ORIGINS OF WATER AT THE EXPLORATORIUM IN CENTRAL SAN FRANCISCO BAY

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by

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San Francisco, California

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CERTIFICATION OF APPROVAL

I certify that I have read *Origins of Water at the Exploratorium in Central San Francisco Bay* by Maeve Kathleen Daugharty, and that in my opinion this work meets the criteria for approving a thesis submitted in partial fulfillment of the requirement for the degree Master of Science in Physical Oceanography: Geosciences at San Francisco State University.

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We investigate the origins of water at the Exploratorium in San Francisco Bay through analysis of forcing data, salinity, and temperature. Water from the estuary mouth was consistently present in Exploratorium waters, indicating a persistent oceanic signal.

During Storm Season, water from north Central Bay, North Bay, and South Bay were present, signifying contributions from local tributaries. When mixing was significant, water proximal to the Delta was included.

During Upwelling Season, water from the deep ocean, the California Current, Pacific Subarctic Water, and the Gulf of the Farallones were potential oceanic constituents at the Exploratorium, in addition to freshwater and Bay-wide water.

Waters from the South Bay, the southern Central Bay, and the mouth converged with Exploratorium waters, isolating North Bay waters during Relaxation Season. Oceanic surface water was the most likely oceanic constituent with some potential for the California Undercurrent and Pacific Equatorial Water to circulate through the Gulf of the Farallones, into the Bay, and to the Exploratorium.

I certify that the Abstract is a correct representation of the content of this thesis.

Chair, Thesis Committee

May 9, 2014
Date

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Introduction

In 2013, the Exploratorium Museum (Exploratorium) relocated to San Francisco's Pier 15 in the southwestern quadrant of the Central San Francisco Bay (Central Bay), approximately 13 km from the mouth of the Bay (Figure 1). Taking advantage of its new waterfront residence, the Exploratorium educates visitors about the importance of the estuary and the ocean beyond. As part of this effort, water quality parameters including temperature, depth, and salinity have been monitored since March, 2013. In addition, Exploratorium scientists collect weekly water samples to identify phytoplankton and zooplankton species present in Bay waters. Cloern (personal communication, 2012) posed the question of where sampled waters originate and how their origins change over time. We explore the question of water origins in Central Bay through the examination of freshwater and coastal ocean influences using in situ, conductance temperature depth (CTD) data in the context of seasonal patterns. The Bay, its surrounding watersheds, the adjacent coastal Pacific Ocean, and the atmosphere define the study system (Bay system).

Seasons

Coastal California's Mediterranean climate consists of dry summers and wet winters. Precipitation patterns in the Bay are driven by large-scale atmospheric forcing, where high regional atmospheric pressure creates a ridge which redirects storms over the Pacific Ocean northward, and low regional pressure gives way to offshore storms (Cayan and Peterson 1989 cited by Peterson et al. 1996). Through analyses of wind stress data from nine coastal buoys, Garcia-Reyes and Largier (2012) distinguished three governing seasons along central and northern California: Storm Season (December, January, February), Upwelling Season (April, May, June), Relaxation Season (July, August, September), and transitional months (March, October, November). They described the Storm Season winds as generally weak with intermittent strengthening by passing storms; the more persistent, strong, upwelling-favorable (equatorward) winds of Upwelling Season, subject to frequent weakening and reversals; and the weak, equatorward, rarely reversing winds of Relaxation Season.

These seasons comprise a useful framework in analyzing annually recurring patterns in the Central Bay. Seasons in the California Current System (CCS) and the Bay have long been described with varying terminology and time periods. To differentiate from these, the seasons defined by Garcia-Reyes and Largier (2012) will be referred to collectively as CCS Seasons and individually as Storm Season, Upwelling Season, and Relaxation Season.

Bay System Overview

A conceptual model of the Bay system (Figure 2) shows large scale influences on water composition at the Exploratorium and Central Bay considered in this study. The Sacramento River-San Joaquin River Delta (Delta) provides approximately ninety percent of the Bay's freshwater, and Coyote Creek is the major natural freshwater source for the South Bay (Conomos et al. 1985). Freshwater forms a seaward-flowing surface layer over Bay waters that is mixed by storm winds and tides. The surface layer transports water from throughout the estuary through Central Bay and to the Pacific Ocean.

Solar heating of the shallow waters of the South Bay causes sufficient evaporation of surface waters to increase salinity. The impacts of evaporation in the South Bay and its influence on salinity in Central Bay are implicitly captured in salinity analyses.

Currents and upwelling over the California continental shelf convey and mix a variety of water masses that become available for transport into the Bay (Conomos et al. 1979). Because the Gulf of the Farallones acts as a center of exchange between coastal and California Current System (CCS) waters (Steger et al. 2000) and a detention center for Bay outflow and oceanic waters (Wing et al. 1998 cited by Gough et al. 2010), a range of waters are brought towards the mouth of the Bay throughout the year. Upwelling-favorable winds transport oceanic water at depth, which is cooler and more saline than surface water, towards the sandbar sill at Fourfathom Bank (Largier 1996). Waters at depth must ascend the sill in order to enter the Bay's mouth, which requires strong upwelling-favorable winds and periods of weakening or reversal (Largier 1996). During Upwelling Season, cooler more saline waters may enter the Bay. During Relaxation Season, after winds have weakened, warmer, less saline surface layers are available for transport into the Bay (Conomos et al. 1985).

The Bay

The Bay has a northern reach, referred to as the North Bay and embodied by Suisun Bay, San Pablo Bay, and Central Bay, and a southern reach embodied by the South Bay. Submerged channels extend along the floor of the northern and southern reaches and form their confluence at the Golden Gate channel, the estuary mouth. The average Mean Lower Low Water (MLLW) depth in the Bay is 6 m, while the regions of submerged channels have depths of 10 to 20 m, and the maximum depth of 100 m occurs in the mouth (Conomos et al. 1979). Freshwater runoff travels at the surface of North and South Bay waters, converges in Central Bay, and exits through the mouth. Because of its proximity to the Delta, waters in Suisun Bay are the most freshwater-influenced in the system, San Pablo and Central Bay are progressively more saline, and the South Bay functions as a marine lagoon, with small freshwater input relative to the volume of the Bay (Conomos 1979).

San Francisco Bay tidal currents and elevations are driven from the open ocean. Diurnal tides advance along the coastline from south to north (Mofjeld et al. 1995 cited by Steger et al. 1998) with certain components adjusting to tidal flow through the estuary mouth (Steger et al. 1998). Complex bathymetry at the Gulf of the Farallones imposes significant spatial variation in the tides (Petruncio 1996 cited by Steger et al. 1998). Spatial variability of exchange at the mouth manifests in lateral steady exchange flow, where the majority of tidal flow enters towards the south, and the majority of freshwater exits towards the north (Martin et al. 2007).

Tides in the Bay are mixed semidiurnal with four components of differing height (higher high, lower low, lower high, and higher low) occurring in each 24.48 hour tidal day (Conomos et al. 1979). Because higher high tide is followed by lower low tide, the maximum difference in hydraulic pressure head, or barotropic forcing, and highest velocities occur during this cycle of ebb (Largier 1996). The Bay experiences spring tides, which generate the highest tidal range and coincide with the full moon and new moon, as well as neap tides, which create the lowest tidal range and occur at the moon's first and third quarters (Conomos et al. 1979). Tidal exchange is also impacted by inter-annual cycles: the spring and fall equinoxes bring weak tides, and summer and winter solstices bring strong tides (Schemel 1998).

In addition to tidal exchange, flow through the estuary mouth is affected by stratification induced by freshwater discharge and heating of surface waters (Largier 1996). During storms, precipitation and freshwater inflow freshen Bay surface waters setting up vertical stratification and circulation, which are significant when Delta outflow exceeds 500 m^3s^{-1} (Largier 1996). Vertical stratification can be disrupted before the end of the ebb cycle or it can endure into or beyond the following flood cycle, depending on the strength of the tide (Lucas et al. 1998). In the Spring, the Bay waters are warmed by increasing air temperatures while the surface waters in the Gulf of the Farallones become cooler and more saline due to upwelling (Largier 1996). The resulting horizontal stratification endures until later summer and boosts exchange at the estuary mouth when upwelled waters are available (Largier 1996). Following late summer, both Bay and coastal ocean surface waters continue to warm while freshwater inflow is at its lowest, resulting in minimal stratification (Largier 1996).

Conomos et al. (1979) observe longitudinal salinity and temperature distributions in the Bay. Tidal exchange through the estuary mouth and freshwater inflow drive the salinity distribution throughout the Bay, with seasonal river inflow establishing broad salinity ranges (Conomos et al. 1979). The North Bay is partially mixed during periods of high freshwater inflow, which create a strong density gradient from the Delta to the mouth, and well-mixed during the dry months of summer (Conomos et al. 1979). The longitudinal salinity spread in the North Bay from the Delta to the mouth increases seaward and varies significantly in both winter and summer (Conomos et al. 1979).

In the summer, South Bay waters are mixed by a combination of tidal energy and wind (Conomos et al. 1979), yielding a near constant salinity (Walters et al. 1985). The South Bay maintains salinities near that of the ocean especially in the summers of dry years (Conomos et al. 1979). During periods of high freshwater input into the Bay, the density gradient between the dense, saline waters of the South Bay the fresh, surface layer in Central Bay drives a baroclinic current which mixes the waters of these adjacent embayments (Walters et al. 1985).

River inflow is subject to larger temperature fluctuations than oceanic waters (Conomos et al. 1979). In winter, temperatures in the North Bay increase slightly in the seaward direction due to colder freshwater inflow (Conomos et al. 1979) and colder inland temperatures. In summer, North Bay temperatures decrease in the seaward direction due to warmer freshwater inflow and colder, upwelled ocean water (Conomos et al. 1979). South Bay winter temperatures are between Delta and oceanic values, suggesting heating by the atmosphere and cooling by Delta flows (Conomos et al. 1979). In the summer, South Bay waters are heated by solar insolation and remain warmer than waters at the mouth (Conomos et al. 1979).

Freshwater

The Delta watershed occupies approximately forty percent of the area State of California (Conomos et al. 1985). A significant quantity of Sacramento-San Joaquin River flow is impounded, consumed, or diverted upstream of the Bay with annual exports sometimes exceeding 50% of inflow (Cloern and Jassby 2012). Sacramento River reservoir releases in summertime augment summer low flow conditions (Conomos et al. 1985). Watershed modifications have significantly modified the Bay's estuarine circulation and salinity responses. Shellenbarger and Schoellhamer (2011) found that a modification in average annual freshwater flow to the Bay at Mallard Island in Suisun Bay as small as one cubic meter per second (m^3s^{-1}) alters salinities throughout the Bay by 0.0030 to 0.0069. Peterson et al. (1989 cited by Peterson et al. 1996) cite changes in Delta flow as the principal source of salinity dilution in the Bay. Because the Delta contributes the majority of freshwater to the Bay, estimated Delta discharge entering the Bay is the focus of freshwater analyses. Following convention, Delta inflow is defined as the discharge value located upstream of exports, and Delta outflow, downstream of exports, represents the remaining discharge that enters the Bay.

Other freshwater sources include direct precipitation and runoff, the Napa and Petaluma Rivers in the North Bay, and Coyote Creek, Alameda Creek, and the Guadalupe River in the South Bay. The South Bay's tributary area and associated runoff are relatively small (Conomos and others 1979; Hager and Schemel 1996 cited by Schemel 1998), and its shallow depths are vulnerable to seasonal temperature increases from solar input (Shellenbarger and Schoellhamer 2011). South Bay conditions are impacted by Delta outflow when values are high (McCulloch and others 1970; Imberger and others 1977 cited by Schemel 1998). Discharge from South Bay tributaries makes significant contributions during large local storm events, otherwise, wastewater effluent dominates freshwater input in this region (Schemel 1998).

The Coastal Pacific Ocean

The California Current system, the eastern edge of the north Pacific sub-tropical gyre, is defined by the surface-flowing equatorward California Current and the less documented, poleward California Undercurrent, which flows at depth. During Upwelling Season, equatorward winds force the California Current and promote the upwelling of deep ocean water towards the estuary mouth. The California Current transports the relatively cool, fresh Pacific Subarctic Water (PSAW), and coastal upwelling can modify this water by bringing cold higher salinity water to the surface.

As equatorward winds subside during Relaxation Season, the California Current is displaced by the California Undercurrent, which shifts shoreward (Conomos et al. 1985). The California Undercurrent transports warm, saline Pacific Equatorial Water (PEW) poleward. Complex circulation in the Gulf of the Farallones, where PSAW and PEW have been observed, impacts the types of water available for intake into the Bay (Steger et al. 2000).

Approximately nine km seaward of the Bay's mouth, exiting ebb tide current velocities decrease, allowing sediment to drop out and form the Fourfathom Bank. The crescent-shaped sandbar is approximately 10 meters deep and a narrow, 20-meter deep dredged channel defines the controlling depth for oceanic water to enter the Bay (Largier 1996). Largier (1996) noted that the most significant intrusions of upwelled water migrate into the Bay after the relaxation of upwelling winds; as the winds weaken, the coastal sea surface height recovers, pushing coastal waters landward along with upwelled waters at the estuary mouth. Intermittent upwelling, then, may have a greater effect on exchange than prolonged events (Largier 1996). In the absence of upwelling winds, the transport of deeper oceanic waters over the sandbar sill is curtailed, leaving fresher, warmer surface water available for exchange (Conomos et al. 1985).

Exploratorium Water Origins

To answer the questions of water origins at the Exploratorium, we investigate the following: How do freshwater discharge data, coastal upwelling winds, and Central Bay atmospheric data change throughout the year? Do forcing mechanisms reflect CCS Seasons? Do Bay-wide responses align with CCS Seasons or does the Bay system follow different seasonal patterns? Are upwelling events evident in coastal winds detectable in Central Bay waters? When freshwater and coastal ocean forcing signals overlap, how are Central Bay waters impacted? What does an investigation of system-wide CTD data tell us about the origins of water samples collected at the Exploratorium? What do seasonal patterns in the Bay tell us about the origins of these water samples and how they change over time?

Data

We examined stream flow data, wind direction and speed, Central Bay rainfall depth, Central Bay air temperature, and conductance temperature depth (CTD) data from seven locations. Table 1 summarizes datasets and station names used throughout this study. Dataset location, name, and color-coding used in data plots are shown in Figure 3. The study period extends from September 30, 2008 through March 31, 2014, though availability of data varies among stations.

The data used to define Bay water mixtures are moored CTD sensors at six locations in San Francisco Bay and one in the coastal region. Hourly observations were obtained, providing the highest temporal resolution dataset available over a broad area of San Francisco Bay. The sensor on the north side of Carquinez Strait at California Maritime Academy (CMA), which lies east of Suisun Bay, is the closest to the Delta. This sensor sampled the lowest salinities of the seven CTD stations studied. The Romberg Tiburon Center maintains a CTD sensor off of its north pier in northern Central Bay (RTC). These two sensors are 1.0 m below Mean Lower Low Water (MLLW). Bodega Marine Laboratory operates a CTD sensor at the southern side of the Golden Gate close to Fort Point pier (FTP) in San Francisco at a depth of approximately 2.7 m below MLLW. Given its position in the mouth of the Bay, FTP registered the highest salinities of the Bay stations. Data from Bodega Marine Laboratory's shoreline sensor (BML) located at the Laboratory in Bodega Bay was used to capture coastal ocean temperature and salinity at a depth of approximately 3.0 m below MLLW. The United States Geological Survey (USGS) operates a CTD sensor at 1.8 m below MLLW at Alcatraz (ALC) in southern Central Bay, relatively near the estuary mouth, and one at the San Mateo Bridge (SMB) in the South Bay. Data from the upper SMB sensor, located 1.2 m below MLLW, were used. The Exploratorium and the Romberg Tiburon Center operate a CTD sensor at the Exploratorium's Pier 15 location approximately 1.4 m below MLLW (EXP). Because the Exploratorium CTD sensor was deployed in March 2013, the temperature and salinity responses in southern Central Bay are also investigated using ALC data as a proxy. Temperature measurements at Alcatraz began on October 1, 2010, therefore, the study period for this portion of analysis begins then. Data at three of these sites – RTC, CMA, and the Exploratorium (EXP) - have not been reviewed, cleaned, or analyzed previously, and collectively this group of multi year, temporally aligned, quasi-continuous Bay-wide and coastal ocean data has not been studied.

Dayflow, developed by the California Department of Water Resources, uses daily Sacramento and San Joaquin River inflows, water exports, rainfall, and agricultural withdrawals to estimate Delta outflow into the Bay at Chipps Island, a value which cannot be measured directly because of tidal interaction (Koller 2014). Because this dataset is comprised of daily data, hourly values were synthesized through linear interpolation to enable statistical analysis with other hourly data. The upper part of the Coyote Creek watershed is relatively undeveloped, with the exception of two reservoirs, while the lower watershed is urbanized. Coyote Creek discharge data were obtained from a United States Geological Survey (USGS) stream gage located 400 feet upstream of Highway 237 in Milpitas, CA, relatively close to the Bay's southern edge (United States Geological Survey, 2014).

To evaluate the impact of local coastal winds on the composition of waters in the Bay, we obtained wind speed and direction from National Data Buoy Center coastal ocean buoys 46026 (B26) and 46013 (B13). These two sources were combined to form a relatively complete dataset of coastal winds near the mouth. Wind data were decomposed into x and y coordinates (using right hand rule conventions) to approximate across shore and alongshore wind components, respectively.

Local hourly rainfall and air temperature data were recorded from the Romberg Tiburon Center (RTC) weather station collocated with the RTC Central Bay CTD.

Methods

This study focuses on large scale mechanisms that drive the composition of waters at the Exploratorium over a five year study period. Forcing mechanisms are shown in the conceptual model (Figure 2), and the responses of Bay system waters are captured in high frequency, near surface, salinity and temperature data.

Statistical Analyses

We investigate the links between freshwater input, coastal ocean upwelling, and salinity and temperature throughout the Bay system through monthly means and lagged cross covariance. Cross covariance assesses the degree to which two signals deviate from their mean in a similar manner (for example, does a relative increase in Central Bay salinity occur with a relative increase in coastal ocean salinity). A lagged analysis shifts the signals to account for a lag in fluctuations (for example, if a relative increase in Central Bay salinity occurs an hour after a relative increase in coastal ocean salinity, there is a one hour lag between them).

Visual Assessment

We use plots of freshwater discharge, Central Bay rainfall, nearby coastal alongshore winds, and Central Bay air temperature to explore the alignment of large scale forcing in the Bay system with CCS Seasons. Interannual patterns are investigated in forcing data as well.

