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Ancient Blue Oaks Reveal Human Impact on San Francisco Bay Salinity

San Francisco Bay is one of the most important estuaries on the west coast of the Americas. Its water quality is controlled primarily by streamflow from the Sacramento and San Joaquin rivers. In fact, freshwater inflow from the Sacramento-San Joaquin Delta explains 86% of the salinity variability at the mouth of the San Francisco Bay estuary [*Peterson* et al., 1989]. The massive diversion of streamflow by the California State Water Project and the Central Valley Project, part of the largest man-made water control system on Earth [*Reisner*, 1988], has raised salinity in the estuary on daily seasonal, and annual timescales [*Nichols* et al., 1986; *Peterson* et al., 1989].

Reduced freshwater inflow and increased salinity are part of a larger syndrome of anthropogenic impacts that imperil water quality and ecosystem function in this important estuary. Regional drought conditions not only lead to high salinity, but also to increased concentrations of contaminants and nutrients in San Francisco Bay. Biologically available metal concentrations and dissolved nutrients reached record levels during the 1976–1977 drought and had serious consequences on the pelagic food web and fisheries in the Bay [Nichols et al., 1986].

Salinity variations are also strongly linked to total biological productivity in the estuary especially in response to changes in the geographic position of the null zone, the region of convergence between fresh surface and saline bottom currents in the northern reach of the Bay [Nichols et al., 1986; *Jassby* et al., 1995]. A near-bottom salinity threshold has been used since 1995 as a sensitive indicator of the ecological response to changing freshwater inflow into the estuary (U.S. Environmental Protection Agency standards listed in the *Federal Register* Part II:4463–4709, 1995). During the post-World War II era of rising salinity, many populations of aquatic organisms in the Bay have declined, due in part to decreased freshwater inflow higher salinity, and changes in the geography and geometry of the null zone. Because salinity and freshwater inflow are so tightly coupled, high salinity conditions are also synonymous with low inflow, lower freshwater flushing, higher concentrations of pollutants in the Bay, and salt water intrusion into the agricultural complex of the Sacramento-San Joaquin Delta.

The degree to which freshwater diversion has altered the natural variability of San Francisco Bay salinity has been difficult to quantify given the short period of salinity measurement and the large natural variation in streamflow and estuarine salinity. A new tree ring reconstruction of surface salinity for Fort Point on the south shore of the Golden Gate, using extreme moisture-stressed blue oak trees (*Quercus douglasii*; Figure 1), indicates that the appropriation of freshwater by state and federal water projects has led to unnatural salinity extremes and long-term trends that are unprecedented in the Bay for over 400 years.

Precipitation-Sensitive Blue Oak and Fort Point Salinity

Blue oak tree ring chronologies can provide an accurate, long-term perspective on the natural variability of San Francisco Bay's salinity because blue oak growth and estuarine salinity both tend to integrate precipitation and temperature conditions over the winter-spring season. Winter-spring precipitation and temperature then translate into river discharge conditions that actually control flushing and salinity changes in the Bay. Blue oak tree ring chronologies are highly and positively correlated with winter-spring precipitation and Sacramento-San Joaquin streamflow and are negatively correlated with spring temperature and monthly, seasonal, and annual salinity throughout the estuary.

Blue oak trees often form the lower forest border on the foothills of the Coast Range and Sierra Nevada, a forest environment where blue oak radial growth critically depends on precipitation during the winter/spring/early-summer season. We have developed 12 new blue oak chronologies throughout the native range of this species in California, and these chronologies record one of the strongest precipitation signals ever detected in tree ring data. All 12 blue oak chronologies are significantly correlated with winter-spring salinity in San Francisco Bay but the highest correlations are recorded by the five chronologies closest to the Bay in central California (Figure 2). This contrasts somewhat with the spatial pattern of precipitation influence on salinity, because most of the freshwater inflow that controls salinity comes from more remote sectors of the drainage basin in the Sierra Nevada and Northern Coastal Range [e.g., *Dettinger and Cayan*, 2001].

