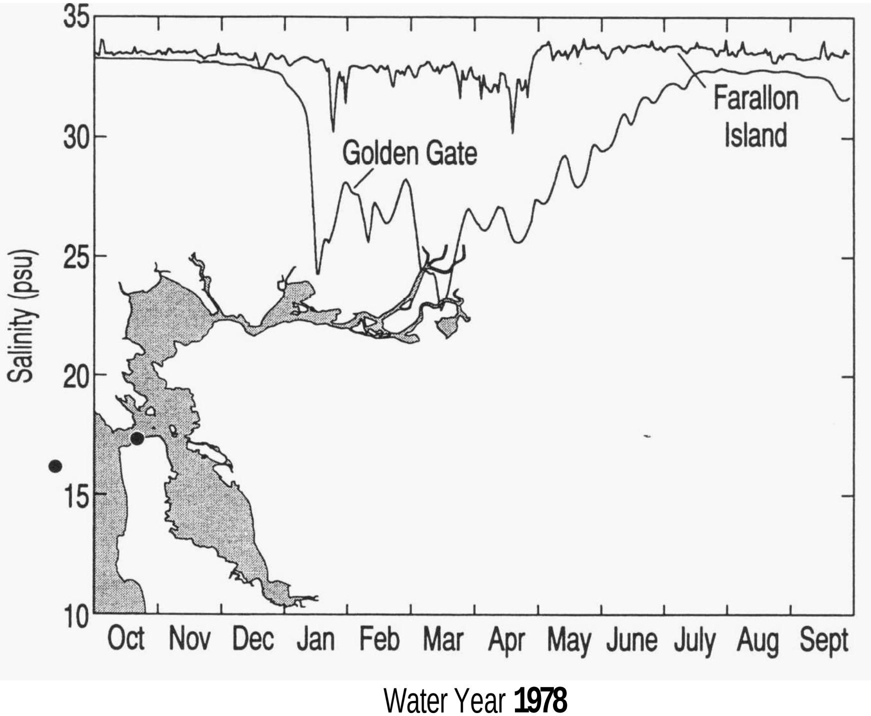

FIGURE 7. Daily near-surface salinity at Farallon Island and simulated daily salinity at Golden Gate winter 1978. Simulated values are from the numerical box model.

about 48 km offshore, and at Bodega Bay, 60 km to the north (Fig. 1). Gaps in daily Farallon Island salinity were filled using spline methods.

The typical annual cycle shows that salinities near the mouth of San Francisco Bay becomes much fresher in late winter early summer than at Farallon Islands (Fig. 6.7). These large, fresh-water anomalies at the Golden Gate are largely due to an increase in delta flow (Uncles & Peterson, in press). On a monthly time scale, over 80% of the salinity variability at the Golden Gate can be explained solely by delta flow (Peterson ***et al.*** 1989). However, the coastal ocean clearly affects the bay. After freshening events, the bay gradually becomes more saline, usually well after the coastal ocean returns to a saline condition (Fig. 6,7). This slow, delayed salinity increase suggests that the dominant processes that return salt to the bay are tidal mixing and diffusion.

Event-scale processes, such as storm driven exchanges are probably of less importance than tidal diffusion, but still can affect the salinity field in the bay. For example, upwelling events associated with the changing wind patterns in spring bring saltier water onto the shelf (Strub & James, 1988). The possible subtle role of these changes in spring coastal salinity on San Francisco Bay requires much more detailed near-surface and near- bottom observations near the bay's mouth than exist today (*cf*, Uncles & Peterson, in press). In essence, the effects on the bay of relatively rapid changes in the coastal ocean as associated with a strong spring transition are unknown but may serve as a valuable tracer as the change propagates into the estuary.

Processes in the bay also affect the coastal ocean; low-salinity anomalies are seen in the Farallon Island records. The low-salinity spikes are stronger in wet years, (1986 vs. 1978), are smaller than equivalent spikes at the Golden Gate, and typically appear after spikes appear at the Golden Gate (Fig. 6,7). It is likely that low salinity plumes from the bay are important, but are not the sole source of this spring freshening. Other processes, such as local precipitation and runoff, upwelling, and advection also affect salinity in the coastal ocean. In particular, wind can mix the surface layers, causing a temporary increase in surface salinity.