With an understanding of seasonal forcing in the Bay system, we interpret shifts in Bay-wide and coastal ocean temperature and salinity and potential links to forcing data, such as the impacts of Delta outflow on salinity and temperature throughout the Bay, or the appearance of high salinity waters in Central Bay with upwelling-favorable winds.

Monthly temperature-salinity (T-S) diagrams of color-coded station data reveal when different water masses come together and when they diverge. We observe the spatial, Bay-wide distribution of salinity and temperature to identify the origins of waters at the Exploratorium during one water year and apply the Central Bay, ALC proxy station to draw conclusions about water origins under different interannual conditions. We address temporal overlap of freshwater and coastal ocean forcing in the Bay system and show how water origins at the Exploratorium are impacted.

Results

Interannual and seasonal cycling evident in freshwater, coastal wind, and air temperature data are reflected in the salinity (Figure 4) and temperature (Figure 5) response of the Bay system. CCS Seasons are apparent in the Bay's forcing and response systems with a tendency towards early onset and lingering in the Bay; Bay system seasons exhibit significant overlap. Salinity patterns in the Bay system mirrored the Delta outflow hydrograph and exhibited extended periods of heightened values which reflect coastal upwelling. Salinity increases manifested in the Bay's nearby coastal station, BML, before appearing in the Bay. Temperatures in Bay and coastal waters generally replicated RTC air temperature fluctuations, exhibiting similar interannual anomalies and seasonal oscillations. Water temperatures were progressively warmer in the landward direction, except during Storm Season, when a system-wide temperature gradient reversal occurred. The reversal was prolonged beyond Storm Season by the presence of threshold storms. T-S diagrams showed that near surface waters from different stations in the Bay were horizontally mixed to a degree dependent on the strength of storm winds and magnitude of Delta outflow. This created a mixed estuary condition during Storm Season and a partitioning across Central Bay which typically began during Upwelling and continued into Relaxation Season. After Bay partitioning, the North Bay remained freshwater influenced and the South Bay became increasingly saline and warm, exhibiting the influence of the coastal ocean but remaining distinct from BML. Salinity and temperature at EXP were evaluated within this context.

Freshwater

Water years (WY), used herein, run from October 1 of a given year through September 30 of the following year, the designated water year. The California Department of Water Resources (DWR) classifies water years as *wet, above normal, below normal, dry, critical* (California Department of Water Resources 2013). DWR water year classifications in the Sacramento and San Joaquin Valleys for the study period (Table 2) show wet conditions in 2011 and critical to below normal otherwise. 2008 is shown in Table 2 as the antecedent condition to 2009.

The Delta hydrograph (Figure 6, with BML salinity response to be addressed later) and monthly peak Delta outflow (Table 3) reflect excessive storm activity in 2011 and comparatively low flow conditions otherwise. In the figure and the table, light gray signifies Storm Season, medium gray signifies Upwelling Season, and dark gray signifies Relaxation Season. This color-coding is used throughout this study. 2009 is classified as dry with critical antecedent conditions in both watersheds. Based on peak flow values, runoff volume, or the area under the hydrograph curve, and DWR classification, 2012 is the second driest water year in the study period. The wettest year by all measures is 2011. Therefore, 2009 best represents dry conditions with dry antecedent conditions, 2012 represents dry conditions with wet antecedent conditions, and 2011 reflects wet conditions. 2010 and 2013 will be considered moderate.

The Coyote Creek hydrograph (Figure 7) showed runoff patterns similar to those in Delta outflow, with generally synchronized timing of peaks and drier periods. Flow magnitudes differed and local anomalies appeared, but general storm system timing and relative storm size were consistent. The maximum Delta outflow in the study period, approximately 6200 $m^3 s^{-1}$, occurred on March 26, 2011 (March 2011 storm). The maximum Coyote Creek flow in study period, approximately, 44 $m^3 s^{-1}$, occurred on March 24, 2011.

As expected, storms tended to occur during Storm Season. Significant Delta outflow also appeared during Upwelling Season in every year of the study period. The largest amount occurred during the 2011 Upwelling Season, as indicated in the apparent flow volume in Figure 6 and in monthly peak flow values. Significant Delta outflow also occurred in April of 2010 and 2012.

Peak flows appeared in the Coyote Creek hydrograph during Upwelling Season in 2010, 2011, and 2012, and rainfall at the RTC Weather Station, Figure 8, appeared in Upwelling Seasons for all water years. In general, rainfall at RTC shared timing of large storms and dry periods with Delta outflow and Coyote Creek. System-wide atmospheric forcing was evident in the consistent patterns of these spatially separated watersheds, despite significant upstream watershed manipulation in both the Delta and Coyote Creek watersheds and local anomalies apparent in the three datasets.

Storm Season freshening of the Bay and coastal ocean is expected to be maximized in 2011, minimized in 2009 and 2012, and moderate in 2010 and 2013. Freshening during Upwelling Season is expected to occur from the end of March through June of 2011, and April of 2010 and 2012. Based on Delta outflow, March and April of 2011, April of 2010, and April of 2012 are candidates for Storm Season, in addition to CCS Storm Season months.

Air Temperature

RTC Weather Station air temperature (Figure 9) reflected subtle interannual fluctuations, with elevated values in 2009 and 2013 visible in monthly mean values (Table 4). Rather than an annual sinusoidal pattern, the seasonal pattern is saw-toothed. Air temperatures were lowest in Storm Season, when storm fronts reduce air temperatures (Schemel 1998), steadily increased through Upwelling and Relaxation Seasons, and rapidly declined in October and November. Elevated, 2009 and 2013 mean annual RTC water temperatures and similar seasonal fluctuations at RTC and throughout the Bay system (Figure 5) link atmospheric forcing and near surface water temperatures.

Coastal Ocean Wind

Interannual patterns in wind from coastal buoys near the Bay (Figure 10) manifested in Storm Season with frequent wind reversals and surges of strong winds. Larger than average mean monthly poleward winds for a given year generally appeared in December, January, February, and March. In the absence of data for 2011, we expect that the highest values manifest during the March 2011 storm but cannot analyze upwelling winds during that year. Because coastal storm systems migrate into the Bay, we expect the horizontal mixing of near surface Bay water to coincide with coastal storm winds. Local Bay winds will also contribute to mixing, but because they will significantly not impact the composition of Bay waters, they were not analyzed.

Strong, upwelling-favorable (equatorward) winds with periods of wind relaxation or reversal characterize Upwelling Season. Equatorward winds from coastal buoys near the Bay generally coincided with the CCS Upwelling Season, with some interruptions by storms. In addition, Upwelling Season appeared to show early onset in the Bay system;

upwelling-favorable winds first appeared in March 2009, March 2010, February of 2012, and February of 2013.

Relaxation Season brought relative weakening of upwelling-favorable winds and increased interruptions by wind relaxation and reversals. Consistent with the CCS Relaxation Season, relaxation patterns in the Bay system manifested as a general weakening of upwelling winds in July, August, and September.

Interannual patterns also appeared in the relatively weak Upwelling and Relaxation Season winds in 2009 and 2010 compared to those in 2012 and 2013. These relative differences were reflected in Monthly Mean Equatorward Wind Speed (Table 5) and Monthly Mean Poleward Wind Speed (Table 6). Unusually high Upwelling Season mean monthly poleward wind speeds occurred in May and June, 2011, following the March 2011 storm. Mixing is expected to be significant throughout the 2011 Storm and Upwelling Seasons.

We expect the most significant freshening and mixing of Bay system waters to occur during Storm Season. We also expect freshening and mixing to occur during periods of heightened Delta outflow in Upwelling Season, which occurred in April 2010, March through June, 2011, and April 2012. We expect the strongest signal of upwelled waters to appear in the Bay system in 2012 and 2013 and the weakest signal in 2009 and 2010.

Coastal Ocean Salinity

To examine the effects of freshwater on salinities at the BML coastal station, we superimposed Delta outflow and salinities at BML (Figure 6). In addition, we examined wind data, Delta outflow, and BML and FTP salinity for each year (not shown). Mean monthly salinities at BML and FTP are shown (Table 7 and Table 8).

Coastal ocean salinities were lowest during Storm Season. Dramatic decreases in BML salinity (Figure 6) aligned with peaks in Delta outflow. Local anomalies, such as low values in August and September of 2012, also manifested, indicating that local storms or other events also contributed to freshening at BML.

Salinities increased after upwelling-favorable winds and wind reversal episodes manifested. Each year, at least one marked increase in salinity at BML occurred, after which, disruption by subsequent storms was followed by an immediate salinity rebound. The first increase in salinity was interpreted as a signal of Upwelling Season. Generally, salinity at BML was raised in March, remained heightened through Upwelling Season, and began a very slow decline in Relaxation Season. If storms and salinity heightening occurred in the same month, then a dual presence of Storm and Upwelling Seasons was noted.

FTP followed the same general pattern as BML but with intensified and prolonged freshening while flow from the Delta and other rivers passed through the Bay. Maximum salinity values occurred at BML during Upwelling Season and at FTP during Relaxation Season.

Reduced salinities at FTP and BML in February, March, and April of 2011 confirmed these months as Storm Season despite datagaps in wind. Salinity recovery at BML in April was considered indicative of Upwelling Season, as were the stable salinities that followed the transition.

Bay System Seasons

Seasonal patterns, summarized in Table 9, were drawn from observations in Delta outflow, wind data, and salinity fluctuations at BML, and are consistent with general observations of RTC air temperature data. Consistent with CCS Seasonal patterns, Storm Season patterns in the wind data of buoys near the Bay were evident in December through February of all years where data are available except February, 2013. The Delta outflow hydrograph shows that a storm from January 2013 extended into February, therefore, this month was categorized as Storm Season. While some evidence of storm patterns in wind data appeared in the transitional months of November each year and in October in 2010 and 2011, freshwater flow was low. These were considered transition months. Storm wind patterns lingered in the Bay system, extending into March and April of 2012. Upwelling Season typically appeared in March and ended in June, though signs were seen as early as February of 2012 and 2013.

San Francisco Bay System Salinity

Salinity for the study period (Figure 4) shows a thin band of marine salinity values at the coast (BML) and progressively fresher and more stratified waters landward. Salinity ranges were greatest during Storm Season, when waters were freshened by freshwater inflow and mixed by wind and the tides. The salinity range generally began to retract during Upwelling Season as storms passed through the estuary and collapsed in Relaxation Season when values in the Bay tended to be at their maximum. The transition into Relaxation Season was consistent with the July, August, September designation of Relaxation Season in the Bay system.

The study period also showed a decrease in near surface salinity from the coast to the Delta and an increase in the spread in the range of values, or the tidal elevation salinity stratification, in the landward direction. The coastal, BML station showed the least overall variance of salinity, the smallest tidal change, and the highest salinity values during Upwelling Season. This coastal station exhibited the influence of upwelling through a persistent elevation of salinities during Upwelling Season and of freshwater input through dilution during periods of Delta inflow and local anomalies. The relatively narrow tidal salinity range indicates that the coastal waters have a mixed layer deeper than the location of the instrument.

Salinity at FTP did not share values with the BML data, indicating that even at the mouth of San Francisco Bay, the surface waters were relatively diluted. The gap between FTP and BML salinity reflects the relative freshening of FTP by Bay waters, though FTP was generally more saline than the remainder of the Bay.

Significant overlap between ALC and FTP salinity during Storm Season, Upwelling Season, and Relaxation Seasons demonstrates that this region of the Central Bay was horizontally well mixed near the surface throughout the year. ALC and SMB salinities generally converged during Relaxation Season, especially in drier years.

FTP and ALC values freshened and overlapped increasingly with RTC salinities independent of the strength of poleward coastal winds. Rather, storms with a Delta peak outflow mixing threshold between 900 and 1300 $m^3 s^{-1}$ indicated freshening of coastal waters and mixing throughout Central Bay. A peak Delta outflow of 913 in January 2012 $m^3 s^{-1}$ and a value of 896 $m^3 s^{-1}$ in November 2013 failed to significantly freshen and mix values, while a peak outflow of 1299 $m^3 s^{-1}$ in February 2009 mixed waters between adjacent stations. Peak outflow values that occurred with the onset of freshening and mixing, in addition to 1299 $m^3 s^{-1}$ in February 2009, are 1935 $m^3 s^{-1}$, January 2010; 2545 $m^3 s^{-1}$, December 2011; and 1454, in March 2012. With Delta outflows greater than 2000 $m^3 s^{-1}$, water mixed across stations as well, and with large enough storms (6203 $m^3 s^{-1}$ in March 2011) water from all Bay stations mixed. In all years, wet and dry, mixing continues into Upwelling Season, especially in the presence of threshold storms. In 2013, which experienced lower usual February and March Delta outflow, the salinity range collapsed prematurely in May, with FTP, ALC, (and EXP) significantly mixed and RTC displaying elements of both coastal and fresher waters.

ALC monthly mean salinities (Table 10) were lowest from December through April, slightly longer than in the coastal ocean due to proximity to freshwater input. As expected, salinities were greatest during and immediately following Relaxation Season. Elevated values in March of 2012 and 2013 are consistent with heightened monthly mean values in coastal ocean salinity in the same period. Salinity at RTC reflects contributions of freshwater and coastal ocean water. Values frequently overlapped with FTP and ALC (Figure 4), especially during Storm Season and the onset of Upwelling Season, and extended towards CMA, especially during Relaxation Season. Figure 11 shows salinities without ALC and EXP values so that RTC and FTP are more visible. RTC salinities occupied a larger range of values than FTP and ALC. RTC salinity appears to have equaled or surpassed values at BML (October, November, January, and February, 2009; July and August, 2012) and surpassed values at FTP (October, November, January, February, and April, 2009; June, July, August, 2012). This may be due to slugs of dense, cold, saline oceanic water entering the mouth at a depth beneath that of the FTP sensor and surfacing prior to passing the RTC sensor (personal communication, John Largier 2013). RTC generally shared its high salinity values with ALC and FTP during Storm and Upwelling Seasons in part because ALC and FTP freshened. During Relaxation Season, ALC and FTP became more saline and the range of RTC salinity constricted, retreating into a salinity band disassociated from FTP and ALC. These patterns suggest persistent mixing of surface waters in south Central Bay (FTP and ALC) throughout the year and seasonal mixing of south and north Central Bay (FTP, ALC, and RTC) during

Storm and Upwelling Seasons. The generally more persistent mixing of FTP and ALC waters reflects lateral exchange at the mouth where oceanic waters enter at the south side and freshwater exits to the north (Martin et al. 2007). Anomalies, however, are seen as salinities at RTC reached values in the oceanic range on several occasions.

Further landward and to the north, salinities at CMA fluctuated seasonally, spreading across a large range similar to that at RTC, indicating freshwater and coastal ocean influences. Delta outflow was reflected in CMA salinities that approach zero during storms. CMA salinities increased during Upwelling Season and Relaxation Season and converged with RTC during Relaxation Season.

SMB salinities remained within a narrow band, reflecting a high degree of mixing in the shallow South Bay. The SMB salinity band fluctuated seasonally with the other stations, remained within RTC's broad salinity band, and overlapped with or approached values at ALC. SMB salinity overlapped with other Bay values during larger storms and retreated into increasingly higher values during Upwelling Season and Relaxation Season. During Relaxation Season, SMB, FTP, and ALC salinities converged.

Links among Central Bay stations (FTP, ALC, and RTC), the North Bay (CMA) and north Central Bay (RTC), and the North Bay and south Central Bay (ALC) supported by lagged cross covariance of salinity, for which values greater than 0.80 are reported (Table 11). Cross covariance among FTP, RTC, and ALC salinity is strong during Storm Season and higher during Upwelling Season. Covariance values greater than 0.80 do not exist for

Relaxation Season. That additional lagged cross covariance greater than 0.80 did not result is likely attributed to datagaps; each dataset had missing points, and the total number increased when datasets were paired for analysis. Cross covariance of 0.80 between FTP and EXP and ALC and EXP for complete but not seasonal data suggests that with additional years of data, strong seasonal cross covariance would result. In addition, covariance between ALC and EXP supports the use of ALC as a proxy. FTP and ALC shared greater covariance than RTC and FTP, as expected, given the majority of tidal flow enters the mouth towards the south (Martin et al. 2007). ALC and SMB shared an overall high covariance which is strengthened during Upwelling Season, when south Central Bay and South Bay waters converge. CMA and ALC covaried during Storm Season, showing the extent of mixing in the estuary, and during Upwelling Season, illustrating the lingering effects of Delta-derived outflow in Central Bay. Strong covariance between CMA and RTC during Upwelling Season also demonstrates mixing of waters throughout the estuary. That cross covariance greater than 0.80 between CMA and RTC did not result may be due to absent CMA data for the Relaxation Season of 2012 and a gap in Relaxation Season, 2013.

Lags of eight hours between FTP and ALC seem reasonable, if long, and lags of nine hours between RTC and ALC suggest complex circulation of waters in Central Bay over direct transport between these locations. A zero lag between RTC and FTP may mean a simultaneous freshening of surface waters through rainfall and direct runoff, which may account for the high covariance during both Storm and Upwelling Seasons. The zero lag between the Upwelling Season ALC and SMB covariance also implies that freshening that may also link these two stations. A three hour lag between CMA and RTC is reasonable, and an 11 hour lag between CMA and ALC is consistent with the nine hour lag between RTC and ALC. The negative lag between CMA and ALC during Storm Season, however, invalidates those results, since freshwater does not move up the estuary.

San Francisco Bay System Temperature

Interannual anomalies are generally consistent with RTC air temperatures where data are available; mean annual temperatures were a maximum in 2013 (14.6) and 2009 (14.2) at RTC, in 2013 (13.8) and 2010 (13.3) at FTP, in 2013 (15.8) and 2009 (15.9) at CMA, and in 2013 (11.8) and 2010 (11.8) at BML. At ALC and SMB, where data are available for 2011, 2012, and 2013, the maximum mean temperature occurred in 2013 (14.0 at ALC, 16.7 at SMB). The 2010 heightened FTP and BML values show coastal deviation from the shallower waters of the Bay.

Large scale seasonal temperature oscillations within the Bay (Figure 5) typically followed those of air temperatures at RTC and Sacramento River temperatures at Mallard Island (not shown): sharp temperature drops in October and November, cool temperatures in Storm Season, steady increases during Upwelling, and maximum values during Relaxation Season. River inflow to the Bay was cooler than the coastal ocean in winter and warmer than the coastal ocean in summer (Conomos et al. 1979). The range of Bay and coastal ocean water temperatures constricted during cooling; temperatures at each station exhibited the tightest range during this period and remained constricted through Storm Season. Temperatures spread during Upwelling Season when air temperatures increased progressively in the landward direction and warmed Bay waters accordingly. Temperature ranges spread during Upwelling and Relaxation Seasons as the Bay continually responded to cooler tidal waters.