Fig. 1. A wind-sculpted 340-year-old blue oak (Quercus douglasii) *at Pacheco State Park, California (view is toward the south). These moisture-stressed trees provide a superb ring-width proxy for regional precipitation, streamflow, and salinity in San Francisco Bay.*

However, the five moisture-stressed blue oak chronologies nearest the Bay are simply more sensitive to precipitation than the available blue oak chronologies from northern California. In addition, some 10% of the freshwater inflow to San Francisco Bay does come from local tributaries [*Conomos*, 1979], so the strong salinity correlation of the Mt. Diablo chronology nearest the Bay may, in part, reflect the precipitation and runoff from the immediate drainage basin (r = 0.90; Figure 2). Precipitation over the central coast region where the five chronologies are located is also very well correlated with precipitation over the entire Sacramento (r = 0.92) and San Joaquin (r = 0.89) river basins for the January-July season.

Monthly salinity measurements are available for Fort Point from 1922 to 1994, though values are missing for 1946 and 1948. The Fort Point record is highly correlated with other salinity stations in the Bay, particularly when the data are seasonalized or annualized.

For example, January-July salinity at Fort Point and Alameda near the center of the Bay are correlated at r = 0.86 (P < 0.0001) for 1939–1985. Blue oak growth and monthly salinity at Fort Point are most highly correlated during and just after the wet season (January-July) when much (50%) of the precipitation that supports growth and river discharge occurs, and when most (82%) of the Sacramento-San Joaquin streamflow that flushes the Bay also occurs. The significant correlation between growth and salinity in June and July, following the wet season, partly reflects variability in the timing and magnitude of spring snowmelt seasons.

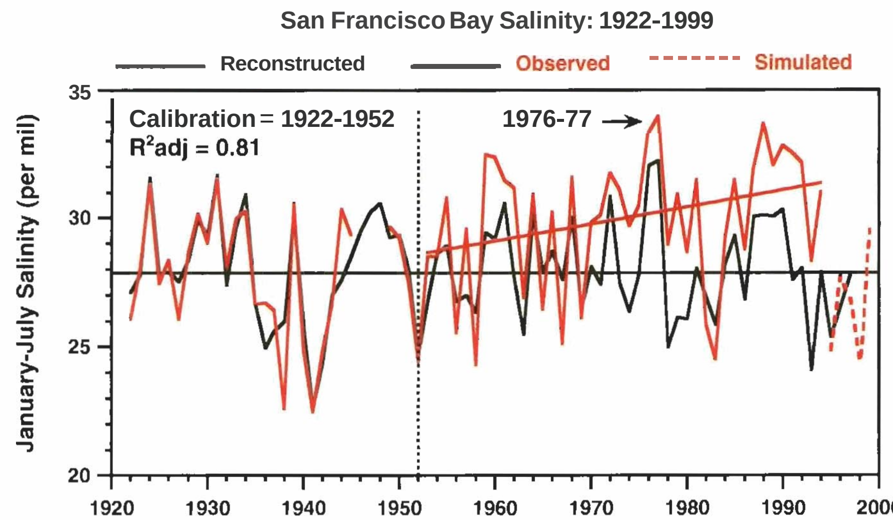

Fig. 3. Observed and tree ring reconstructed January-July surface salinity at Fort Point, 1922–1997. The reconstruction was calibrated with the salinity data from 1922–1952 (1946 and 1948 are missing, and 1947 is hidden). The horizontal line is the mean of the observed salinity for 1922–1952 (27.87‰). The rising trend line was fit to the instrumental salinity data for 1953–1994. Simulated January-July salinity for the 10 km² San Francisco Bay segment 49 is plotted from 1995 to 1999. This simulation estimates the freshening that occurred in the high runoff regime of the late 1990s, but this freshening still did not achieve the low salinity values expected for such high streamflow under pre-diversion conditions.