Anecdotal accounts of the 1862 flood state that a brackish plume of water from San Francisco Bay reached the Farallon Island (Young 1929). We suggested that smaller Sacramento-San Joaquin River floods may also cause some of the low salinity spikes at Farallon Island. The oceanography of the Gulf of the Farallons, however, is complex and poorly understood (Noble, Ramp & Kinoshita 1992). Thus, at this stage, understanding the relationships between the bay's salinity and that of the coastal ocean may have more to do with interpreting variability in the Gulf of the Farallons than variability in the bay. As a simple conceptual model (Fig. 8), plume trajectories may tend towards offshore or northward pathways during pre-spring and post-fall transitions and offshore or southward during post-spring and pre-fall transitions (Conomos 1979; Breaker & Bratkovich 1993; Strub & James 1988; Noble, Ramp & Kinoshita 1992). These wind- responding transitions are stronger and more persistent in some years than others and, therefore, serve only as a generalized framework for interpreting coastal ocean variability.

Observations at Bodega Bay to the north were initiated in 1976, but it is hard to use these data to study the interaction between the bay and the coastal ocean. Major rainfall-runoff storms produce low salinity spikes at both locations (Fig. 9) because major storms are generally regional in size. Bodega Bay has its own local response to such storms, sometime freshening as much as San Francisco Bay, sometimes less. In addition, low salinity water can be advected between the bays by coastal currents. Thus, a relatively detailed knowledge of the precipitation and wind regimes is needed to help resolve possible interactions between the locations.

TIDAL VARIABILITY

Large differences in the time scales of salinity fluctuations are caused by changes in delta flow and tidal currents. To minimize the effects of delta flow at tidal frequencies we first examine tidal variations during low and constant delta flow. In this section, we focus on salinity variations in the mid-estuary reach.

Low Delta Flow

Tidal and spring-neap variations in salinity during low delta flow were simulated with a simple statistical-dynamical model. The model is:

$$y(t) = b_o x(t) + b_1 x(t-1) + b_2 x(t-2) + ..e(t) \quad (2)$$

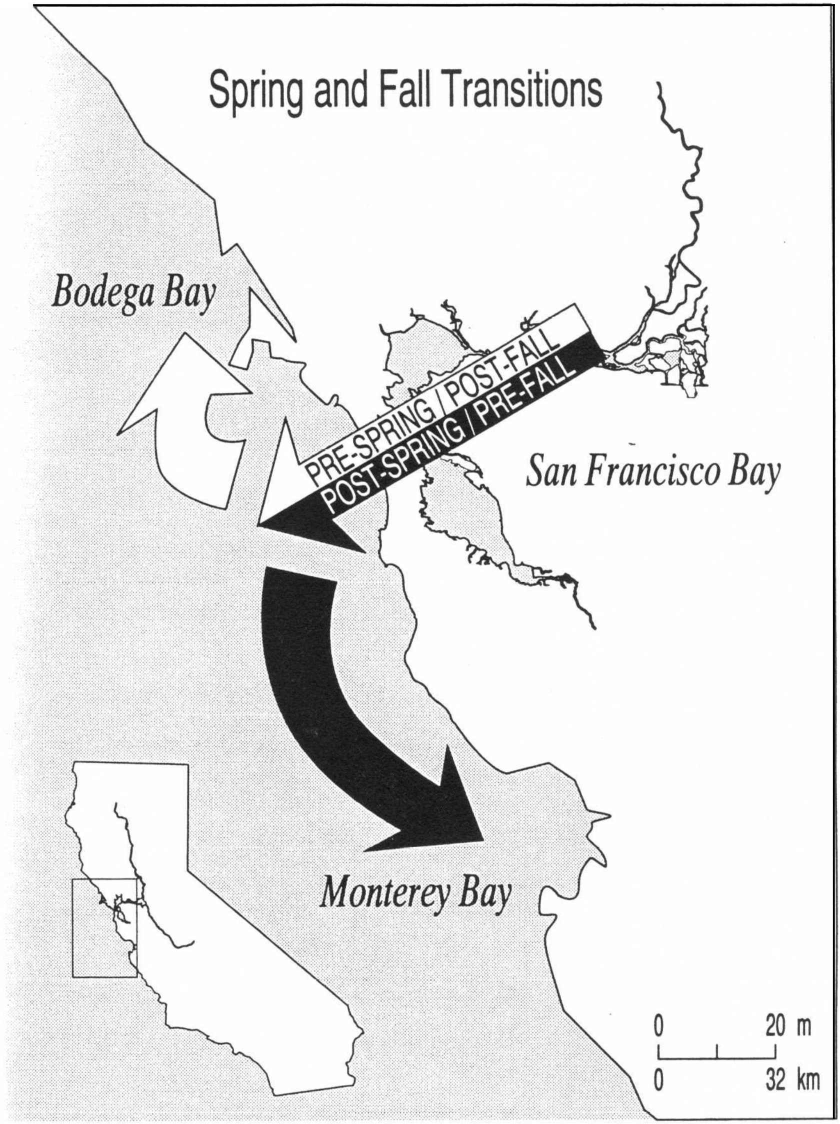

FIGURE 8. Sketch of plume pathways with wind from the north (post-spring and pre-fall transition and from the south (pre- spring and post-fall transition).

where present salinity, $y(t)$, is a linear combination of present time (t) and past forcing, $x(t-n)$, where n is a 1 hour backwards time step. For example, t-3 is the value of the forcing from 3 hours earlier; bn are the response coefficients (Table 4).

The forcing time series is estimated sea surface elevation (ESSE) at Golden Gate for calendar days 14 through 39, 1992 (Fig. 10 upper panel). Near-surface and near-bottom salinity at a station near western Carquinez Strait (Fig. 1, station # 4)

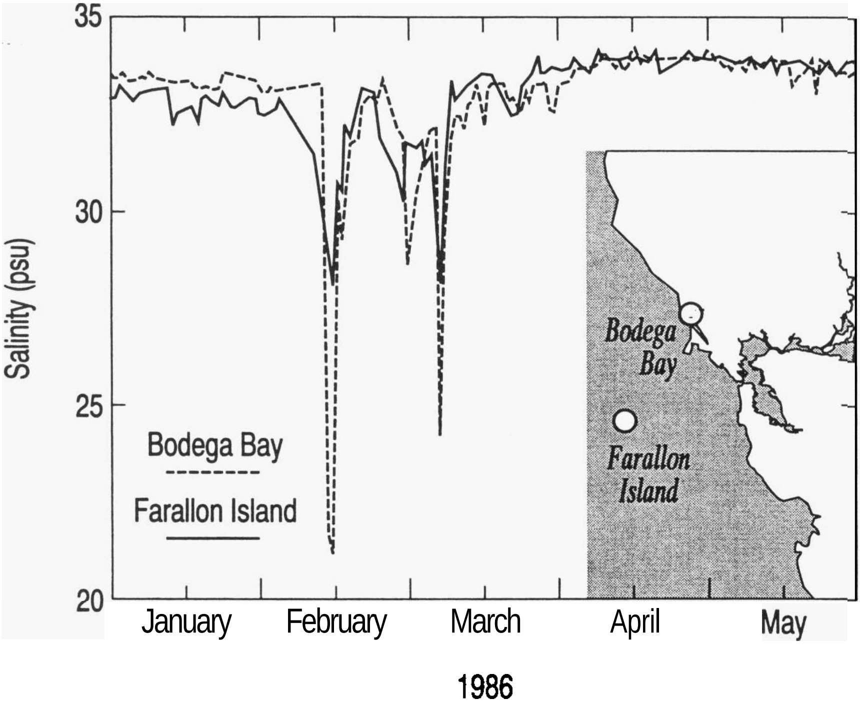

FIGURE 9. Daily near-surface salinity at Farallon Island and Bodega Bay winter 1986.

TABLE 4. Model parameters and simulation statistics.[1]

Observations	*Model Parameters*	*Estimate*	*% of Variance Simulated*	*Standard Deviation of Residual (PSU)*
Surface	b_0	0		
	b_1	0		
	b_2	0	77	± 0.99
	b_3	2.47		
	b_4	0.34		
Bottom	b_0	0		
	b_1	0		
	b_2	0		
	b_3	3.02	83	± 0.92
	b_4	0.26		

[1] Includes the 4 days 36 through 39 not used to estimate model parameters.