During Storm Season, when river inflow and air temperatures triggered progressive landward cooling, the temperature gradient of Bay waters reversed, with the partial exception of SMB temperatures, which did not typically fall below those at RTC. In December, the temperature gradient typically began its shift towards cooler values in the landward direction, a configuration reflected in Figure 5 and in T-S diagrams (Figure 12, Figure 13). The reversal was established by December (2009, 2011, 2012, 2013, 2014) or January (2010), and ended sometime in January (2014), February (2012 and 2013), March (2009, 2010), or April (2011). Table 12 shows Peak Delta outflow values with temperature gradient reversal periods shown with an asterisk.

While the March 2011 storm was sufficiently large and prolonged to sustain reversed conditions, the series of freshwater surges in March 2012 (peak flow 1454 $m^3 s^{-1}$) and April 2012 (peak flow 1260 $m^3 s^{-1}$) following a dry Storm Season (peak flow 913) were not large enough to overcome the accelerated warming of Bay waters already underway. Flows in February 2009 (peak flow 1299 $m^3 s^{-1}$) and March 2009 (peak flow 1526 $m^3 s^{-1}$), the driest year in the study record, were likely sufficient to prolong the temperature gradient reversal until mid-March because they occurred while conditions were still reversed. Similarly, relatively moderate flows in February 2010 (peak flow 1247 $m^3\ s^{-1}$) and March 2010 (peak flow 932 $m^3\ s^{-1}$) sustained the reversal. Low flow conditions in November 2012 (peak flow 405 $m^3\ s^{-1}$) were sufficient to initiate the reversal while much larger subsequent flow failed to sustain it. This suggests that air temperatures, which became cooler inland in October, November, and during Storm Season, contributed to triggering the gradient reversal, while Delta outflow may have contributed considerably to determining the duration. Monthly mean RTC air temperature with reversal periods indicated with an asterisk (Table 13) shows the onset occurred in months with low mean RTC air temperatures. The delayed reversal in 2010 despite the lowest December air temperature in the study period may be due to a combination of low Delta outflow and high temperature antecedent conditions in the Bay; 2009 was the second warmest year at RTC and CMA but not at FTP and BML.

Temperature-driven baroclinic currents between the cooler Bay and the warmer coastal ocean characterize Storm Season. If the reversed temperature gradient is indicative of Storm Season, then Seasons in the Bay hold as defined in Table 9 with additional rationale for categorizing April 2011 and February 2013 as Storm Season.
Mirroring salinity responses, temperatures at ALC and FTP shared considerable overlap. RTC values extended up to CMA values. BML and FTP temperatures converged in Storm Season, deviated during Upwelling Season, and separated during Relaxation Season. Divergence was most pronounced in 2013, when air temperatures at RTC and

water temperatures throughout the Bay system were high compared to other years. Divergence was also distinct in Relaxation Season of 2012, when an uncharacteristic drop in salinity at BML suggests a local event, such the release of freshwater, that could explain a drop in temperature. FTP remains slightly cooler and more heavily influenced by oceanic waters than the Central Bay stations.

Consistent with salinity cross covariance, high covariance between RTC, FTP, and ALC temperatures during Storm and Upwelling Season indicate mixing (circulation) in Central Bay (Table 14). Salinity values with a lagged cross covariance greater than 0.80 are identified in Table 14 with an asterisk. The nine hour lag between RTC and ALC, the zero lag between RTC and FTP, and the eight to ten hour lag between FTP and ALC are consistent with salinity lag times. Incidences of high temperature covariance that are not supported by salinity covariance are considered less significant than those that are.

Temperatures between CMA and the Central Bay did not have strong covariance during Upwelling and Relaxation Seasons (values less than 0.80 not shown), which is as expected, since water temperatures diverge. That lagged salinity covariance was strong between CMA and Central Bay stations suggests a transport of waters that change temperature but maintain salinity characteristics.

Temperature-Salinity Diagrams

Monthly T-S diagrams reflect interannual, seasonal, and tidal fluctuations in near surface temperature and salinity for a given month. During quiescent periods, horizontal stratification of water between stations was reflected in segmented T-S pairs. Freshening and mixing of near surface waters by rainfall, freshwater inflow, and storm winds were visible in the spreading of T-S pairs across stations. Vertical stratification was not captured by these near surface measurements, therefore, vertical mixing is not addressed herein.

T-S pairs during a dry Storm Season (Figure 13) and in the October and November transition months (Figure 14) were segmented by station. When Delta outflow exceeded the mixing threshold (900 to 1300 $m^3 s^{-1}$), salinity values freshened. Moderate Delta outflow (1935 $m^3 s^{-1}$, January 2010) yielded moderate freshening and mixing of waters between adjacent stations (Figure 12), while greater outflow (6203 $m^3 s^{-1}$, March 2011) produced significant freshening and mixing across the estuary (Figure 15) or across three or more stations (2525 $m^3 s^{-1}$, December 2013, Figure 16). Upwelling Season also exhibited a typical segmented condition (1006 $m^3 s^{-1}$, April 2010) (Figure 17) and a significantly mixed condition (3860, April 2011) (Figure 18).

T-S pairs shifted dramatically towards BML configuration during the 2013 Upwelling Season, which is characterized by strong upwelling winds and reversals. The transition of conditions as Upwelling Season is underway (Figure 19) to its closure (Figure 20) is especially notable at FTP, ALC, and EXP (to be addressed further), which became nearly as saline as BML. RTC and CMA shifted from fairly fresh and cool T-S values (Figure

19) towards warmer, more saline values with a reduced salinity range (Figure 20). In 2010, however, when upwelling winds and reversals were weak compared to 2012, the spread of salinities from early on (Figure 17) to closure (Figure 21) at FTP and RTC had increased, rather than collapsed, and the resemblance to BML T-S pairs at all stations was minimal.

With the passing of freshwater, RTC detached from FTP and spanned the gap between FTP and CMA during Relaxation Season (Figure 22). SMB temperatures rose well above the others, exhibiting elevated warming of shallow South Bay waters. South Bay T-S pairs became increasingly distinct from those of the North Bay, as increased air temperatures heated the shallow South Bay waters and oceanic waters entered a relatively undiluted Bay through the southern side of the mouth. This configuration is most exaggerated in July 2012 (Figure 23), which is a dry year following a wet year. BML, ALC, and FTP were grouped along the salinity axis while RTC and CMA were isolated by fresher waters. The nearly constant salinity at SMB, FTP, ALC, and SMB reflect a post-storm season equilibrium and a partitioning between the South Bay, south Central Bay, and the coastal ocean and the North Bay. T-S pairs at FTP and ALC generally remained combined during Relaxation and continued to shift towards those at BML until September or October, when Bay temperatures began their dramatic decline towards Storm Season.

T-S Diagrams of the fall transition months showed that FTP, RTC, and ALC (where available) consistently comingled. Incorporation of SMB with Central Bay water occurred in October 2011, and November 2011, 2012, and 2013. In October 2012 or October 2013, SMB salinity aligned with Central Bay but temperatures remained slightly warmer. EXP was integrated with FTP, RTC, and ALC water in October and November of 2014 (SMB data not available). Freshening and mixing of flows was not evident in fall transition months.

T-S patterns reflected a well mixed estuary with the onset of Storm Season. The degree and duration of the mixed condition was largely dependent on the magnitude of Delta outflow. Partial mixing during moderate storms incorporated waters from adjacent stations and extended mixing of the estuary during large storm events incorporated waters across stations. A partitioning across the Central Bay separated North and South Bay waters. After partitioning, the North Bay remained a freshwater influenced estuary, and the South Bay became increasingly saline and warm, displaying susceptibility to heating, a lack of freshwater inflow, and proximity to tidal exchange. Partitioning generally occurred during Relaxation Season but showed signs of earlier onset in June of 2012 and 2013. The final Relaxation Season stages of partitioning did not fully incorporate the BML station, which persistently remained significantly cooler and slightly more saline than the other Bay system stations. Central and South Bay waters remained split from North Bay waters during the fall transition while temperatures rapidly declined at all stations towards the Storm Season conditions.

Exploratorium

The timing of CCS Seasons and those seen in the Bay system is generally consistent, with tendency for seasons to overlap in the Bay. Years with strong upwelling winds, relaxation periods, and reversals, such as 2012 and 2013, displayed the longest Upwelling Seasons in the Bay system, while the one year with excessive rainfall, 2011, experienced an extended Storm Season. Bay system seasons were defined to reflect the influences that shape the characteristics of waters in the Bay and the corresponding shifts in the origins of water at the Exploratorium.

EXP data monitoring began at the onset of 2013's Upwelling Season (Figure 24). Salinities at BML were elevated and salinities in the Bay were increasing. EXP is shown following a nearly identical seasonal rise as FTP and the slightly fresher ALC (apparent vertical shifting of instruments and datagaps notwithstanding). EXP appeared tightly banded, whereas ALC, away from the shoreline and more likely to be mixed with north Central Bay waters, had a greater spread of values. The more saline portion of RTC overlapped with Central Bay salinities. During Upwelling and Relaxation Seasons, salinities at FTP, EXP, and ALC increased and converged. Salinity declined during the October and November transition, when EXP became slightly fresher than FTP.

Temperature showed the same tendency: the South Central Bay, the coastal ocean, and the more oceanic region of the north Central Bay were mixed, and the South Bay and North Bay were typically warmer. The introduction of cooler oceanic waters during

Upwelling Season and the absence of freshwater in Relaxation Season are shown in the convergence of Central Bay waters and the relative divergence of North and South Bay waters. SMB temperatures remained distinct from the Central Bay throughout Upwelling and Relaxation season.

This progression is visible in T-S diagrams that contain EXP data. April (Figure 25) May (Figure 26) and June, 2013 (Figure 20) showed an early progression into estuary partitioning and strong overlap of T-S pairs by FTP, EXP, and the slightly fresher ALC. By July, 2013 (Figure 27), FTP, EXP, and ALC were aligned into consistent salinity and temperature values, SMB detached, and RTC and CMA detached. August, 2013 (Figure 28) showed even stronger partitioning as FTP, EXP, and ALC became nearly as saline as BML, leaving the North Bay with distinct T-S pairing. September, 2013 (Figure 29) marked the end of partitioning. October, 2014 (Figure 30) and November, 2014 (Figure 31) displayed freshening and a rapid descent in temperature, during which FTP, EXP, and ALC remained strongly linked. December, 2014 (Figure 32) maintained this link, even as RTC and CMA salinities spread in response to the onset of Storm Season. The tight grouping of these south Central Bay stations persisted in January, 2014 (Figure 33) and February, 2014 (Figure 34).

Discussion

The Bay System

The salinity and temperature fields within the Bay are driven by the seasonal fluctuations of the Delta freshwater system and the Pacific Ocean's CCS. Significant Delta outflow, surges of strong winds and reversals in nearby coastal wind patterns, and freshening of Bay system waters typified Storm Season. Freshwater temperatures dropped below those of coastal ocean waters, and the Bay system temperature gradient decreased in the landward direction. Significant Delta outflow coincided with the mixing of surface waters across the estuary, while moderate Delta outflow mixed surface waters from adjacent stations.

Upwelling Season was evident in strong upwelling-favorable winds, heightened coastal ocean salinity, and minimized coastal ocean temperature. The concurrence of freshwater input and upwelling of deep oceanic waters yielded an overall increase in the salinity of Bay waters during Upwelling Season. As freshwater temperatures rose above those of the coastal ocean, the Bay system's temperature gradient recovered and water temperatures increased in the landward direction. The interaction of cold ocean water with warm freshwater expanded the range of Bay water temperatures. Surface waters in the Bay were moderately mixed during periods of freshwater input, but North and South Bay waters typically began to separate by the end of Upwelling Season.

The absence of storms, the lingering effects of upwelling, and ongoing oceanic input resulted in maximum salinity values in the Bay during Relaxation Season, whereas coastal oceanic salinity gradually declined. Heightened air temperatures were reflected in maximum water temperatures throughout the Bay system. Without the freshening and mixing of surface waters by storms, waters in the North Bay and South Bay separated. By the end of Relaxation Season, the salinity in the South Bay and south Central Bay approached a near constant, coastal oceanic value, while the North Bay salinity range remained broader and fresher.

Interannual variation in the Delta outflow, coastal winds, and air temperature also influenced water characteristics in the Bay. During periods of prolonged and heightened Delta outflow, the reversed temperature gradient extended beyond February and waters throughout the estuary freshened and mixed. During seasons of strong upwelling-favorable winds, the oceanic signal was evident in elevated salinity values across the system, and the Bay partitioning that followed Upwelling Season was enhanced. Enhanced partitioning between North Bay and South Bay waters was also observed during the driest, warmest year in the study period, underscoring the role of freshwater and of heating and evaporation in the South Bay. Interannual air temperatures fluctuations at RTC were reflected in Bay water temperatures, reflecting a system with a common atmospheric link.

Exploratorium Water Origins

Shared FTP, ALC, and EXP salinity and temperature values showed that water from south Central Bay and the estuary mouth were present at the Exploratorium from March 2013 through March 2014. ALC and FTP salinity data for the study period reflected shared values, as did temperature data, which were available at ALC from December 2011 through February 2014. Using ALC as a (somewhat fresher) proxy for EXP, we can infer from more extended data that this southern region of Central Bay, where the Exploratorium resides, included waters from the estuary mouth regardless of season.

Extending this proxy into seasonal fluctuations captured in the study period, Exploratorium waters freshened and cooled during Storm Season and integrated a portion of north Central Bay water regardless of interannual conditions. With a moderate degree of mixing in the estuary, Exploratorium waters included South Bay components and a higher degree of water from north Central Bay. South Bay and North Bay tributaries, precipitation, and direct runoff likely contribute to Exploratorium waters during these periods. Significant mixing brought surface water from across the estuary and as far north as Carquinez Straight to the Exploratorium, adding the likelihood of Delta-derived flow to Exploratorium origins.

As freshwater circulated through the estuary and combined with deep oceanic waters delivered to the mouth during Upwelling Season, salinity at the mouth steadily increased. T-S diagrams show an escalating oceanic signal in Exploratorium waters, which were comprised of water from the mouth and Central Bay, including the more saline portion north Central Bay. By June, heightened salinity and temperature were evident. A range of oceanic water was likely present at the Exploratorium. The surface-flowing California Current, PSAW, deep oceanic water, and flow from the Gulf of the Farallones were potential constituents of Exploratorium waters during Upwelling Season. In years with strong upwelling-favorable winds and reversals (2012 and 2013), salinities increased in this mixture of waters, therefore, a stronger deep oceanic component was likely present at the Exploratorium during these periods.

Storm Season and Upwelling Season overlapped in the Bay system. At ALC, and, by extension, the Exploratorium, periods of moderate and significant mixing integrated South Bay, which would included freshwater from local tributaries, summertime reservoir releases, and seasonally heightened wastewater treatment plant discharge. An increased north Central Bay component, including flow from local North Bay tributaries, was also present during significant mixing.

After the partitioning of the Bay in early Relaxation Season, Exploratorium water was comprised of water from the estuary mouth, south Central Bay, and the South Bay. With freshwater input at a minimum and coastal ocean salinity relatively elevated from Upwelling Season, the oceanic signal was strongest during Relaxation Season. T-S diagrams reflected near constant, near oceanic salinities, while temperatures remained warmer than those in the coastal ocean. Oceanic surface water was the most likely component, but if water detained and mixed by the Gulf of the Farallones circulated into the Bay, then California Undercurrent components may have been present, including PEW.

During the fall transition, the coastal ocean signal weakened, and salinity and temperature dropped. Waters from the mouth, the Central Bay, and the South Bay comprised Exploratorium waters.

Water origins at the Exploratorium based on five years of Bay system data and one year of Exploratorium records reflects a starting point which can be used to analyze past water samples and to estimate existing origins given Bay system conditions as defined by Delta outflow and coastal wind. The water origins analysis can be augmented with at depth data as they become available at the Exploratorium. Data from multiple points in the water column would be useful in identifying specific oceanic components. Analysis of historical floating buoy records at RTC might be useful in identifying oceanic waters in Central Bay, especially given occasional heightened salinity values at RTC. CTD casts in the mouth of the Bay conducted by RTC in 2012 may also reveal the nature of oceanic waters at depth that enter the Bay, as well as an investigation of water quality data collected monthly by USGS.

Because freshwater, oceanic water, and Bay waters are mixed during transport to the Exploratorium, assigning T-S pairs to specific water sources without a chemical tracer is difficult. Examining dissolved oxygen (DO) might prove useful, however, continuous, stationary DO data are limited in the Bay system. Of the stations used in this study, dissolved oxygen measurements were made at RTC since January of 2012 and at CMA since March of 2009, in addition to measurements at the Exploratorium.

A preliminary analysis of density surfaces and spiciness was conducted. Density and spiceness are functions of temperature and salinity and indicative of water type. Negative but near zero spiciness values at the coastal station during Upwelling Season suggest evidence of bland, PSAW. Positive values at BML during Relaxation Season suggest the presence of PEW. A more extensive evaluation at BML and a similar analysis of at depth data at the Exploratorium may create links to specific oceanic water types.