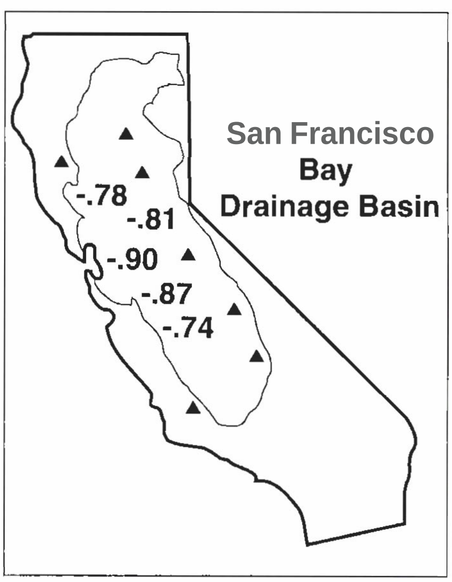

fig. 2. The five blue oak chronologies used to reconstruct salinity are located by their correlation coefficients with Fort Point salinity (January-July for 1922–1952). The five sites (north-south) are Clear Lake State Park, American River; Mt. Diablo State Park, Pacheco State Park, and Pinnacles National Monument. The seven other blue oak chronologies now available are indicated by triangles. The Fort Point salinity station is located at the mouth of San Francisco Bay, on the south shore of the Golden Gate.

A Tree Growth Proxy for Estuarine Salinity

Water diversion from the Sacramento-San Joaquin Delta increased dramatically after World War II [*Reisner*, 1988]. We use the Fort Point winter-spring salinity data from 1922 to 1952 to calibrate the tree ring reconstruction of salinity because the salinity data are stationary in mean and variance over this period and they are highly coherent with the natural and undisturbed blue oak record of precipitation over this interval. Serious modifications to the estuary did, of course, occur before 1952 [*Nichols* et al., 1986], but they do not appear to have dramatically altered the January-July average salinity measured at Fort Point from 1922 to 1952.

A regional average of the five most proximate blue oak chronologies was used as a predictor in bivariate regression with salinity at Fort Point for the 1922–1952 time interval:

$$Y_t = 3.455 - 6.509X_t \qquad (1)$$

where Y_t is the estimated January-July salinity average at Fort Point in parts per thousand (‰) for year *t*, and X_t is the corresponding ring-width value for the regional blue oak chronology in year *t*. The regional blue oak chronology is a proxy for the combined effects of regional precipitation and streamflow and explains 81% of the January-July salinity variance during the 1922–1952 calibration period (R^2adjusted = 0.81; Figure 3). This transfer function (equation 1) was used to estimate January-July salinity at Fort Point for all years from 1604 to 1997.

The diversion-impacted salinity data from 1953 to 1994 were used to verify the high-frequency interannual variability of this reconstruction. The tree ring estimates of salinity are highly correlated with observed salinity at Fort Point from 1953 to 1994 (r = 0.70, P < 0.0001). Even with the anthropogenic trend in salinity, the reconstruction passes most standard verification statistics used to evaluate dendroclimatic reconstruction fidelity (for example, the reduction of error = 0.37, but the paired t-test on observed and reconstructed means and the coefficient of efficiency both fail because they are sensitive to differences in mean).

There is a significant linear trend of +0.06‰ per year in the observed January-July average salinity data from 1953 to 1994 (P = 0.0679; Figure 3), while the trend from 1922 to 1952 is slightly negative and not significant (−0.03‰ per year; P = 0.5005). Some of this post-diversion salinity trend might be linked to natural variations in atmospheric circulation, changes in the seasonal runoff maxima, and coastal zone upwelling [*Peterson* et al., 1989]. But most appears to reflect the diversion of up to 50–60% of winter-spring streamflow from the Delta [*Nichols* et al., 1986].

The anthropogenic impact on salinity extremes and trend after circa 1952 can be detected through comparison with winter-spring precipitation over California or the tree ring reconstruction of salinity. The observed precipitation and reconstructed salinity series both lack a significant linear trend for the period from 1953 to 1994. The 1953–1994 trend in December-April precipitation for a regional average of California climatic divisions 1, 2, 4,