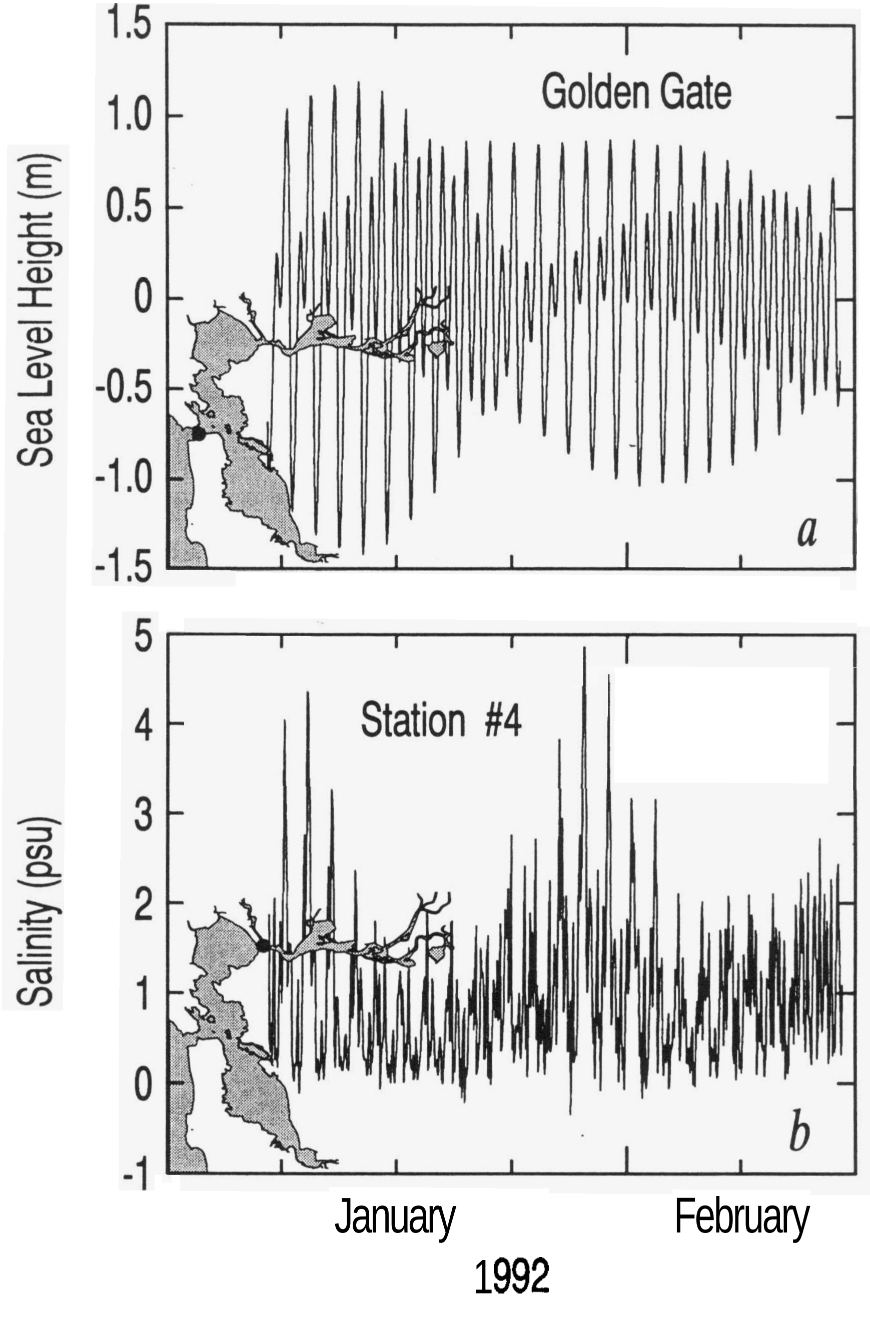

FIGURE 10. Upper panel: estimated estuarine surface elevation at Golden Gate calendar days 14 through 39,1992. Lower panel: observed salinity stratification (bottom minus surface salinity) at station # 4 for the same period.

were simulated based solely on Golden Gate ESSE. The model structure was estimated from salinity observations of days 14 through 35. This model was also used to extend the simulation to include 4 more days beyond the model-building period (days 36 through 39).