Table 1 Data source

Description	Name	Entity	Website
Estimate of Delta flow to Bay (Dayflow "Out")		California Department of Water Resources	http://www.water.ca.gov/dayflow/
Coyote Creek gage ("USGS 11172175 Coyote C AB HYW 237 A Milpitas CA") flow		United States Geological Survey	http://waterdata.usgs.gov/ca/nwis/sw
Buoy 46026 (8/1/2008-5/12/2011) wind direction and speed	B26	National Oceanic and Atmospheric Administration, National Data Buoy Center	http://www.ndbc.noaa.gov/
Buoy 46013 (5/12/2011-12/31/2013) wind direction, wind speed	B13	National Oceanic and Atmospheric Administration, National Data Buoy Center	http://www.ndbc.noaa.gov/
Romberg Tiburon Center Weather Station rainfall	RTC rainfall	San Francisco State University, Romberg Tiburon Center	http://sfbeams.sfsu.edu/download.htm
Romberg Tiburon Center Weather Station Air Temperature	RTC air temp-erature	San Francisco State University, Romberg Tiburon Center	http://sfbeams.sfsu.edu/download.htm
California Maritime Academy CTD	CMA	San Francisco State University, Romberg Tiburon Center	http://sfbeams.sfsu.edu/download.htm
Romberg Tiburon Center CTD	RTC	San Francisco State University, Romberg Tiburon Center	http://sfbeams.sfsu.edu/download.htm
Alcatraz Island CTD USGS 374938122251801	ALC	United States Geological Survey	http://nwis.waterdata.usgs.gov/nwis
Fort Point CTD	FTP	University of California, Davis, Bodega Marine Laboratory	http://www.bml.ucdavis.edu/boon
Exploratorium CTD	EXP	Exploratorium in partnership with Romberg Tiburon Center	http://oceanview.pfeg.noaa.gov/erddap
San Mateo Bridge CTD USGS 11162765	SMB	United States Geological Survey	http://nwis.waterdata.usgs.gov/nwis
Bodega Marine Laboratory CTD	BML	University of California, Davis, Bodega Marine Laboratory	http://www.bml.ucdavis.edu/boon

Table 2 Water Year classification

	Water Year Classification	
WY	Sacramento Valley	San Joaquin Valley
2008	Critical	Critical
2009	Dry	Dry
2010	Below normal	Above normal
2011	Wet	Wet
2012	Below normal	Dry
2013	Dry	Critical

Table 3 Monthly Peak Delta Outflow ($m^3 s^{-1}$)

WY	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	mean
2009	364	494	411	397	1299	1526	435	898	319	221	194	197	563
2010	620	216	381	1935	1247	932	1006	847	720	232	213	250	717
2011	433	464	2545	2258	1523	6203	3860	1537	1592	1202	379	414	1868
2012	647	405	194	913	375	1454	1260	753	311	302	275	198	590
2013	271	896	2525	1285	475	504	612	340	270	206	176	194	646
mean	467	495	1211	1358	984	2124	1435	875	642	432	247	251	934

Table 4 Monthly Mean Air Temperature (°C)

WY	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	mean
2009	16.5 +/- 3.6	14.2 +/- 2.9	9.2 +/- 2.3	11.1 +/- 3.4	10.8 +/- 2.4	11.8 +/- 3.0	12.9 +/- 4.3	14.0 +/- 3.2	15.6 +/- 2.9	15.3 +/- 3.3	17.2 +/- 3.8	17.4 +/- 3.3	13.8
2010	15.3 +/- 2.8	13.1 +/- 2.7	9.0 +/- 2.4	10.0 +/- 1.9	11.4 +/- 1.8	12.0 +/- 3.1	12.1 +/- 2.9	13.4 +/- 2.8	15.6 +/- 3.5	14.4 +/- 2.4	14.8 +/- 3.8	17.2 +/- 4.0	13.2
2011	15.3 +/- 3.4	12.8 +/- 4.2	10.8 +/- 2.1	9.4 +/- 2.9	10.1 +/- 3.7	11.3 +/- 2.5	12.6 +/- 3.0	13.3 +/- 3.1	14.5 +/- 3.2	15.6 +/- 2.9	14.8 +/- 2.3	16.6 +/- 3.4	13.1
2012	16.5 +/- 3.1	11.8 +/- 2.5	9.9 +/- 2.9	10.5 +/- 2.6	11.1 +/- 2.4	10.9 +/- 2.4	12.8 +/- 3.3	14.1 +/- 3.3	--	--	16.6 +/- 3.6	14.5 +/- 2.8	12.9
2013	15.8 +/- 3.4	13.8 +/- 2.9	10.5 +/- 2.7	9.3 +/- 2.5	10.3 +/- 2.7	11.8 +/- 2.8	14.1 +/- 3.6	15.3 +/- 3.4	15.9 +/- 3.3	15.0 +/- 2.8	16.4 +/- 3.0	17.9 +/- 2.9	13.8
2014	14.8 +/- 3.8	13.3 +/- 2.6	9.8 +/- 3.0	11.5 +/- 2.3	--	--	--	--	--	--	--	--	12.4
mean	15.7	13.1	9.9	10.3	10.7	11.5	12.9	14.0	15.4	15.1	16.0	16.7	13.4

Table 5 Monthly Mean Equatorward Wind Speed ($m^3\ s^{-1}$)

WY	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	mean
2009	-2.5 +/- 1.7	-2.5 +/- 1.8	-3.3 +/- 2.1	-2.1 +/- 1.7	-3.2 +/- 2.2	-3.7 +/- 1.9	-4.3 +/- 2.2	-3.3 +/- 1.9	-3.6 +/- 1.8	-3.3 +/- 1.4	-3.0 +/- 1.4	-2.8 +/- 1.6	-3.1
2010	-3.3 +/- 2.0	-3.1 +/- 1.9	-2.4 +/- 1.6	--	-2.8 +/- 1.7	-3.9 +/- 2.2	-4.4 +/- 2.4	-4.8 +/- 2.0	-4.8 +/- 2.1	-3.2 +/- 2.1	-3.7 +/- 1.8	-3.4 +/- 2.0	-3.6
2011	-3.1 +/- 2.0	-3.4 +/- 2.1	-3.4 +/- 2.9	-3.2 +/- 2.4	--	--	--	-6.5 +/- 3.3	-6.8 +/- 3.3	-3.9 +/- 3.2	-4.7 +/- 2.9	-4.2 +/- 2.5	-4.3
2012	-3.7 +/- 2.2	-4.7 +/- 2.4	-2.9 +/- 1.8	-4.2 +/- 2.9	-6.0 +/- 2.7	-4.3 +/- 3.0	-5.9 +/- 2.9	-7.3 +/- 2.7	-6.6 +/- 3.4	-5.8 +/- 3.0	-4.9 +/- 2.7	-4.0 +/- 2.8	-5.0
2013	-4.1 +/- 2.7	-3.1 +/- 2.1	-4.4 +/- 2.4	-4.9 +/- 2.9	-5.4 +/- 2.8	-5.7 +/- 2.7	-6.6 +/- 3.5	-6.9 +/- 3.2	-7.1 +/- 3.4	-3.5 +/- 2.8	-4.5 +/- 3.1	-4.9 +/- 2.7	-5.1
2014	-4.2 +/- 2.9	-4.5 +/- 3.0	-4.3 +/- 2.9	--	--	--	--						-4.3
mean	-3.5	-3.6	-3.4	-3.6	-4.3	-4.4	-5.3	-5.8	-5.8	-3.9	-4.2	-3.9	-4.2

Table 6 Monthly Mean Poleward Wind Speed (m^3 s^{-1})

WY	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	mean
2009	1.5 +/- 1.5	2.6 +/- 2.2	3.5 +/- 3.1	3.7 +/- 2.6	3.42 +/- 2.8	3.0 +/- 2.9	1.6 +/- 1.6	0.9 +/- 0.8	0.6 +/- 0.6	0.4 +/- 0.4	0.7 +/- 0.6	0.6 +/- 0.6	1.9
2010	1.2 +/- 1.1	2.1 +/- 1.6	5.9 +/- 4.2	--	2.4 +/- 1.8	1.9 +/- 1.9	1.5 +/- 1.8	1.4 +/- 1.1	0.7 +/- 0.6	0.5 +/- 0.4	0.8 +/- 0.6	0.6 +/- 0.5	1.7
2011	1.9 +/- 1.7	3.0 +/- 2.6	3.7 +/- 2.4	4.4 +/- 2.5	--	--	--	3.0 +/- 2.6	3.5 +/- 3.0	1.0 +/- 0.7	0.7 +/- 0.5	1.7 +/- 1.1	2.5
2012	1.6 +/- 1.1	4.7 +/- 2.2	2.4 +/- 1.7	3.0 +/- 2.3	3.9 +/- 2.6	2.7 +/- 2.1	2.2 +/- 1.4	1.6 +/- 1.0	1.2 +/- 1.1	1.6 +/- 1.4	0.8 +/- 0.6	1.0 +/- 0.8	2.2
2013	1.7 +/- 1.4	3.6 +/- 2.1	4.0 +/- 2.9	4.4 +/- 2.4	2.1 +/- 1.7	2.6 +/- 1.9	1.4 +/- 1.3	2.6 +/- 2.3	1.9 +/- 1.4	0.9 +/- 0.8	1.5 +/- 1.1	1.7 +/- 1.2	2.4
2014	1.7 +/- 1.4	2.4 +/- 1.8	3.0 +/- 2.3	--	--	--	--						2.4
mean	1.6	3.1	3.8	3.9	2.9	2.6	1.7	1.9	1.6	0.9	0.9	1.1	2.2

Table 7 BML Monthly Mean Salinity

WY	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	mean
2009	33.6 +/- 0.1	33.3 +/- 0.1	32.9 +/- 2.5	32.8 +/- 1.1	32.8 +/- 0.4	32.6 +/- 2.6	33.3 +/- 2.3	33.5 +/- 0.5	33.6 +/- 0.1	33.6 +/- 0.2	33.4 +/- 0.2	33.3 +/- 0.2	33.2
2010	33.1 +/- 0.5	33.2 +/- 0.3	33.1 +/- 0.1	32.4 +/- 1.6	32.1 +/- 0.9	32.9 +/- 0.6	33.0 +/- 0.4	33.7 +/- 0.1	33.5 +/- 0.1	33.4 +/- 0.2	33.6 +/- 0.1	33.5 +/- 0.1	33.1
2011	33.4 +/- 0.2	33.3 +/- 0.1	32.8 +/- 0.4	32.4 +/- 0.6	32.8 +/- 0.5	31.8 +/- 0.7	33.6 +/- 0.3	33.7 +/- 0.1	33.3 +/- 0.4	33.3 +/- 0.3	33.1 +/- 0.3	33.0 +/- 0.3	33.0
2012	32.5 +/- 0.2	33.1 +/- 0.2	32.9 +/- 0.1	32.9 +/- 0.3	33.2 +/- 0.3	33.2 +/- 0.8	33.1 +/- 0.3	33.6 +/- 0.2	33.8 +/- 0.1	33.4 +/- 0.3	32.9 +/- 0.2	33.2 +/- 0.3	33.1
2013	33.1 +/- 0.1	32.8 +/- 0.3	32.5 +/- 0.2	32.7 +/- 0.4	33.6 +/- 0.1	33.7 +/- 0.1	33.7 +/- 0.2	33.8 +/- 0.1	33.7 +/- 0.1	33.5 +/- 0.1	33.4 +/- 0.1	33.3 +/- 0.1	33.3
2014	33.3 +/- 0.1	33.2 +/- 0.1	32.9 +/- 0.1	32.8 +/- 0.1	32.6 +/- 0.2								33.0
mean	33.2	33.2	32.9	32.7	32.8	32.8	33.3	33.6	33.6	33.4	33.3	33.3	33.2

Table 8 FTP Monthly Mean Salinity

WY	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	mean
2009	32. 2 +/- 0.2	31.4 +/- 0.5	30.8 +/- 0.4	30.1 +/- 0.5	30.5 +/- 1.1	28.6 +/- 1.5	30.7 +/- 0.5	30.9 +/- 0.5		31.9 +/- 0.4	32.1 +/- 0.3	32.1 +/- 0.2	31.0
2010	31.8 +/- 0.6	31.2 +/- 0.5	31.3 +/- 0.5	29.8 +/- 1.8	27.7 +/- 1.6	28.2 +/- 1.8	29.4 +/- 1.2	29.8 +/- 1.6	29.2 +/- 1.4	31.4 +/- 0.7	28.7 +/- 1.1	31.9 +/- 0.3	30.0
2011	31.9 +/- 0.3	31.4 +/- 0.3	29.5 +/- 2.4	26.5 +/- 2.9	28.7 +/- 1.4	24.4 +/- 5.1	23.9 +/- 4.4	28.1 +/- 2.3	28.7 +/- 2.1	30.0 +/- 1.4	31.0 +/- 0.6	31.0 +/- 0.7	28.8
2012	30.6 +/- 0.7	30.9 +/- 0.5	30.6 +/- 0.4	30.8 +/- 0.6	30.2 +/- 0.7	30.3 +/- 1.2	29.2 +/- 1.5	30.4 +/- 1.1	31.6 +/- 0.6	32.0 +/- 0.4	32.0 +/- 0.3	32.1 +/- 0.2	30.9
2013	31.9 +/- 0.3	31.5 +/- 0.3	29.1 +/- 1.8	28.1 +/- 2.3	29.9 +/- 0.9	30.7 +/- 0.7	31.0 +/- 0.7	31.7 +/- 0.5	31.7 +/- 0.5	32.0 +/- 0.4	31.3 +/- 0.2	31.7 +/- 0.6	30.9
2014	32.2 +/- 0.3	31.6 +/- 0.3	31.6 +/- 0.3	31.6 +/- 0.3	31.1 +/- 0.6								31.6
mean	31.8	31.3	30.5	29.5	29.7	28.4	28.8	30.2	30.3	31.5	31.0	31.8	30.3

Table 9 Bay System Seasons

WY	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.
2009	T	T	S	S	S	S U	U	U	U	R	R	R
2010	T	T	S	S	S	S U	S U	U	U	R	R	R
2011	T	T	S	S	S	S	S U	U	U	R	R	R
2012	T	T	S	S	S U	S U	S U	U	U	R	R	R
2013	T	T	S	S	S U	U	U	U	U	R	R	R
2014	T	T	S									

Note: T=Transition, S=Storm, U=Upwelling, R=Relaxation

Table 10 ALC Monthly Mean Salinity

WY	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	mean
2009	31.4 +/- 0.3	30.2 +/- 0.8	30.5 +/- 0.7	30.4 +/- 0.6	29.2 +/- 1.8	26.7 +/- 2.2	29.5 +/- 1.2	29.6 +/- 1.2	30.2 +/- 0.9	30.6 +/- 0.6	30.9 +/- 0.4	31.2 +/- 0.3	30.0
2010	30.7 +/- 0.7	30.4 +/- 0.6	29.9 +/- 0.7	28.5 +/- 2.2	25.0 +/- 2.0	26.3 +/- 1.8	26.7 +/- 1.5	27.5 +/- 2.1	28.4 +/- 1.6	29.6 +/- 1.0	30.3 +/- 0.6	0.5	28.7
2011	30.4 +/- 0.5	--	25.7 +/- 3.5	24.4 +/- 3.1	26.5 +/- 1.9	21.2 +/- 5.2	20.3 +/- 4.2	25.3 +/- 2.6	26.6 +/- 2.0	28.5 +/- 1.6	29.8 +/- 0.8	30.0 +/- 1.0	26.2
2012	30.1 +/- 1.0	30.5 +/- 0.7	30.2 +/- 0.8	29.1 +/- 1.3	29.2 +/- 1.3	29.1 +/- 1.6	27.5 +/- 1.8	29.3 +/- 1.5	31.0 +/- 0.8	31.6 +/- 0.5	31.7 +/- 0.5	31.8 +/- 0.4	30.1
2013	31.6 +/- 0.5	30.6 +/- 0.6	25.8 +/- 2.5	25.6 +/- 2.6	28.2 +/- 1.2	29.0 +/- 1.0	29.3 +/- 1.0	30.3 +/- 0.9	30.9 +/- 0.6	31.7 +/- 0.6	32.1 +/- 0.5	32.0 +/- 0.5	29.8
2014	32.1 +/- 0.5	31.7 +/- 0.5	30.9 +/- 0.6	30.4 +/- 0.4	29.7 +/- 0.8								31.0
mean	31.0	30.7	28.8	28.1	27.9	26.5	26.7	28.4	29.4	30.4	31.0	31.1	29.0

Table 11 Lagged Cross Covariance of Salinity

Stations	All Seasons		Storm Season		Upwelling Season	
	xcov	lag	xcov	lag	xcov	lag
		hrs		hrs		hrs
RTC FTP	0.83	0	0.82	0	0.86	0
RTC ALC	0.87	9	0.87	9	0.91	9
FTP ALC	0.90	8	0.87	8	0.90	8
FTP EXP	0.80	1				
ALC EXP	0.80	-9				
ALC SMB	0.82	-149			0.80	0
CMA RTC	0.80	2			0.83	3
CMA ALC	0.82	-13	0.80	-14	0.81	11

Table 12 Monthly Peak Delta Outflow ($m^3 s^{-1}$)

WY	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
2009	364	494	411*	397*	1299*	1526*	435
2010	620	216	381	1935*	1247*	932*	1006
2011	433	464	2545*	2258*	1523*	6203*	3860*
2012	647	405	194*	913*	375*	1454	1260
2013	271	896	2525*	1285*	475*	504	612

Table 13 Monthly Mean Air Temperature (°C)

WY	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	mean
2009	16.5	14.2	9.2*	11.1*	10.8*	11.8*	12.9	14.0	15.6	15.3	17.2	17.4	13.8
2010	15.3	13.1	9.0	10.0*	11.4*	12.0*	12.1	13.4	15.6	14.4	14.8	17.2	13.2
2011	15.3	12.8	10.8*	9.4*	10.1*	11.3*	12.6*	13.3	14.5	15.6	14.8	16.6	13.1
2012	16.5	11.8	9.9*	10.5*	11.1*	10.9	12.8	14.1			16.6	14.5	12.9
2013	15.8	13.8	10.5*	9.3*	10.3*	11.8	14.1	15.3	15.9	15.0	16.4	17.9	13.8
2014	14.8	13.3	9.8*	11.5*									

Table 14 Lagged Cross Covariance of Temperature

Stations	All Seasons		Storm Season		Upwelling Season		Relaxation Season	
	xcov	Lag (hrs)	xcov	Lag (hrs)	xcov	Lag (hrs)	xcov	Lag (hrs)
RTC FTP	0.94*	0	0.92*	0	0.81*	0		
RTC ALC	0.97*	9	0.91*	9	0.89*	9	0.86	9
RTC SMB	0.94	8	0.89	6				
RTC EXP	0.97	0	0.93	0	0.83	1		
FTP ALC	0.97*	9	0.95*	8	0.86*	9	0.82	10
FTP SMB	0.90	108						
FTP EXP	0.98	1	0.98	0	0.91	1	0.88	1
ALC SMB	0.93*	-1	0.82	0				
ALC EXP	0.98	-9			0.88	-8	0.83	-9
SMB EXP	0.89	-8						
CMA RTC	0.93*	3	0.88	2				
CMA FTP	0.88	-21						
CMA ALC	0.90*	-12						
CMA SMB	0.99	0	0.95	2	0.92	0		
CMA EXP	0.93	4	0.97	0				

References

California Department of Water Resources (2013), *Chronological Reconstructed Sacramento and San Joaquin Valley Water Year Hydrologic Classification Indices*. [online] Available from: http://cdec.water.ca.gov/cgi-progs/iodir/wsihist (Accessed 21 April 2014)

Cloern, J. E., and A. D. Jassby (2012), Drivers of change in estuarine-coastal ecosystems: Discoveries from four decades of study in San Francisco Bay, *Reviews of Geophysics*, *50*(4), doi:10.1029/2012RG000397.

Conomos, T. J., A. E. Leviton, and M. Berson (Eds.) (1979), Properties and Circulation of San Francisco Bay Waters, in *San Francisco Bay: The Ecosystem, Further Investigations into the Natural History of San Francisco Bay Delta with Reference to the Influence of Man*, pp. 47–84, American Association for the Advancement of Science Pacific Division.

Conomos, T. J., R. E. Smith, and J. W. Gartner (1985), Environmental setting of San Francisco Bay, *Hydrobiologia*, *129*(1), 1–12.

