The Zone of Impact of San Francisco Bay Outflow

Plume Patterns and Nearshore Distribution of Pollutants in the Gulf of Farallones

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SUMMARY

Data on water salinity and temperature collected outside San Francisco Bay and from the mouth of the Bay are analyzed to determine spatial patterns of exposure of the open coast to Bay outflow. Shoreline and nearshore sites to the north of Golden Gate (the mouth of the Bay) are more exposed to Bay outflow than sites south of the mouth.

For sites where data are collected, levels of dilution are quantified – and changes in dilution (expressed as percentage freshwater content) over time are related to changes in tides, freshwater outflow, winds, and currents. Dilution levels can be combined with information on the concentration of specific pollutants in the Bay to provide an estimate of typical pollution levels at the coastal observation sites. This method can be expected to yield reliable data for sites within a one-day advection time from the mouth of the Bay, which extends to Point Reyes during strong runoff/outflow events. Estimated pollutant concentrations in this report are not precise forecasts but rather intended to identify areas where there is a high probability of impact associated with outflow from San Francisco Bay. To develop a more robust exposure assessment, salinity data are needed for longer periods and more certainty is required on pollutant levels in water flowing our of the Bay

Observed nearshore patterns of exposure, referred to as a "zone of impact", can be explained in terms of water circulation in the Gulf of Farallones, including tidal jets and plumes associated with outflow, wind forcing and currents in the Gulf, and separation of southward flow past Point Reyes during strong upwelling winds. Work continues on a project to develop an operational index using HF Radar data on surface currents.

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1. INTRODUCTION

San Francisco Bay receives both urban and agricultural runoff, resulting in pollution of Bay waters. As Bay waters flow out to the Gulf of Farallones on each tidal cycle they transport this material into the coastal ocean, where it may impact ecological resources and human activities in nearshore waters. Little is known about the levels and space-time patterns of pollution along the shores of the Gulf and further afield. Specific concern relates to the Areas of Biological Significance (ASBS) and Marine Protected Areas (MPA) demarcated by the State of California, and waters within the National Seashore, National Recreational Area, and National Marine Sanctuary zones demarcated by the federal government. ASBS sites include Bird Rock, Point Reyes Headlands, Double Point, Duxbury Reef, and James Fitzgerald Marine Reserve. MPA sites include Bodega Head, Farallon Islands, Point Reyes, Drakes Estero, Duxbury Reef, Montara, Pillar Point, and Ano Nuevo. Federal sites include the Point Reyes National Seashore (PORE), the Golden Gate National Recreation Area (GOGA), the Greater Farallones National Marine Sanctuary (GFNMS), and the Cordell Bank National Marine Sanctuary (CBNMS).