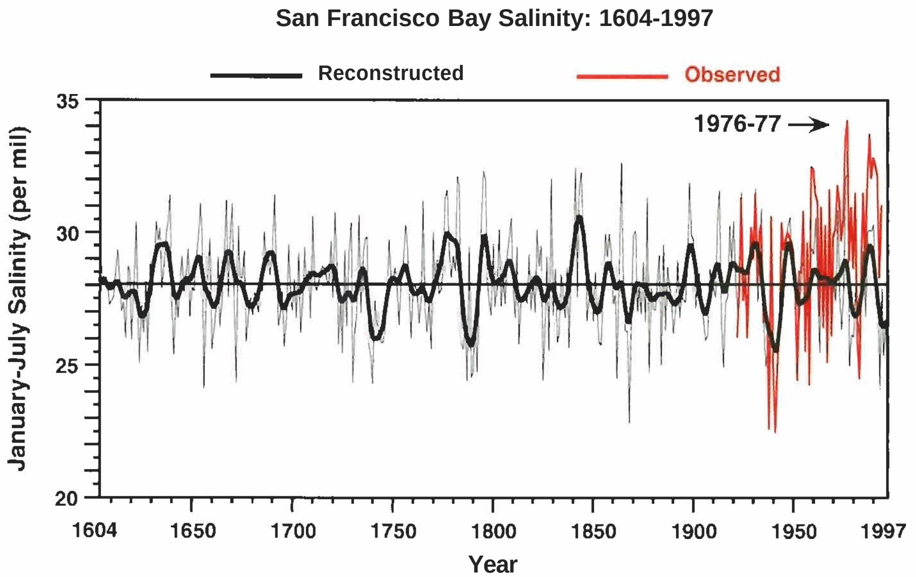

Fig. 4. January-July surface salinity at Fort *Point* reconstructed *from tree rings* for *1604-1997* (light *black time series, mean = 28.05‰, standard deviation = 1.79‰), and a smoothed version highlighting decadal variability (heavy black curve). The observed salinity values measured at* Fort *Point from 1922* to *1994* arc. *shown in red. Note the unprecedented* trend *and increased frequency* of *high salinity extremes* during *the period* of *heavy streamflow diversion after World War II. High salinity extremes* occur during drought, and the *extremes witnessed during the* 1976, 1977, *1988, and 1990 droughts have not been matched* ocer the post 400 years. *Low salinity extremes occurred during certain* coy strong El *Niño events* (for *example,* 1789–179.3, *1828, 1878, 1891, 1941, 1983, and* 1998). *There* is *significant* spectral power in *the ENSO* frequency *band (5.2 years,* P < *0.05, 1604–1997) that is coherent* with *the* Southern *Oscillation Index* (P < *0.05 for 1876–1997*) in *this reconstruction. After 1604, this reconstruction generally confirms* the *long-term salinity fluctuations estimated from lower* resolution hut *much longer sedimentary data* (Ingram *et al.,* 1996*].*

and 5 is only – 1.4 mm per year (P = 0.582). The regional blue oak chronology is very highly correlated with December-April precipitation over these same four climatic divisions (r = 0.81; P< 0.0001 for 1931–1994) and can therefore provide a valuable historical perspective on the magnitude of the anthropogenic impact on estuarine salinity after 1952.

Observed salinities increasingly diverge from reconstructed salinity after 1952, and after 1969, all observed values exceed tree ring estimated salinity except during the strong El Nino event of 1982–1983, when the Bay was temporarily freshened to pre-diversion levels (Figure 3). However, the 1983 freshening still did not equal the low salinity values observed during the 1941 El Nino event, even though "unimpaired" January-July streamflow from the eight major Sierra Nevada rivers averaged 1,983 cms in 1911, compared with 2,913 cms in 1983 [*Dettinger and Cayan*, 2001]. Note that the tree ring data fail to fully reflect this incredible high discharge/low salinity event of 1983 (Figure 3). Heavy precipitation was concentrated in March of 1983, and much of this rainfall in the lower elevation blue oak zone must have run off without sustaining tree growth over the entire growing season.

This 1983 example highlights a weakness in the tree growth/salinity model. The tree ring data are not ideal for estimating intense, short-duration precipitation events, while flashy precipitation events, when stored as snowpack, can moderate Bay salinity across the entire spring-summer snow melt season. However, when heavy precipitation is well distributed across the winter-spring season, as it was in 1941, the blue oak chronologies do a good job of representing the high dischargellow salinity conditions (Figure 3).