Gough, M. K., N. Garfield, and E. McPhee-Shaw (2010), An analysis of HF radar measured surface currents to determine tidal, wind-forced, and seasonal circulation in the Gulf of the Farallones, California, United States, *Journal of*

Geophysical Research, 115(C4), doi:10.1029/2009JC005644. [online] Available from: http://doi.wiley.com/10.1029/2009JC005644 (Accessed 29 March 2014)

Koller, M. (2014), Dayflow, An Estimate of Daily Average Delta Outflow, [online] Available from: http://www.water.ca.gov/dayflow/ (Accessed 17 March 2014)

Largier, J. L. (1996), Hydrodynamic Exchange Between San Francisco Bay and the Ocean: The Role of Ocean Circulation and Stratification, in *San Francisco Bay: The Ecosystem, Further Investigations into the Natural History of San Francisco Bay Delta with Reference to the Influence of Man*, pp. 69–104, American Association for the Advancement of Science Pacific Division.

Lucas, L. V., Cloern, J. E., Koseff, J. R., Monismith, S. G., and Thompson, J. K. (1998), Does the Sverdrup critical Depth model explain bloom dynamics in estuaries?, *Journal of Marine Research*, pp. 375-415.

Martin, M. A., J. P. Fram, and M. T. Stacey (2007), Seasonal chlorophyll a fluxes between the coastal Pacific Ocean and San Francisco Bay, *Marine Ecology Progress Series*, *337*, 51–61.

Peterson, D. H., D. R. Cayan, M. . Dettinger, M. A. Noble, L. G. Griddle, L. E. Schemel, R. E. Smith, R. J. Uncles, and R. A. Walters (1996), San Francisco Bay Salinity: Observations, Numerical Simulation, and Statistical Models, in *San Francisco Bay: The Ecosystem, Further Investigations into the Natural History of San*

Francisco Bay Delta with Reference to the Influence of Man, pp. 9–34, American Association for the Advancement of Science Pacific Division.

Schemel, L. E. (1998), *Salinity and temperature in South San Francisco Bay, California, at Dumbarton Bridge: measurements from the 1995-1998 Water Years and comparisons with results from the 1990-1993 Water Years*, United States Geological Survey, California Department of Water Resources.

Shellenbarger, G. G., and D. H. Schoellhamer (2011), Continuous Salinity and Temperature Data from San Francisco Estuary, 1982–2002: Trends and the Salinity–Freshwater Inflow Relationship, *Journal of Coastal Research*, *277*, 1191–1201, doi:10.2112/JCOASTRES-D-10-00113.1.

Steger, J. M., C. A. Collins, F. B. Schwing, M. Noble, N. Garfield, and M. T. Steiner (1998), An Empirical Model of the Tidal Currents in the Gulf of the Farallones, , *45*(8-9), 1471–1505.

Steger, J. M., F. B. Schwing, C. A. Collins, L. K. Rosenfeld, N. Garfield, and E. Gezgin (2000), The circulation and water masses in the Gulf of the Farallones, *Deep Sea Research Part II: Topical Studies in Oceanography*, *47*(5), 907–946.

United States Geological Survey (2014), USGS Surface-Water Historical Instantaneous Data for California, [online] Available from: http://waterdata.usgs.gov/ca/nwis/uv? (Accessed 17 March 2014)

Walters, R. A., R. T. Cheng, and T. J. Conomos (1985), Time scales of circulation and mixing processes of San Francisco Bay waters, *Hydrobiologia*, 13–36.

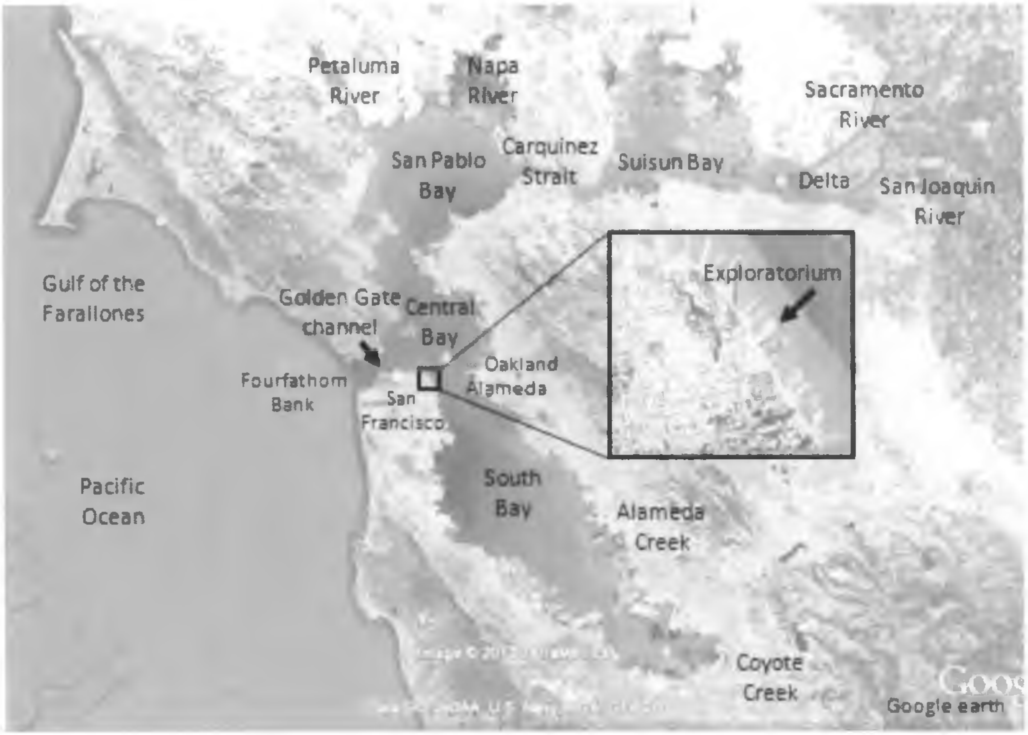


Figure 1 Location map of San Franciso Bay (Bay).

Its four embayments, Suisun Bay, San Pablo Bay, Central Bay, and South Bay, receive freshwater from the Sacramento-San Joaquin River Delta. Other tributaries, such as Coyote Creek in the South Bay, supply freshwater to the Bay. Golden Gate channel, the estuary mouth, connects Bay waters to the coastal Pacific Ocean.

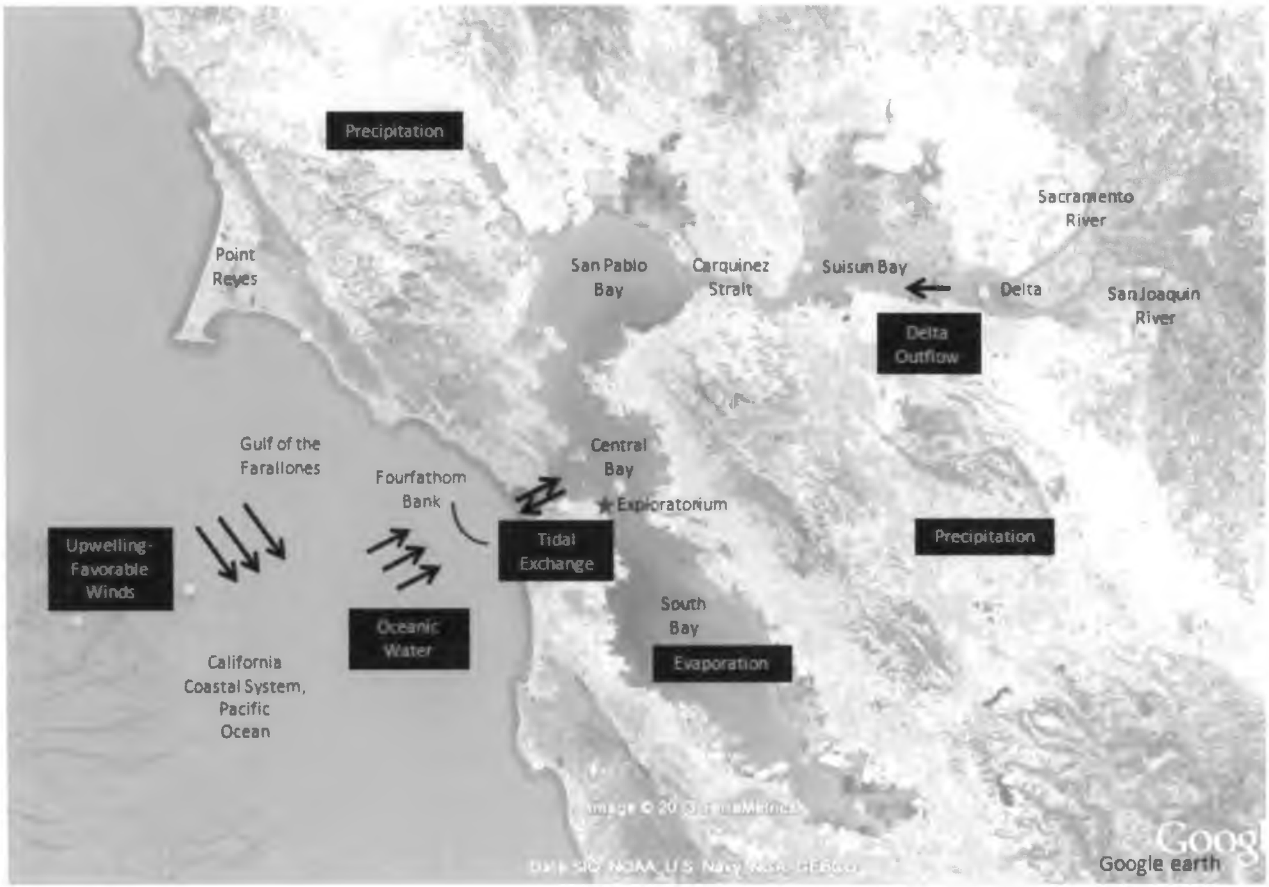


Figure 2 Conceptual model of large scale influences.

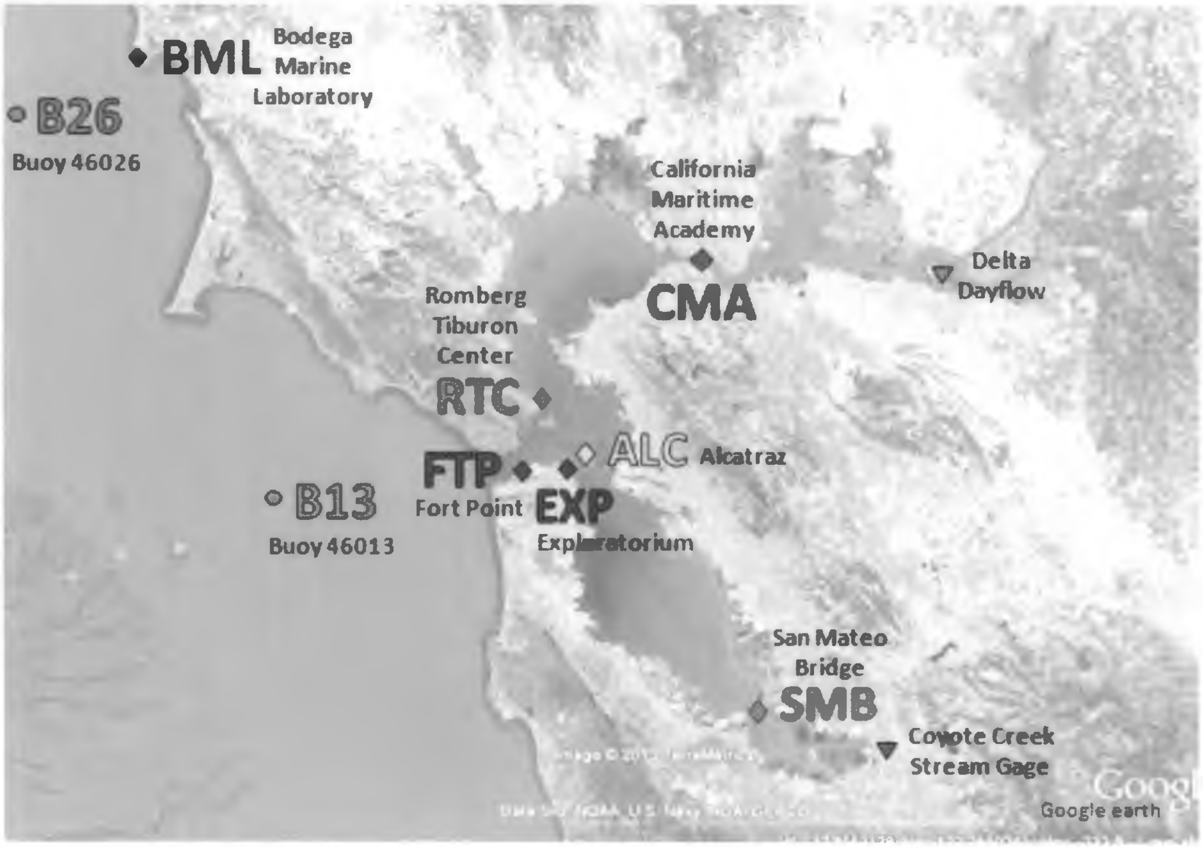


Figure 3 Dataset location map.

CTD instruments, indicated with diamonds, show color-coding used throughout study. Locations of the estimated Delta, Dayflow value at Chipps Island and of the Coyote Creek stream gage are indicated with triangles. Approximate locations of buoys 46026 (B26) and 46013 (B13) are shown with circles.

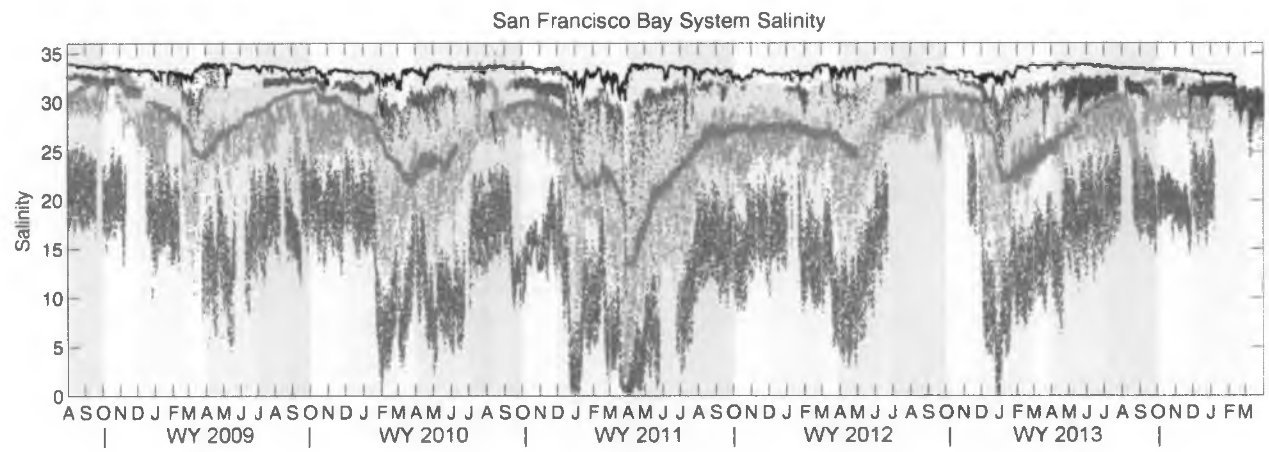


Figure 4 Bay system salinity.

Bay System salinity with Storm Season shown in the lightest grey, Upwelling Season in medium grey, and Relaxation Season in dark grey (color coding consistent where it appears in tables and figures).

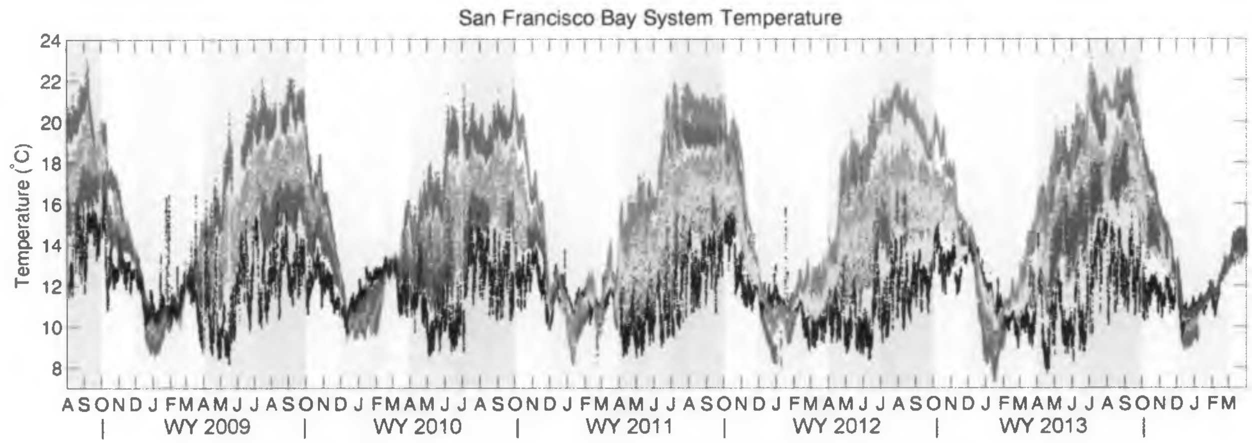


Figure 5 Bay system water temperature.

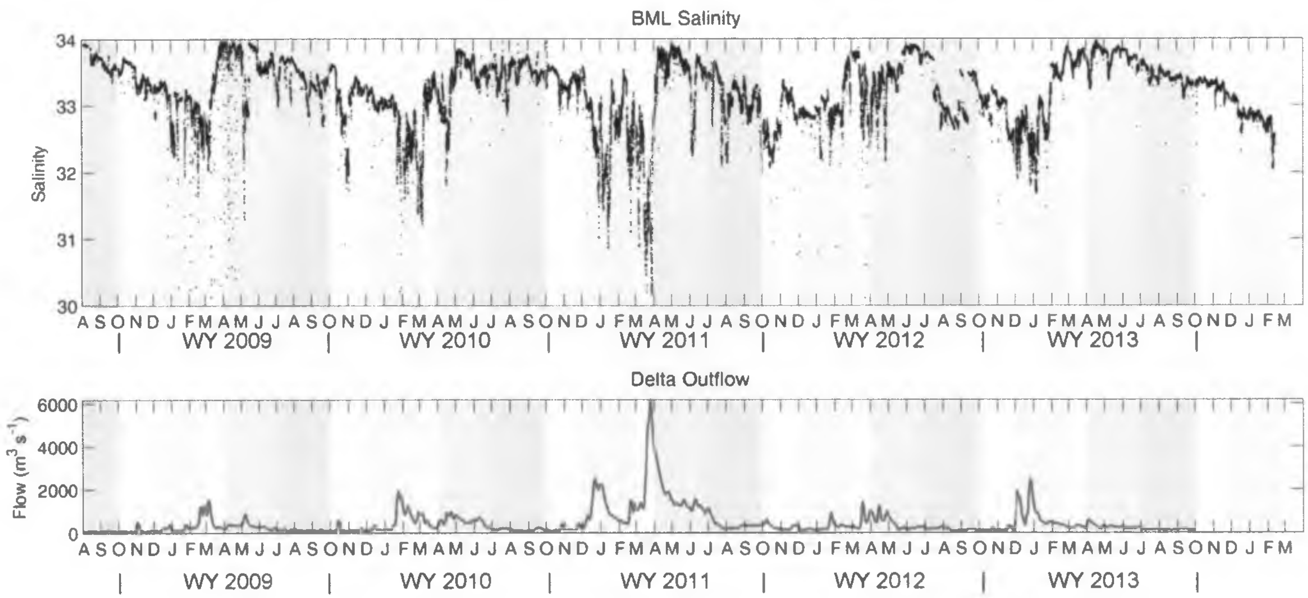


Figure 6 Delta Outflow and BML response.