There is a 3 hour lag in salinity response to ESSE forcing (e.g., $b_0 = b_1 = b_2 = 0$). This is partly because the station is inland from the location of the forcing in a kinematic sense (Golden Gate). Although simple, the model estimates about 80 percent of the hourly salinity variance (less for surface, more for bottom), suggesting changes in delta flow and wind regimes preceding and during the study period were small. Residual values are defined here as observed minus simulated salinity values. This instrumental variable method (Ljung 1987 and 1988) produced residuals with a Gaussian distribution (Fig. 11).

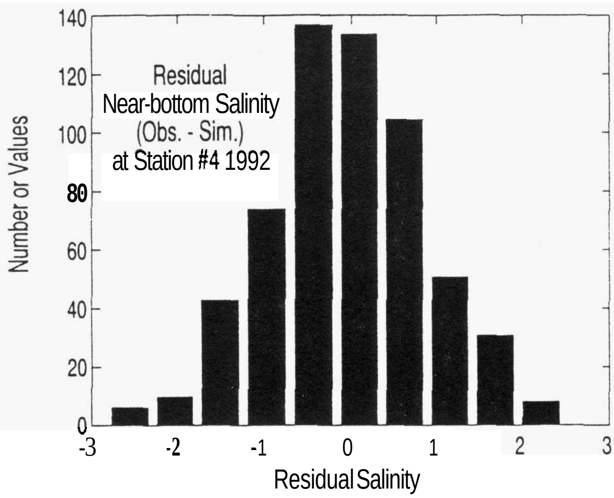

FIGURE 11. Histogram of residual salinity anomalies (observed minus simulated) for near-bottom salinity calendar days 14 through 39, 1992 at station # 4 San Francisco Bay. Simulated values are from a statistical-dynamical model driven by the estimated estuarine surface elevation at Golden Gate.

Both observed and time-series modeled data show the water column was usually stratified during the simulation time period (Fig. 10). Periods of stronger stratification were followed by periods of weaker stratification. The weaker stratification periods tended to occur when tidal amplitudes were highest (Fig. 12). The current speeds associated with changes in surface elevations are estimated from the rate of change in that elevation. In general, stratification develops and increases when currents are weak, and is destroyed when currents are strong (Fig. 13).

However, the stratification pattern is not simply related to the absolute tidal amplitudes. In general, in an elevation sequence of lower-high water followed by higher-low water, some stratification persists if the energy associated with vertical turbulent mixing is less than the potential energy associated with stratification. Apparently the next phase of the cycle is affected by this persistence in stratifica-

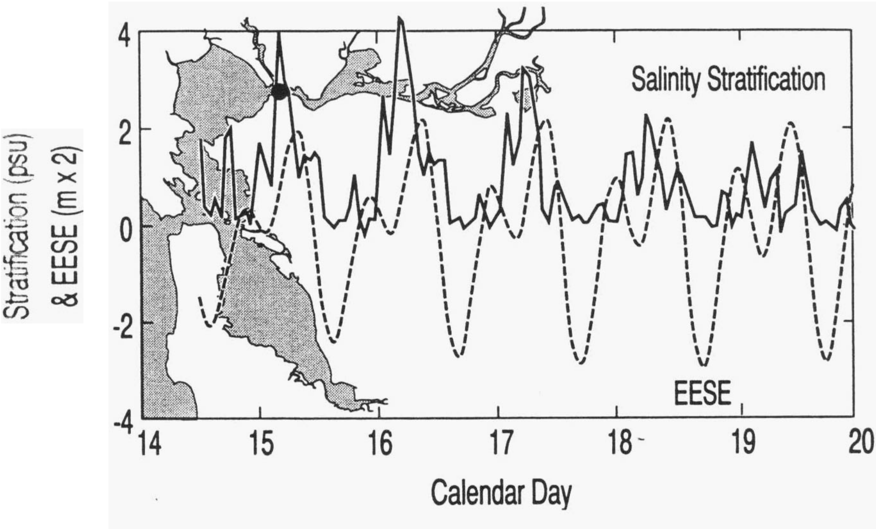

FIGURE 12. Salinity stratification at station # 4 and estimated estuarine surface elevation (EESE) at Golden Gate calendar days 15 through 20, 1992.