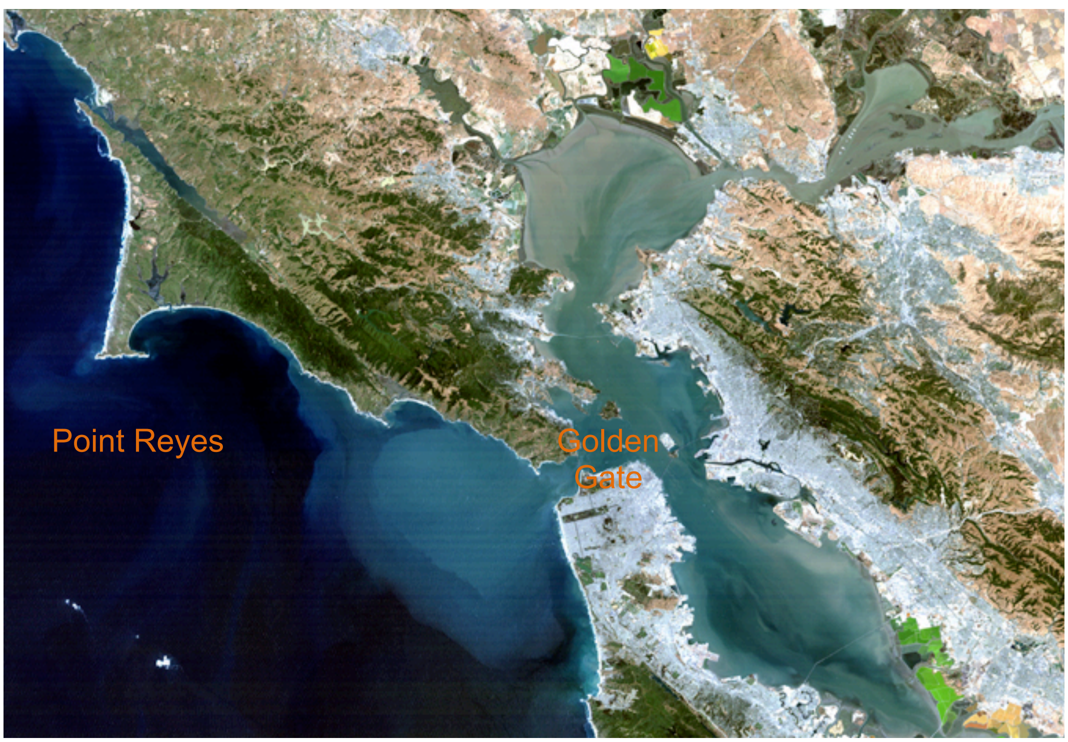

Figure 1. *Outflow from San Francisco Bay evident as a turbid plume. Note the northward extension of turbid waters along the shoreline to Double Point (N of Bolinas).*

In the near-field after export from the Bay, the spatial pattern of pollutants is determined by transport by currents and mixing of outflow with the Gulf receiving waters. Typically chemical and biological reactions occur more slowly – over time scales of a day or longer. But, with more time and distance from the mouth, Bay-derived pollutants are more diluted by mixing and less of a concern. Hence, the focus here is on transport and mixing patterns that control the location and timing of the highest pollutant concentrations expected in the coastal waters outside the Bay. These transport and mixing patterns can be tracked by changing salinity, as we do here.

A Conceptual Model

Prior observations, models and theory (published and unpublished work) and knowledge of regional oceanography, allow one to identify three transport and mixing states: *"upwelling" state* with southward currents, *"relaxation" state* following the cessation of upwelling and characterized by northward currents nearshore, and *"downwelling" state* that occurs briefly during southerly wind events and with strong northward currents.

During northerly winds that drive upwelling, currents run towards the south and the outflow plume from San Francisco Bay is typically transported southward due to both currents and winds. At the same time, the wind drives offshore Ekman transport and upwelling along the coast, so the plume is also pushed offshore and typically extends southwest from the mouth of the Bay with minimal shoreline contact (Figure 2). This scenario is also illustrated schematically in Figure 3.

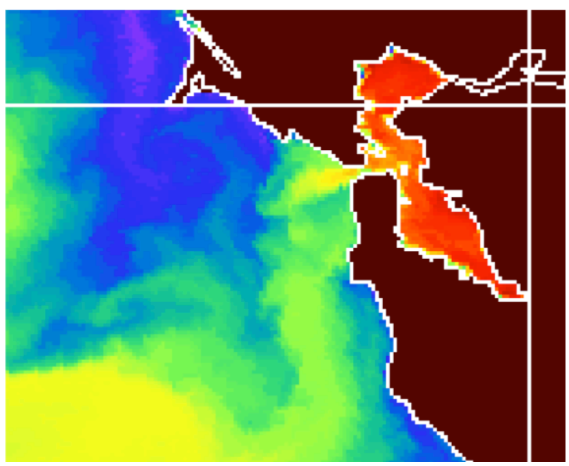

Figure 2. *Outflow from San Francisco Bay evident as a warm surface plume in satellite data of sea surface temperature (SST) – from NOAA AVHRR, 13 June 1993 (warm red colors are warmer waters and cold blue/mauve colors are colder waters). Note the tidal jet at the emanating from the mouth of the Bay (yellow dart) and the southward extension of yellow and green colors indicating the southward advection of Bay waters and separation from the coast. Also note the anticlockwise circulation just south of Point Reyes evident as it entrains cold waters flowing south past the Point.*

When Point Reyes shelters the northern Gulf (Drakes Bay) from northerly winds, an anticlockwise circulation entrains Bay outflow, which can accumulate in this area and exposure nearshore environments to Bay pollutants. However, when upwelling winds are strong, cold upwelled waters will break the surface along the shoreline from Bolinas to Drakes Estero and any residual Bay water is pushed offshore reducing exposure to Bay waters to zero.