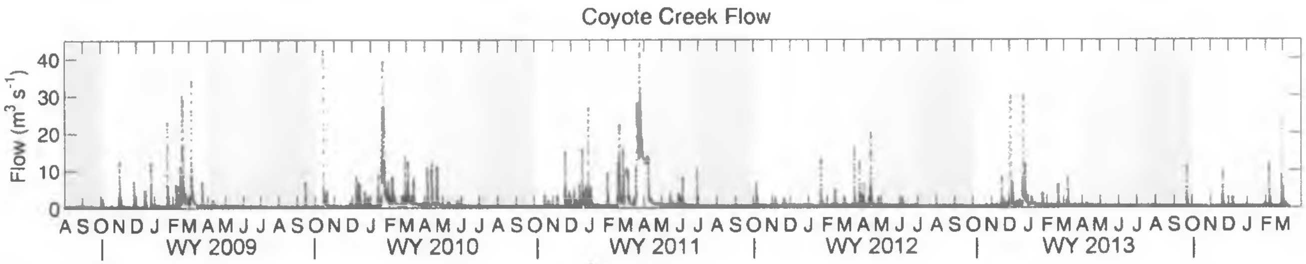


Figure 7 Coyote Creek outflow.

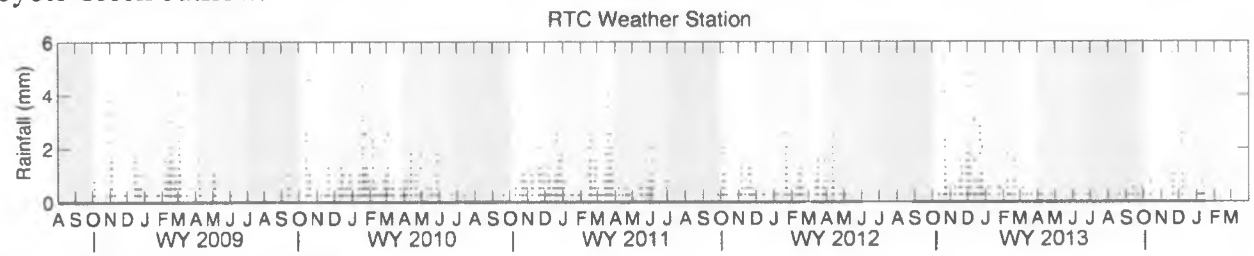


Figure 8 RTC Weather Station rainfall.

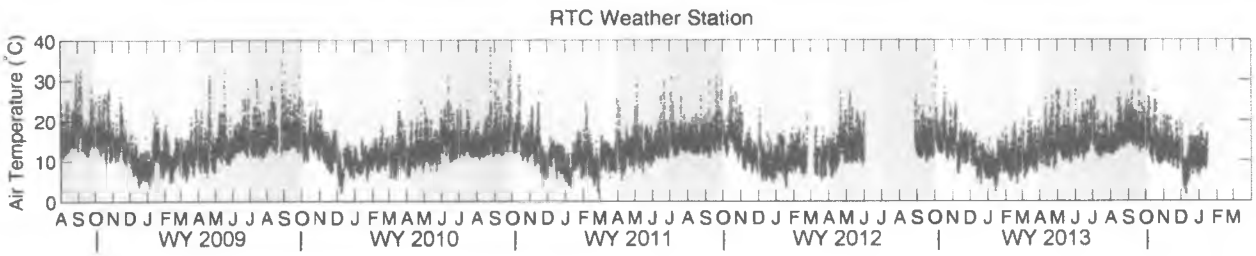


Figure 9 RTC Weather Station air temperature.

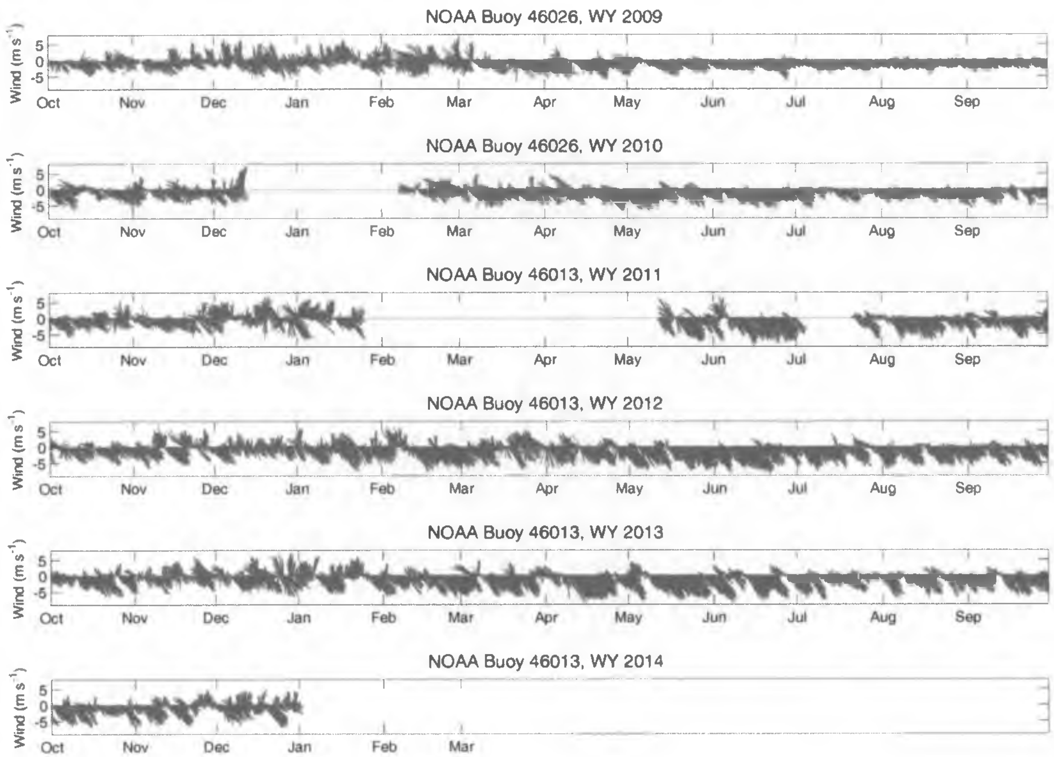


Figure 10 Wind speed and direction from coastal buoys near the Bay mouth.

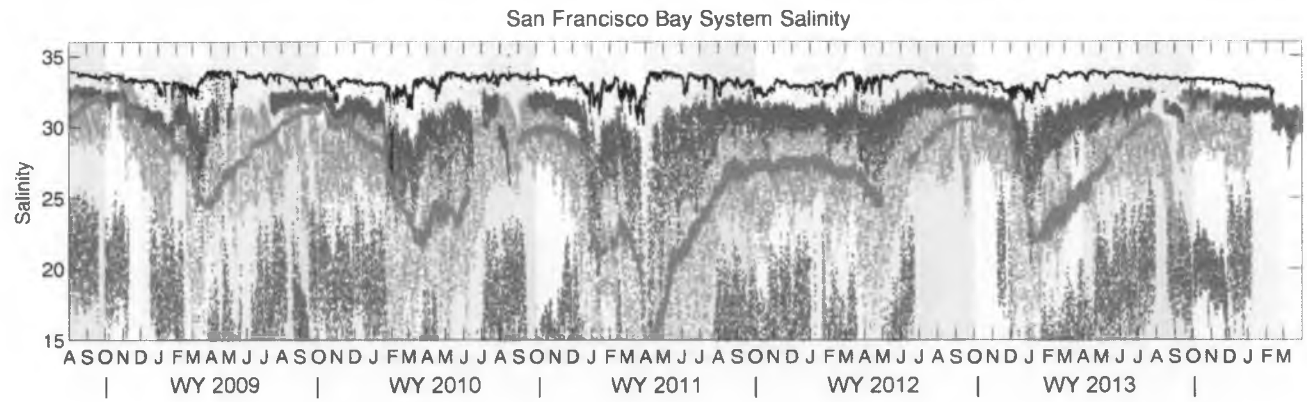


Figure 11 Salinity with ALC and EXP removed for better visibility of FTP and RTC.

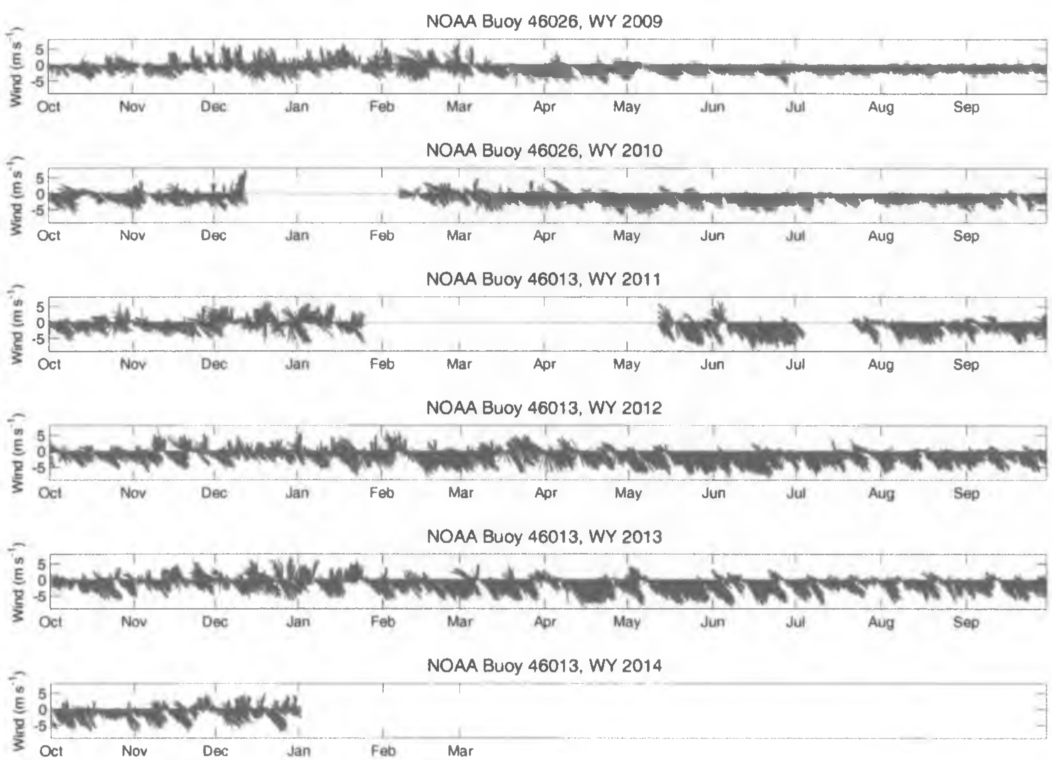


Figure 10 Wind speed and direction from coastal buoys near the Bay mouth.

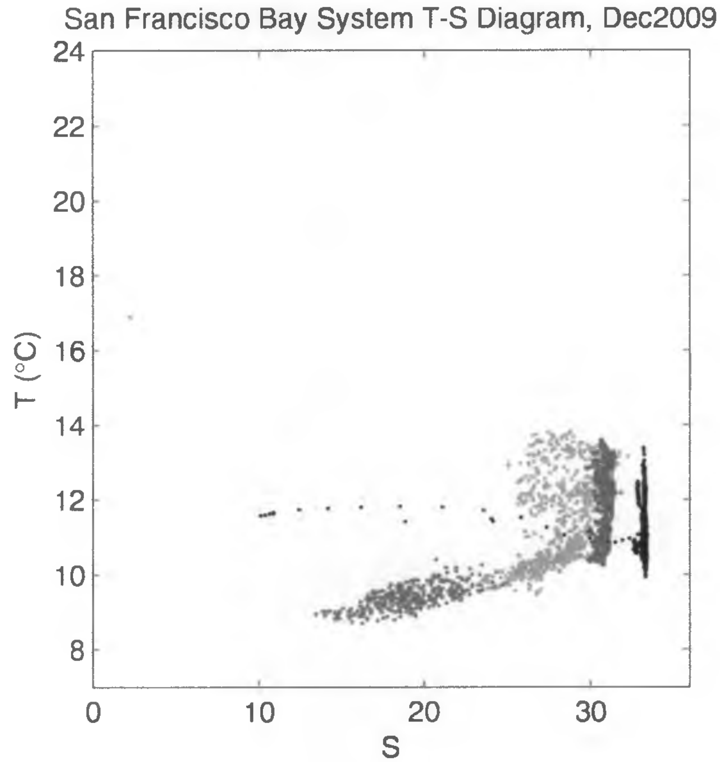


Figure 13 Temperature gradient reversal and segmented T-S pairs during a dry Storm Season.

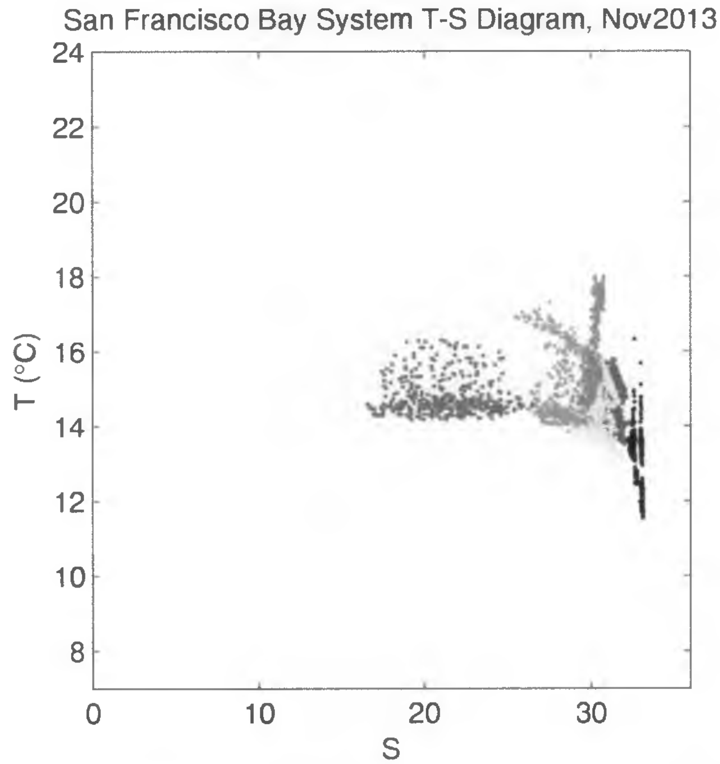


Figure 14 Segemented T-S pairs during November 2013 transition.

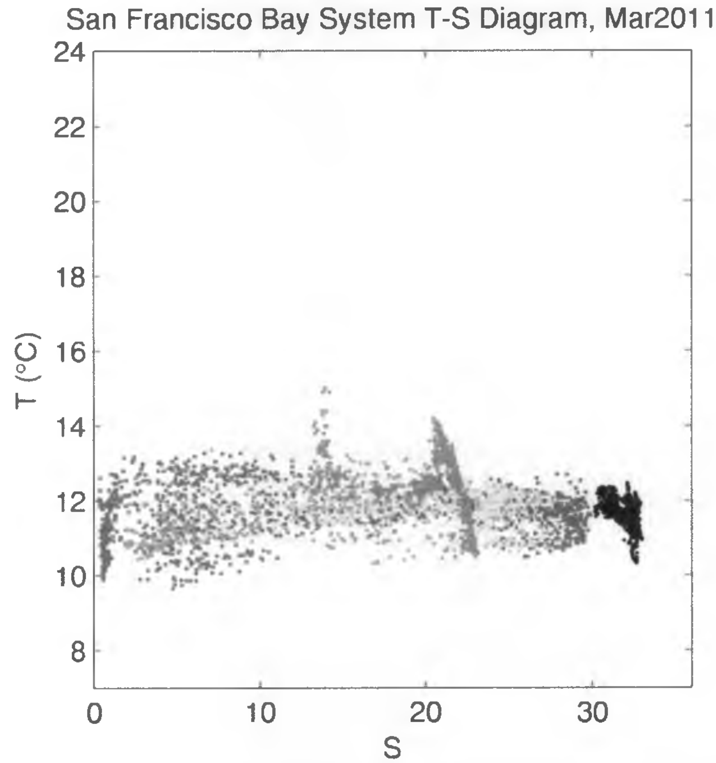


Figure 15 Significant freshening and mixing of Bay waters during Storm Season.

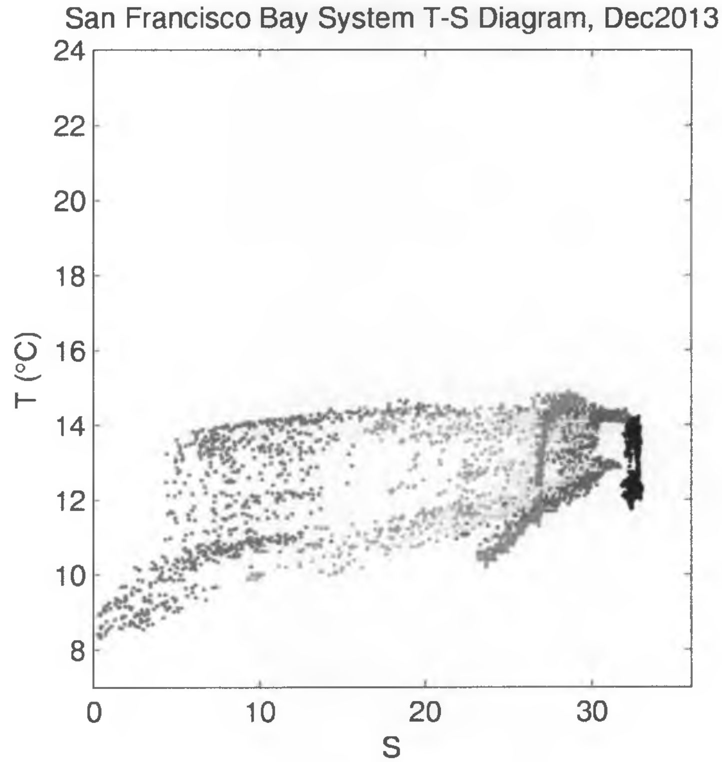


Figure 16 Mixing across three or more stations during Storm Season.