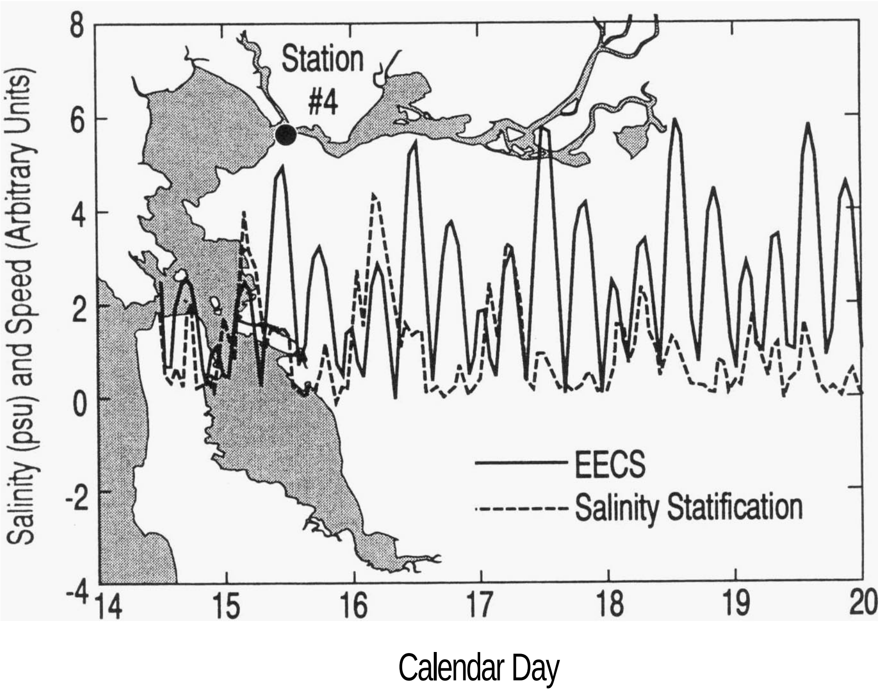

FIGURE 13. Salinity stratification at station # 4 and estimated relative estuarine current speed (EECS) at Golden Gate calendar days 15 through 20, 1992.

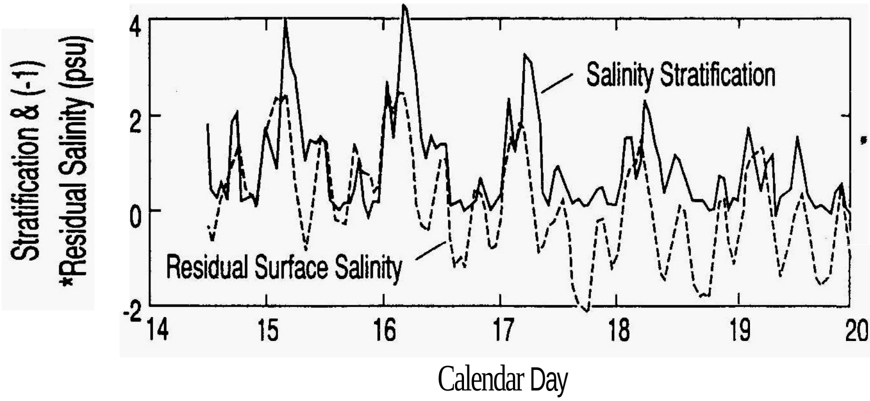

FIGURE 14. Salinity stratification at station # 4 and residual in near-surface salinity (observed minus simulated) at station # 4, calendar days 15 through 20, 1992. Simulated values are from a statistical-dynamical model driven by the estimated estuarine surface elevation at Golden Gate.

tion. It takes tidal cycles with enough energy to mix the water column before stratification breaks down (Fig. 13).

The coupling between stratification events and tidal variations of bottom stress and between feedback effects is complex (Simpson, Sharples & Rippeth 1991; Nunes Vaz & Simpson 1994). In this instance, internal dynamics not captured by our tidal amplitude-driven models appears to produce residual salinities on the order of 1 or 2 psu and time scales from hours to days (Fig 14).