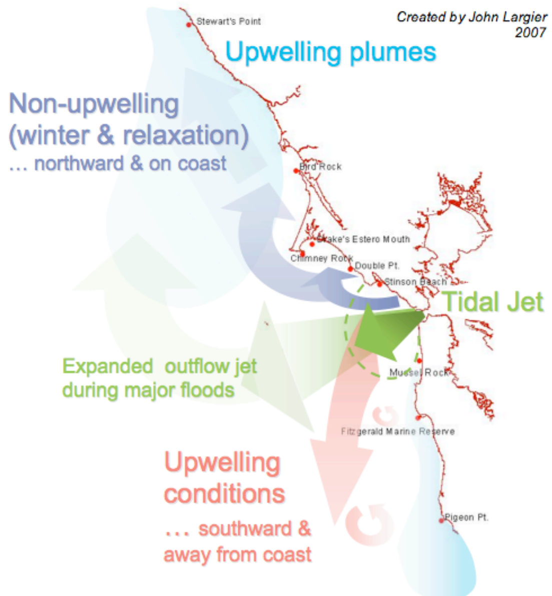

Figure 3. *A tidal jet ejects Bay waters 10-20km from the mouth (large green arrow). Southward export of Bay waters and separation from the shoreline during the upwelling state is symbolized with a large faded red arrow. While some northward transport and accumulation occurs up to Point Reyes during the upwelling state, northward transport beyond Point Reyes occurs only during the relaxation state (large faded blue arrow), or during the downwelling state when southerly winds pile up waters in Drakes Bay resulting in an offshore jet westward from Point Reyes and formation of a large clockwise eddy north of the Point and contact with the shoreline only being re-established at Bodega Head. This westward jet and turning region north of Point Reyes is also observed during strong freshwater outflow (large faded green arrow).*

Northward flow past Point Reyes occurs during relaxation and downwelling states, as illustrated in Figure 3. When Bay outflow is strong, or southerly winds are strong, or upwelling decreases suddenly, the flow impeded enough by Point Reyes that it jets westward from the Point and likely also impacts the Farallon Islands and Cordell Bank. When strong enough to jet westward and separate from Point Reyes, the flow only re-attaches to the shore in the vicinity of Bodega Head. Under these conditions the nearshore waters north of Point Reyes may be only modestly exposed.

2. APPROACH

As low-salinity water exits the Bay, it mixes with ocean waters of known salinity. As salinity is a conservative property (no significant chemical or biological reactions), observed changes in salinity can be used to determine the proportion of Bay water or the proportion of freshwater. This direct observation of the dilution of Bay outflow can provide an estimate of pollutant concentration at these observation sites if the pollutant levels are known in the source waters. While other sources of freshwater may confound this approach, the freshwater flux from San Francisco Bay is much larger than any other freshwater sources in the Gulf of Farallones. It is only during rain events that other smaller watersheds may have an important on influence on salinity – and then only very near to the source of the outflow (e.g., Redwood Creek near Muir Beach).

At each site, salinity provides a direct estimate of the freshwater fraction *FF* at the site:

$$FF = (S_{oc} - S) / S_{oc} \qquad \textit{(Equation 1)}$$

where S_{oc} is the ambient ocean salinity and S is the salinity observed at the site. There is an error due to variability in S_{oc} but this is small during times of land runoff when observed salinities are 1ppt or more lower than the ambient values, which show variability of order 0.1ppt (here we focus on FF greater than 1%, which corresponds to salinity deficits of 0.3ppt or greater and errors in FF that are less than about 30% - decreasing to less than 10% for FF exceeding 3%).

Assuming that biochemical processes have negligible effect on pollutant concentrations, one can estimate the pollutant concentration at a site from knowing the loading in the source freshwater runoff:

$$C = FF.C_{fw} \qquad \textit{(Equation 2)}$$

where C_{fw} is the concentration in freshwater and C is the concentration at the site where salinity was measured – and it is assumed that ocean waters are not polluted.

Typically polluted outflow is not freshwater and has non-zero salinity, in which case one can estimate the bay-water fraction BF at the site from:

$$BF = (S_{oc} - S) / (S_{oc} - S_b) \qquad \textit{(Equation 3)}$$

where S_b is the salinity of the bay-water outflow.

One would then estimate pollutant concentration at the site from the loading of pollutants in the bay outflow:

$$C = BF.C_b \qquad \textit{(Equation 4)}$$

where C_b is the concentration in the bay outflow. Alternatively, one can use the assumption of mixing that yields a linear relation between C and S to obtain an "apparent freshwater concentration" – what would have been in the freshwater inflow to explain the Bay concentrations (even though the pollutant sources are elsewhere in the Bay). This apparent freshwater concentration C'_{fw} is given by:

$$C'_{fw} = [S_{oc} / (S_{oc} - S_b)].C_b \qquad \textit{(Equation 5)}$$

and concentration at the ocean site is given as before by: $C = FF.C'_{fw}$

Salinity sensors were deployed at nine nearshore sites in addition to permanent sites at Bodega Head and Fort Point (Figure 2). Sensors were deployed for 2-3 months in winter, when freshwater flux through San Francisco Bay is strong, and a smaller number were deployed again for 2-3 months in early summer, when freshwater flux is weaker and wind-driven upwelling is active in the Gulf. During upwelling, coastal waters are marginally saltier than in the absence of upwelling (33.9 versus 33.5ppt), but it they are markedly colder (9^{o}C versus 12^{o}C). Thus temperature data can be used to identify periods of upwelling, when no nearshore pollution is expected as surface waters are exported offshore and newly upwelled water is not yet subject to pollutant loading.