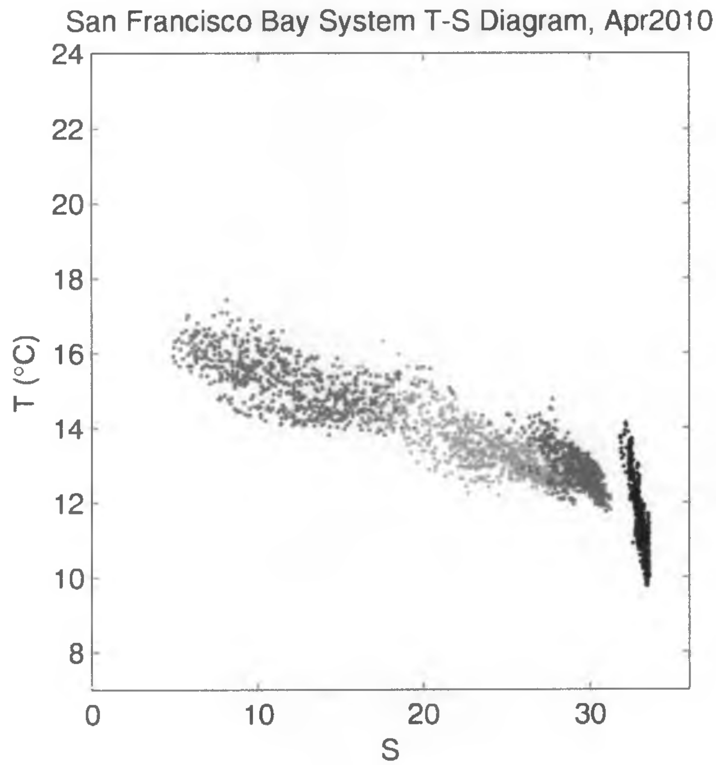


Figure 17 Upwelling Season segmented condition, and onset of Upwelling Season in year with weak upwelling winds and reversals.

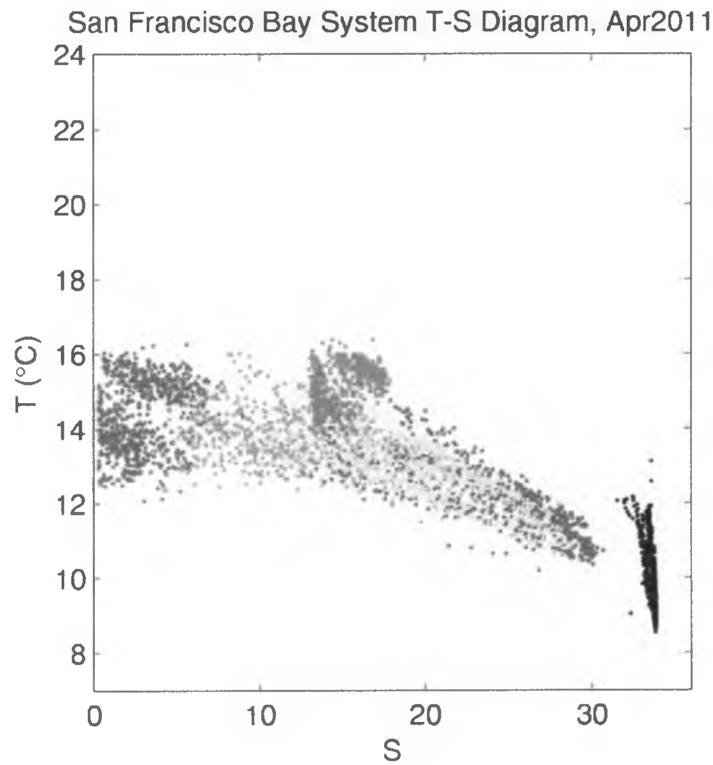


Figure 18 Significant freshening and mixing of Bay waters during Upwelling Season.

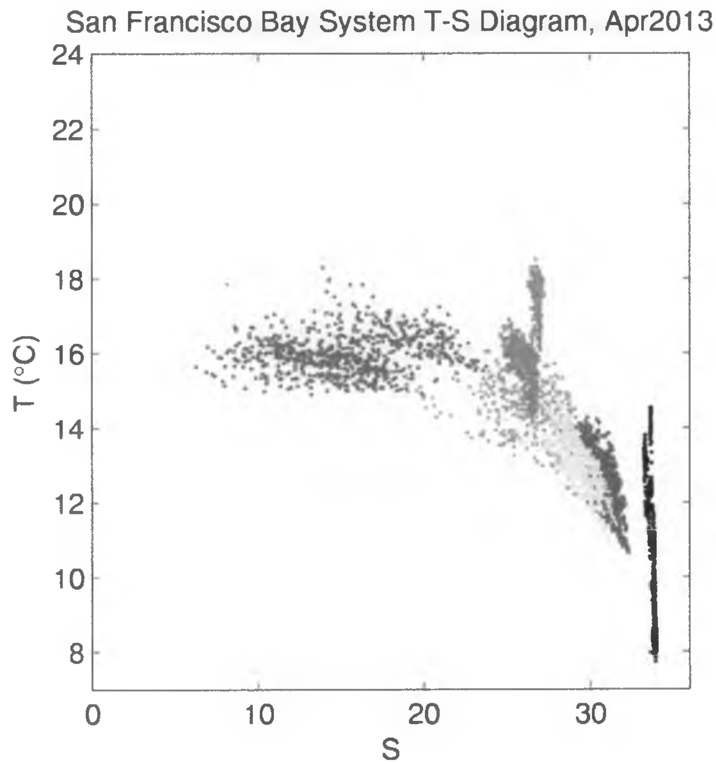


Figure 19 Upwelling Season in a year of strong upwelling-favorable winds and reversals.

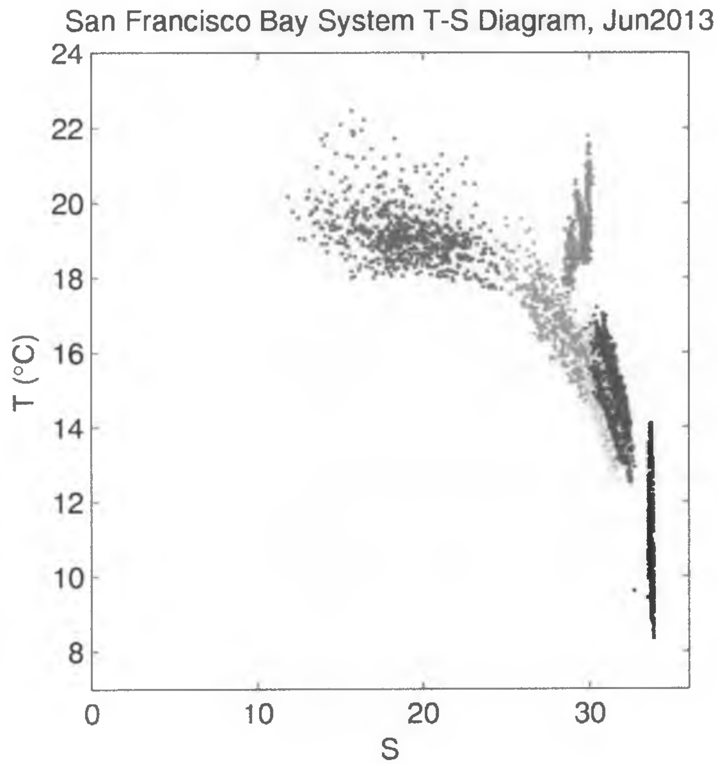


Figure 20 Closure of Upwelling Season in a year of strong upwelling-favorable winds and reversals.

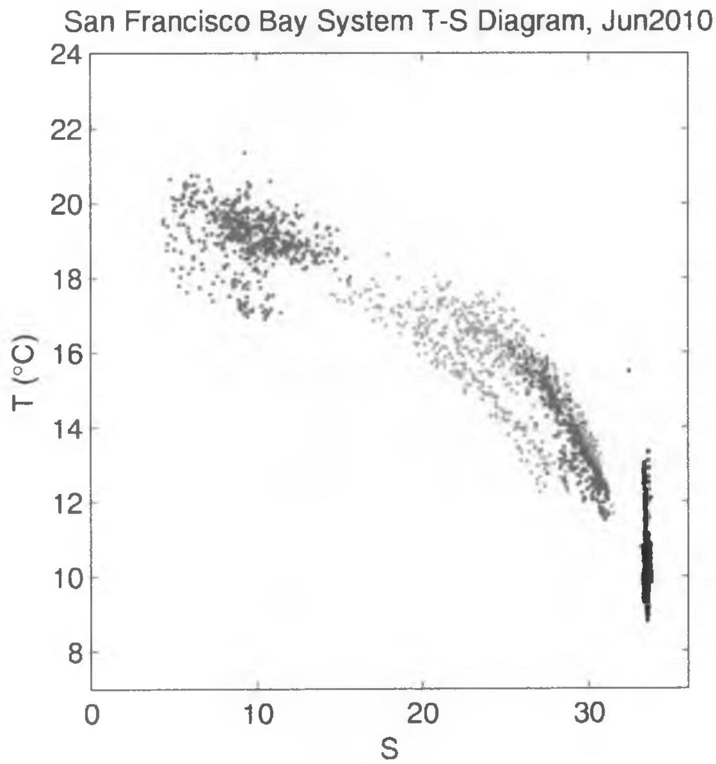


Figure 21 Closure of Upwelling Season in a year of weak upwelling-favorable winds and reversals.

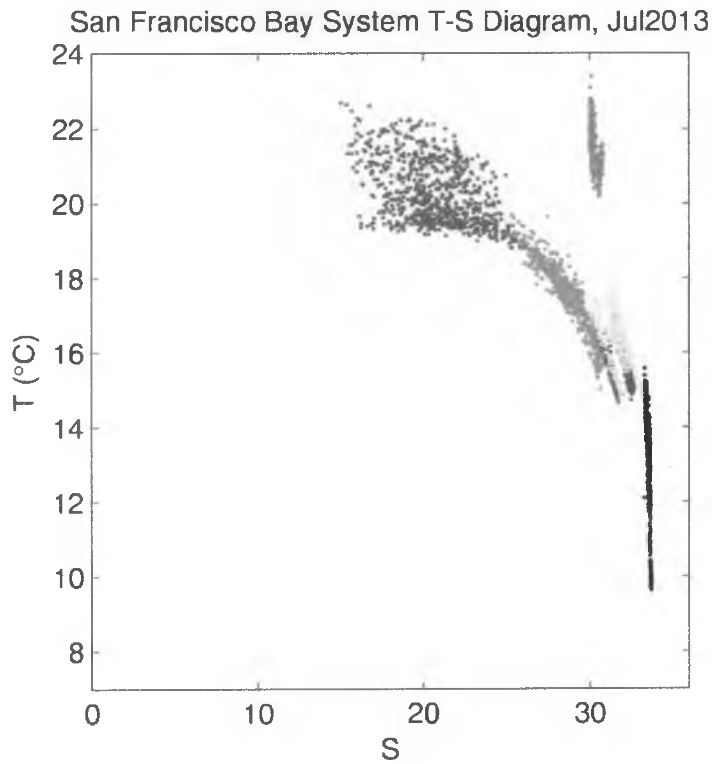


Figure 22 2013 Relaxation Season.

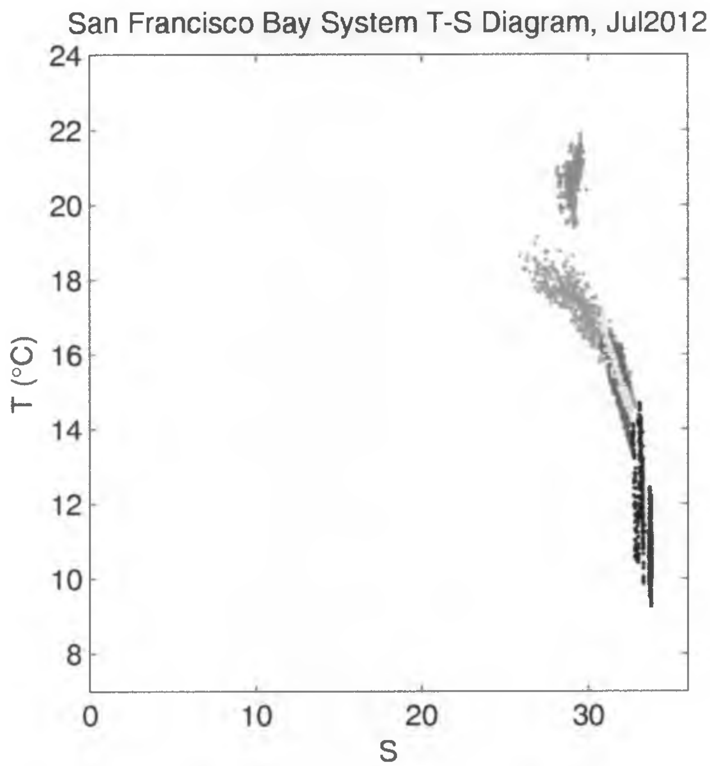
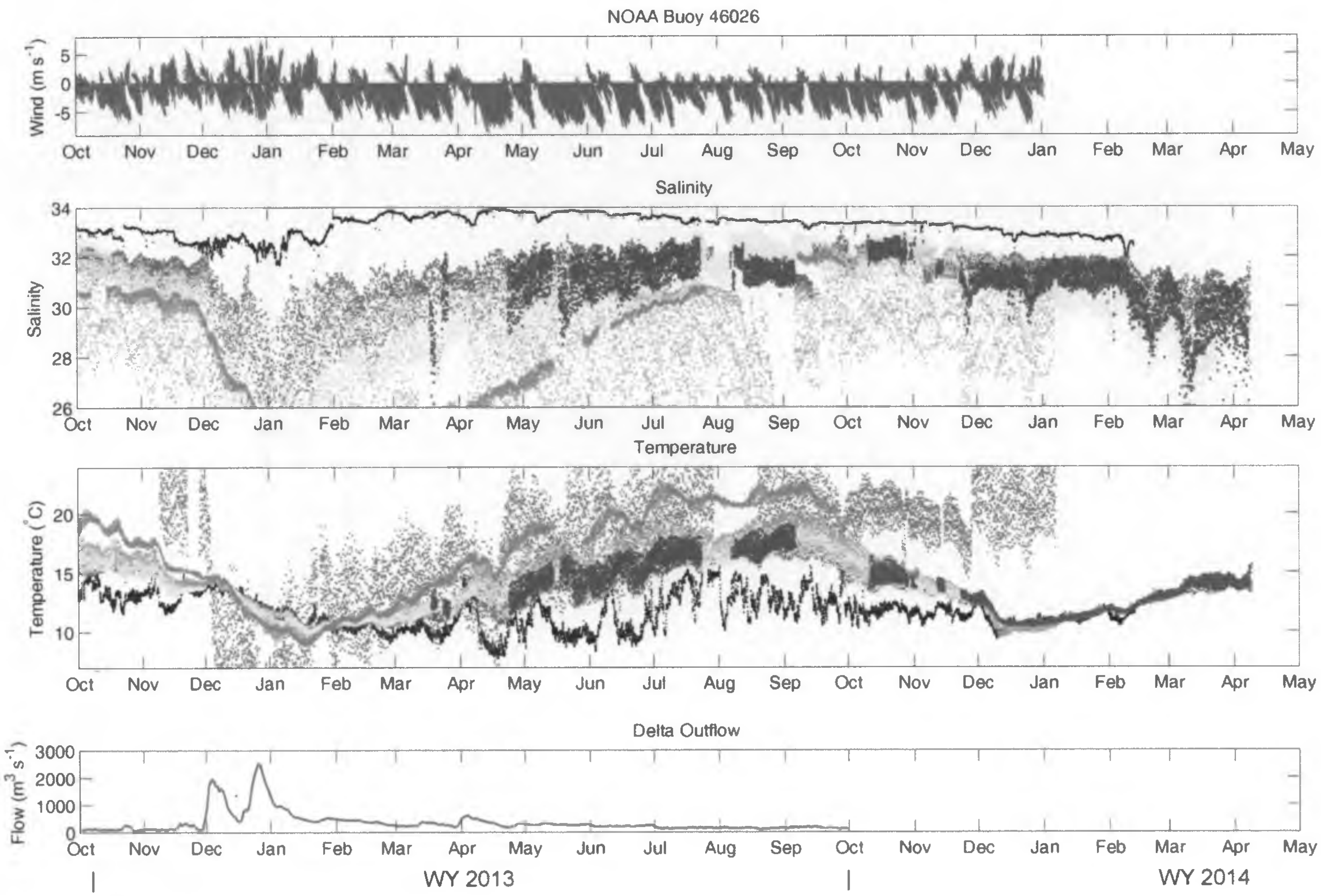


Figure 23 2012 Relaxation Season.


NOAA Buoy 46026
Wind (m s⁻¹)
Salinity
Temperature
Temperature (°C)
Delta Outflow
Flow (m³ s⁻¹)
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
WY 2013
WY 2014

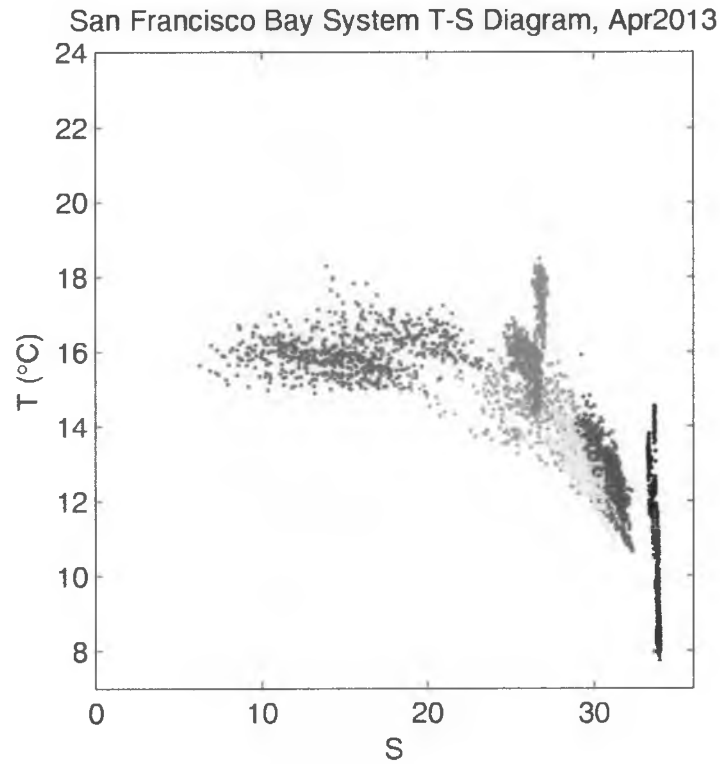


Figure 25 2013 Upwelling Season.