High Delta Flow

The behavior of the salt field during periods of high or variable delta flow can be shown by extending the time series about 100 days to include 3 flood events (Fig. 15a). Tidal frequencies are removed from the time series by low-pass filtering. As expected, the magnitude of the drop in salinity is to some extent proportional to the magnitude of the flood (Fig. 15b). However, the timing of peak flow in relation to peak stratification varies. Presumably stratification follows the back side of peak delta flow as the salt field "reacts" to the flow. If the back side of the peak flow occurs during a neap-tide, stratification is greater than if it occurs during a spring tide.

CLIMATE AND THE HUMAN CONNECTION

The atmosphere is the major control on delta flow through the river basin, and, at subtidal frequencies, delta flow is the major control on San Francisco Bay salinity. The following is a brief overview to emphasize that the role of the atmosphere over the river basin-estuary-coastalocean is all-encompassing.

Most of the precipitation in California occurs in winter and the relative wetness or dryness of winter precipitation is explained largely by a regional California pressure index (CPI, Cayan & Peterson 1989). When the regional atmospheric

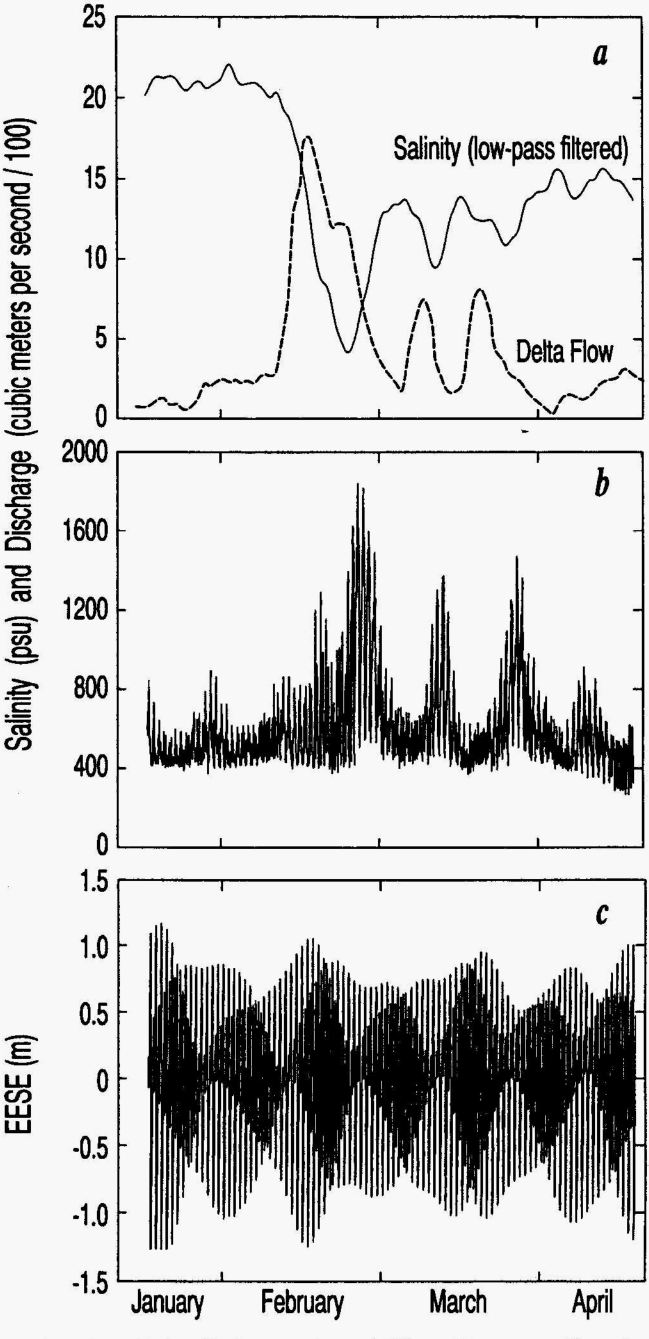

FIGURE 15. Panel A, Delta discharge winter 1992 and low-pass filtered near-surface salinity station # 4, 1992. Panel B, Salinity stratification at station # 4. Panel C, Estimated estuarine surface elevation (EESE) at Golden Gate.