A 400-Year Perspective on San Francisco Bay Salinity

The California drought of 1976–1977 was the most severe of the 20th century and one of the worst of the past 400 years [*Haston and Michaelsen*, 1997] (Figure 4). In 1977, the salinity at Fort Point exceeded the average salinity of the coastal Pacific Ocean, 34.24‰ versus 33.00‰, respectively [*Peterson* et al., 1989] (Figure 3). The reconstruction indicates that the extreme salinity values witnessed tluring both 1976 and 1977 have not been equaled in 400 years (Figure 4). These extreme salinity conditions were certainly aggravated by water diversion from the Delta, with observed salinity exceeding what would have been expected due to the drought alone by an estimated 1.54 and 2.00‰ in 1976 and 1977, respectively (Figure 3). The salinity extremes measured in 1988 and 1990 also exceeded all previous estimates since 1604 (Figure 4).

The increased frequency of high-salinity extremes and the persistent above-average salinity regimes measured after 1952 are both unparalleled over the past 400 years. For example, reconstructed January-July salinity at Fort Point exceeded 31‰ during just 23 out of 349 years before 1953 (6.6%), but salinities above this threshold increased five-fold for 14 of 42 years from 1953 to 1994 (33%) (Figures 3 and 4). The prolonged drought of 1987–1992 was similar in magnitude and duration to the drought of 1929–1934, based on the unimpaired January-July streamflow estimated for eight Sierra Nevada rivers [*Dettinger and Cayan*, 2001]. However, the resulting salinity was much higher in the recent event (Figure 3; mean = 32.56‰ for 1987–1992 versus 29.87‰ for 1929–1934). The reconstruction indicates that the persistent 1987–1992 episode of high salinity was unmatched over the past 400 years (Figure 4). The previous highest 6-year average salinity estimated for the pre-diversion era from 1604 to 1952 was only 30.65‰ during 18/11–1846.

Some of the 19% salinity variance not explained by our model (see Equation 1) might be due to differences in the distribution of precipitation over the Sacramento and San Joaquin drainage basins, which appears to be modulated in part by the North Pacific Oscillation (NPO). Heavy snowpack in the higher elevations of the San Joaquin system tends to melt slowly and depress Bay salinity over the January-July season. Simulations of San Francisco Bay salinity near Fort Point tluring high and low phases of the NPO suggest that changes in runoff timing between the Sacramento and San Joaquin basins might account for as much as 1‰ of January-July salinity [*Knowles*, 2000]. However, if 1‰ is added to all tree ring reconstructed values from 1604 to 1997, the high salinity extremes witnessed at Fort Point during 1977 and 1988 were still unmatched over the entire 400-year reconstruction.

The long Fort Point salinity recording station was unfortunately discontinued in 1994, but the Bay was subsequently freshened by well-above-average precipitation and stream flow in the mid- to late-1990s. The three highest January-July unimpaired streamflows since 1906 for the eight Sierra Nevada rivers were estimated for 1983. 1995, and 1998, respectively [*Dettinger* and *Cayan*, 2001]. However, this recent freshening again did not equal the low salinities expected from similar high runoff events in the pre-diversion era. Simulated January-July surface salinity for San Francisco Bay segment 49 is plotted from 1995 to 1999 in Figure 3. This simulation is based on freshwater inflow and tidal mixing [*Uncles and Peterson*, 1995]. Because the simulation covers a 10 km^2 segment of the Bay extending east from the Golden Gate Bridge, it averages 0.67‰ lower salinity than the single Fort Point record (29.29‰ versus 30.31‰, respectively for 1953–1994). This underestimation increases to 0.78% after 1958 (29.53‰ versus 30.31‰, respectively).

In spite of this difference in mean salinity the freshening simulated during the very strong El Nino of 1998 still did not approach the low salinity recorded during the pre-diversion era

El Niño of 1941 (Figure 3), even though the unimpaired eight-river January-July streamflow was 2,535 cms in 1998, compared with only 1.983 cms in 1941.

The tree ring reconstruction demonstrates that severe drought and high salinity extremes are part of the natural variability of the San Francisco Bay hydrologic system and are certain to recur, even if the diversions of Sacramento-San Joaquin streamflow were to end. Therefore, the future health of this great estuary vitally depends on California's water conservation and pollution control practices and on the management policies of the federal and state water projects.

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