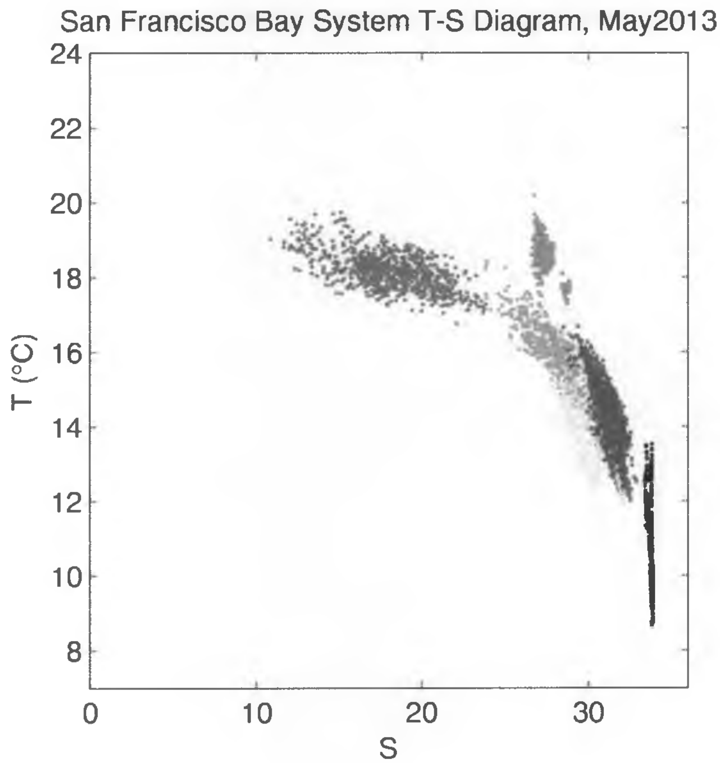


Figure 26 2013 Upwelling Season.

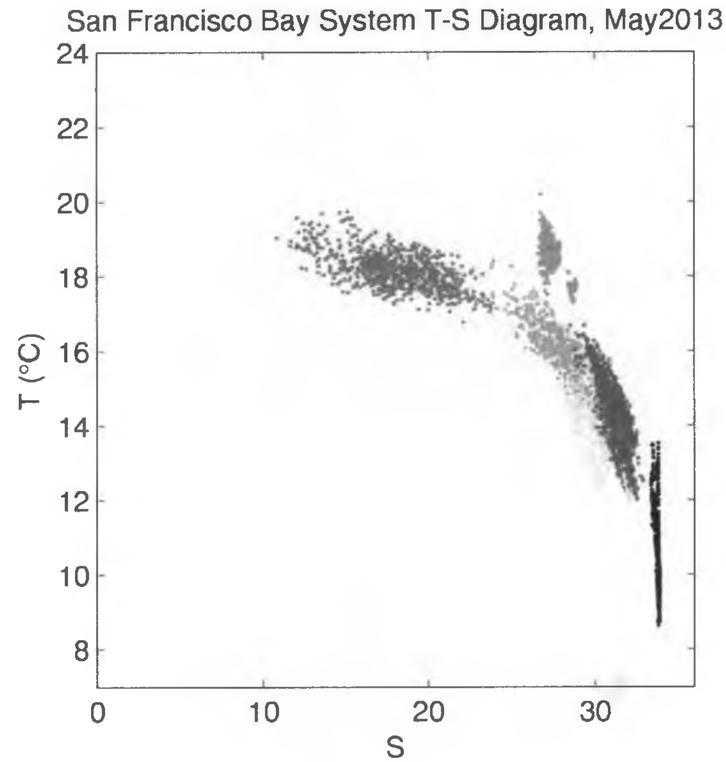


Figure 26 2013 Upwelling Season.

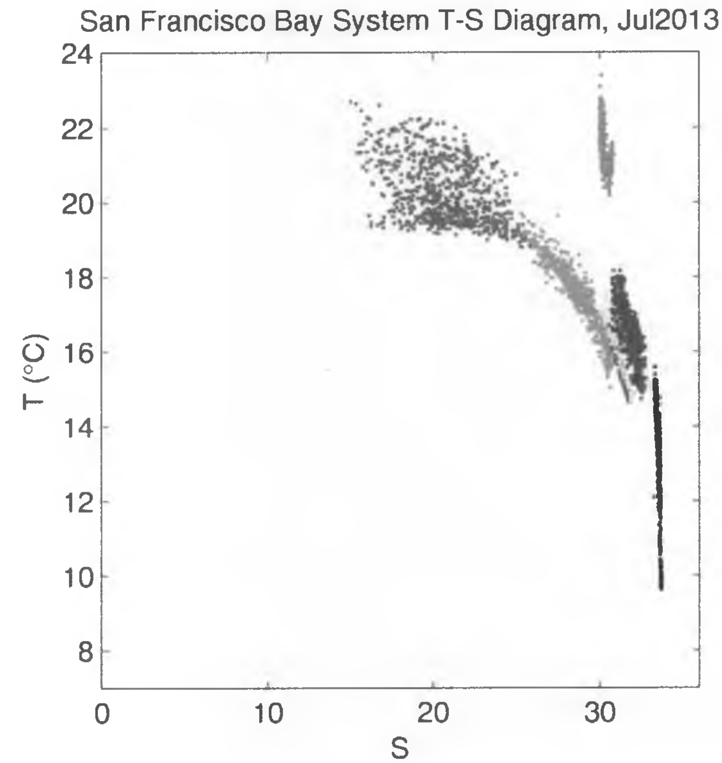


Figure 27 2013 Relaxation Season.

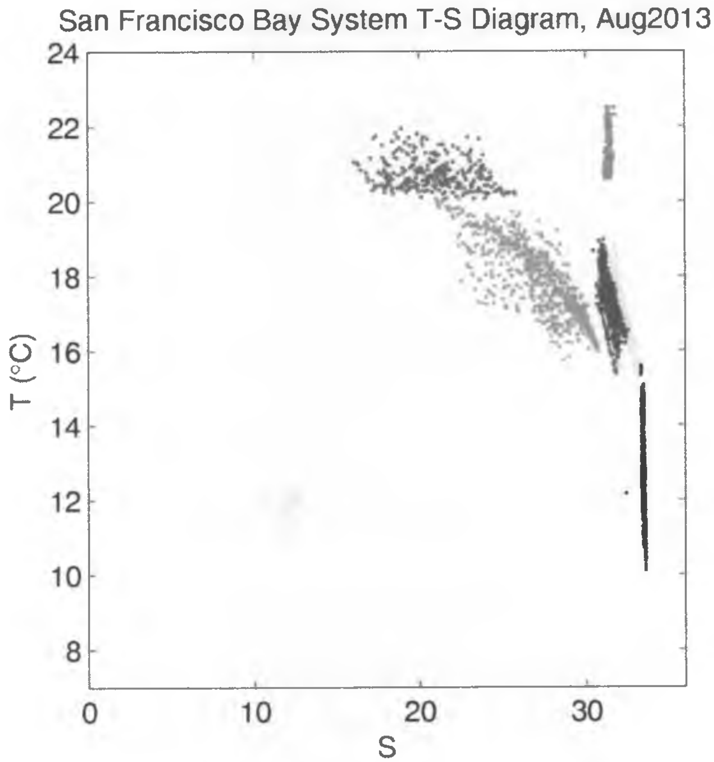


Figure 28 2013 Relaxation Season.

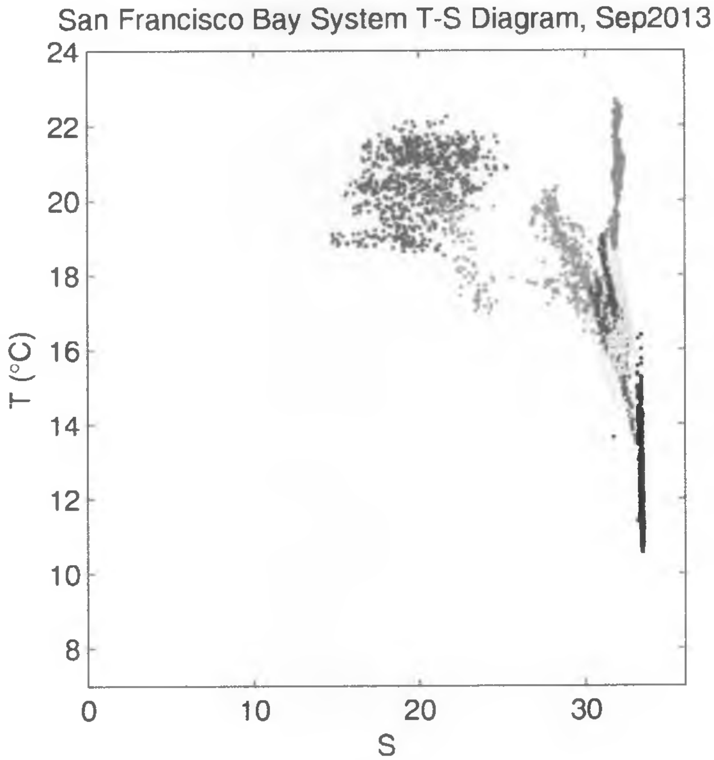


Figure 29 2013 Relaxation Season.

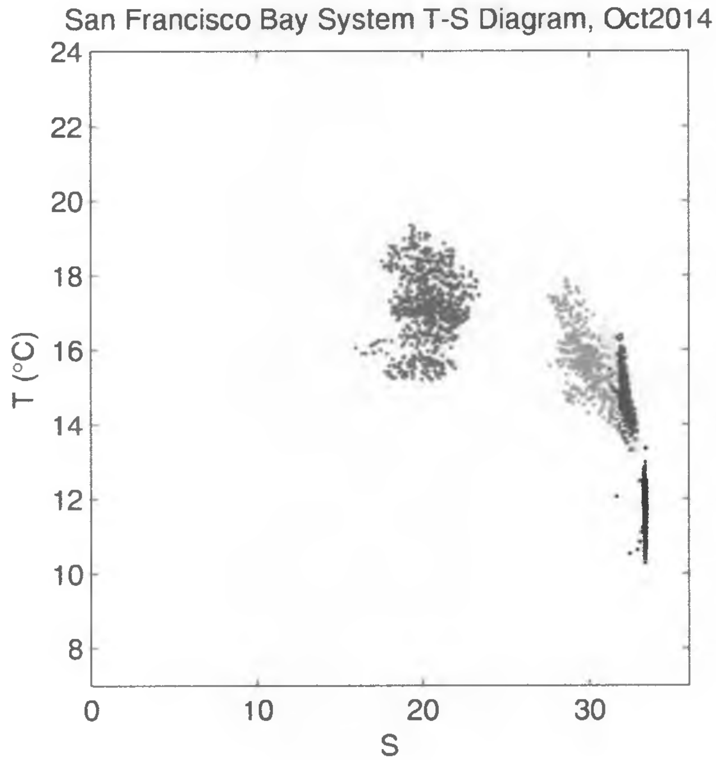


Figure 30 2014 Fall transition.

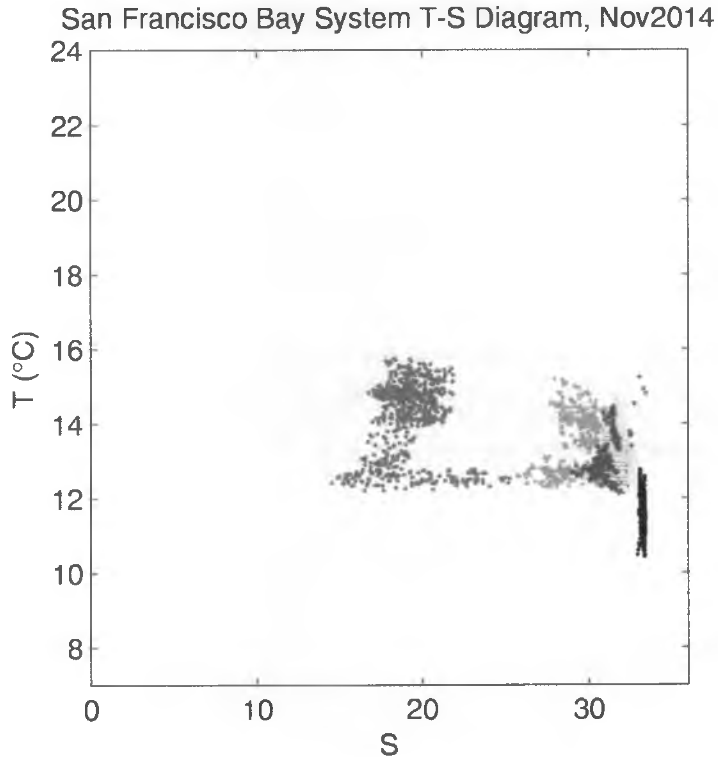


Figure 31 2014 Fall transition.

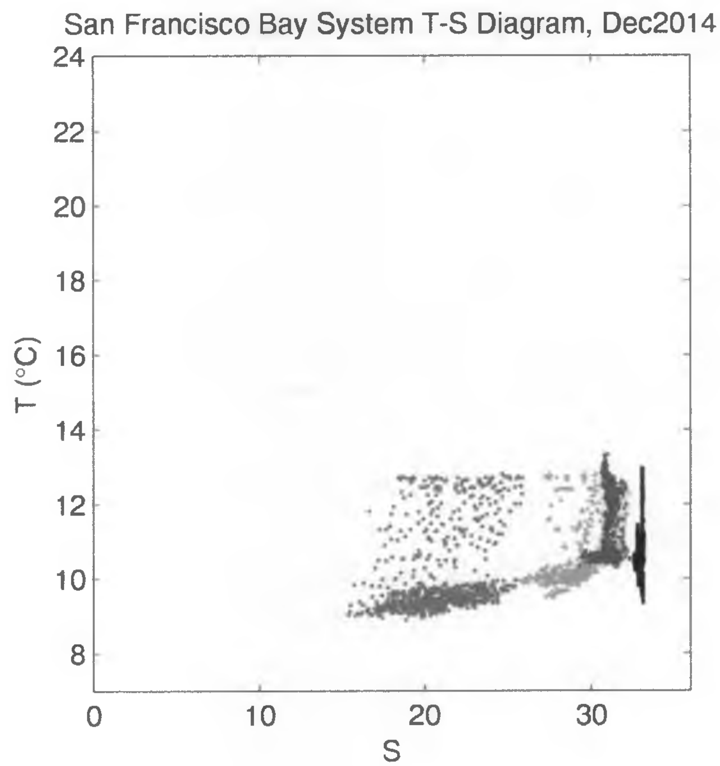


Figure 32 2014 Storm Season.

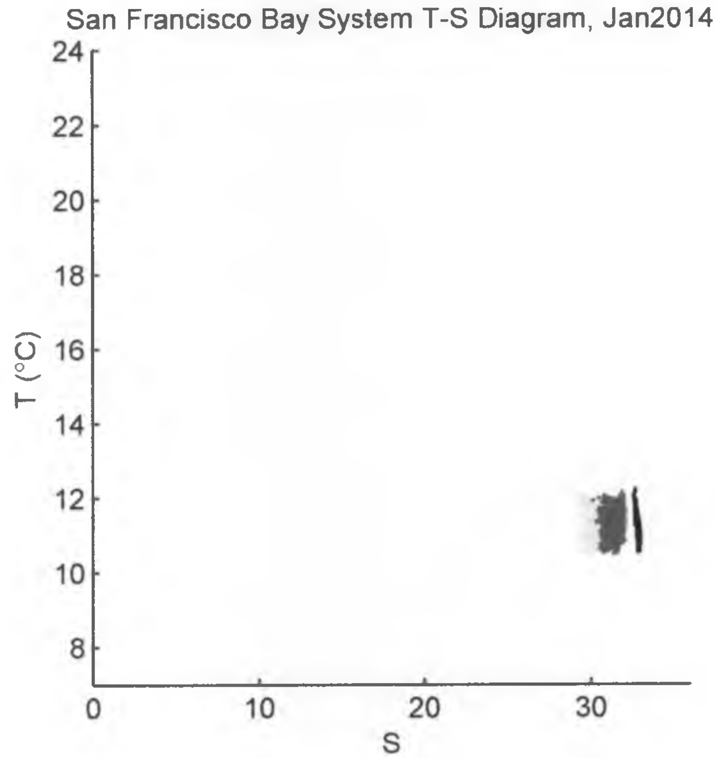


Figure 33 2014 Storm Season.

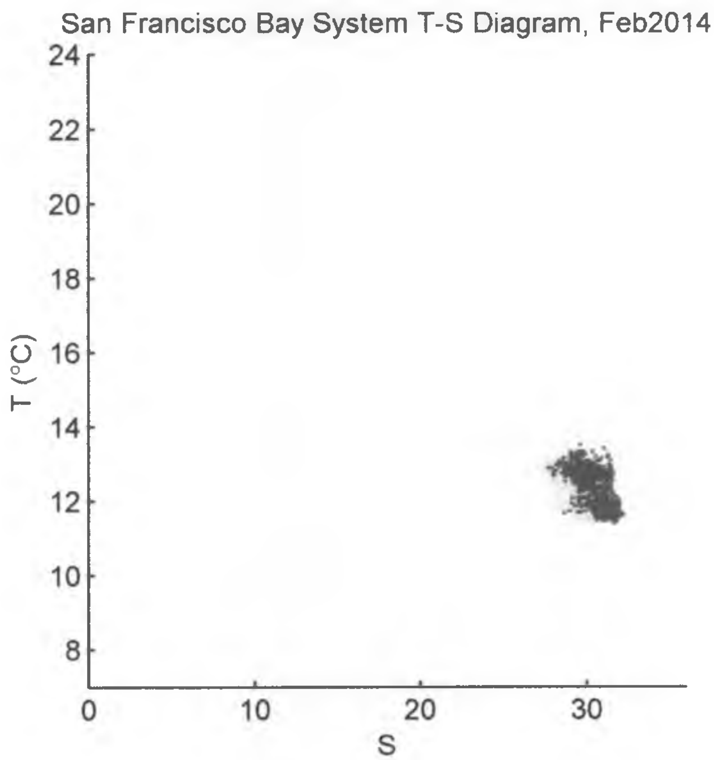


Figure 34 2014 Storm Season