pressure is high, forming a ridge, storms tend to be deflected to the north. When the pressure is low, offshore storms invade California. High or low precipitation can be further classified by air temperature: cool or warm. The four resulting winter-season categories: cool and wet, cool and dry, warm and wet, and warm and dry are associated with four distinct large-scale atmospheric circulation patterns (Cayan & Peterson 1993). Further, in winter, when the Aleutian-Alaskan low atmospheric pressure pattern over the north Pacific strengthens as is typical in El Niño years, California is very wet if that pattern is centered near the west coast of North America (e.g., 1982-1983). If the pattern is farther offshore, a high pressure system tends to occupy the CPI region and California is dry (e.g., 1976-1977).

Dettinger & Cayan (1995) have identified even longer time scales of influential atmospheric circulation patterns. Since the 1940s, north Pacific – western North American atmospheric circulation pressure and temperature fields in January, February, and March have pronounced long-term trends. The temperatures in these three winter months have been rising over the last five decades, resulting in less snowpack at mid-elevation Sierra Nevada mountain basins and an earlier spring snowmelt-driven runoff (the Roos effect – named after Maury Roos, California Department of Water Resources, who identified the trend in decreasing percentage of annual flow during spring). This natural effect accounts for an approximately 10 to **20** % reduction in spring flow as a fraction of total flow since the early 1940s.

This long-term reduction in spring flow as a percentage of the annual flow in the Sacramento – San Joaquin system is disconcerting because it is in the same direction as the artificial reduction in spring delta flow due to fresh water exports to the south. Reductions in spring delta flow is a critical issue in managing the bays fisheries (Jassby 1993).

These climate - delta export covariations are connected even on shorter inter-annual time scales. Because the human demand for water is as high or higher in dry vs. wet years, the percentage of delta flow that is exported is much higher in dry years.

Perhaps the above can best be summarized by showing the trend in spring (May) salinity at Pittsburg since the mid-1950s (Fig. 16). Following completion of the Shasta reservoir (early 1940s) an increasing fraction of delta flow is exported especially in spring. Secondary to this, is a natural-forced reduction in percent of annual Sacramento-San Joaquin river flow during spring (Dettinger & Cayan 1995). In effect spring delta flow has been declining and spring salinity rising. Furthermore, the large interannual swings in the percentage of delta flow exported are also coupled to wet and dry atmospheric circulation regimes. In a sense both the annual fluctuations and trend in salinity in Figure 16 are climate and human-caused, a striking example of why both scientific and management concerns of such a complex system as San Francisco Bay need a broad perspective (Peterson et al. 1995).

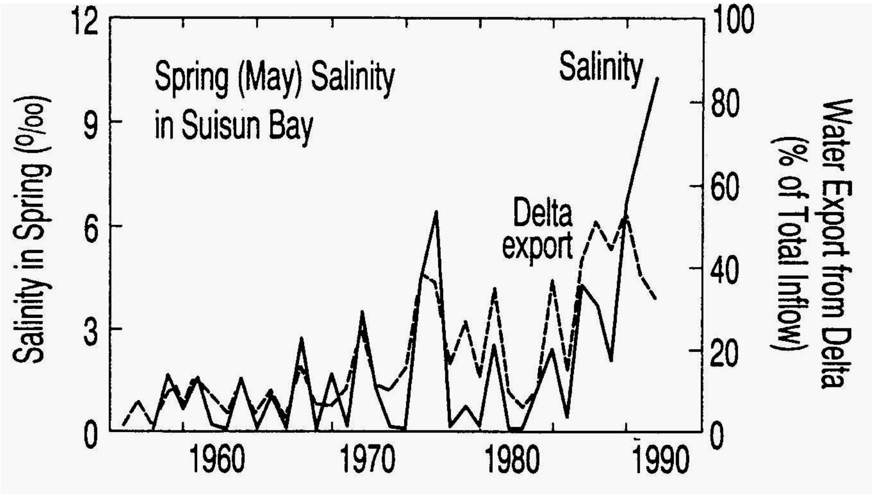

FIGURE 16. Mean-monthly (May) salinity at Pittsburg and water exported from the delta as a percentage of annual inflow.

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