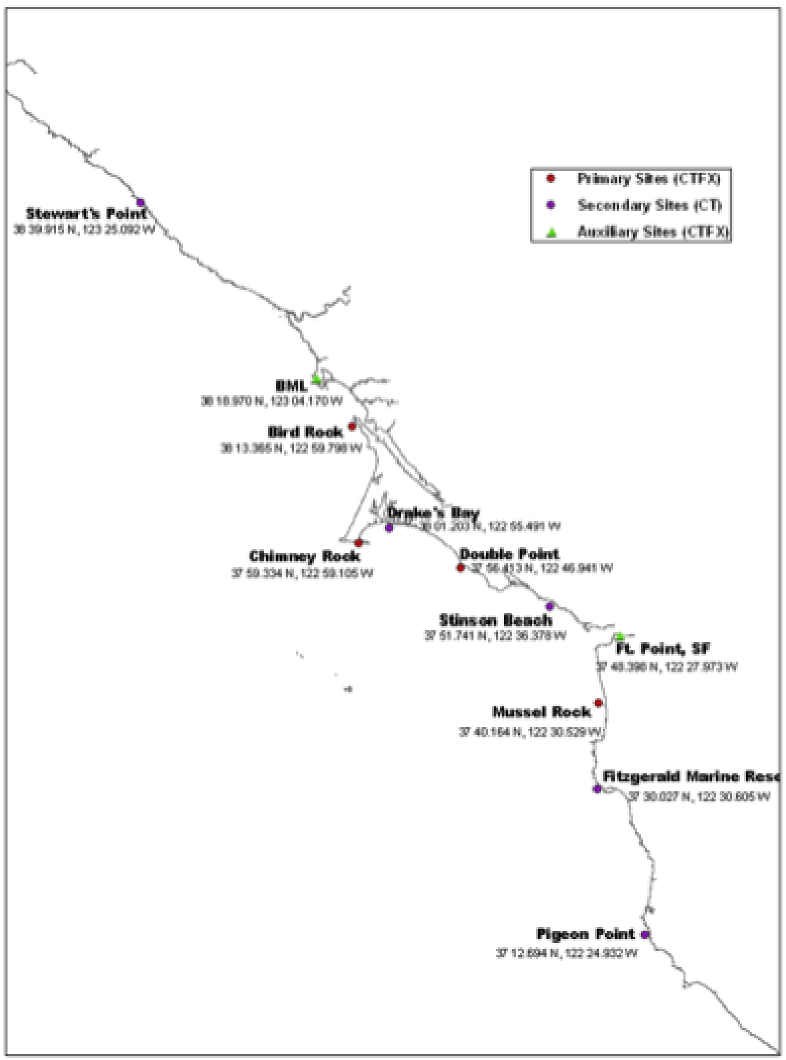

Figure 4. *Nearshore sites where temperature-salinity sensors were deployed.*

Salinity sensors[1] were deployed near-surface at eleven sites along the 10m isobath (typically within 500m of the shore). As shown in Figure 4, most sites were in the vicinity of the mouth of San Francisco Bay and some additional sites provided distant reference stations:

- Stewarts Point – reference site: upwelling center north of study area, subject to Russian River plumes during downwelling
- Bodega Head – long term site, exposed to Bay outflow during storms
- Bird Rock – ASBS site
- Chimney Rock – ASBS site
- Drakes Bay – site close to mouth of Drakes Estero
- Double Point – northern site more than one tidal excursion from the mouth of Bay
- Stinson Beach – northern site within a tidal excursion from the mouth of Bay
- Fort Point – mouth of Bay and long term site
- Mussel Rock – southern site within a tidal excursion from the mouth of Bay
- Fitzgerald Marine Reserve – southern site more than one tidal excursion from the mouth of Bay
- Pigeon Point – upwelling center south of study area

[1] Salinity and temperature data were obtained from SeaBird MicroCaT SBE-37 instruments, which had been recently calibrated and accuracy was order 0.01ppt (salinity) and 0.01^{o}C (temperature).

3. EXPOSURE TO FRESHWATER RUNOFF

3.1 Observed Salinity Variability.

3.1.1 Winter data

Sensors deployed in January 2007 captured several low-salinity events, including the effect of localized runoff following rain in early February and enhanced freshwater outflow from San Francisco Bay in early March.

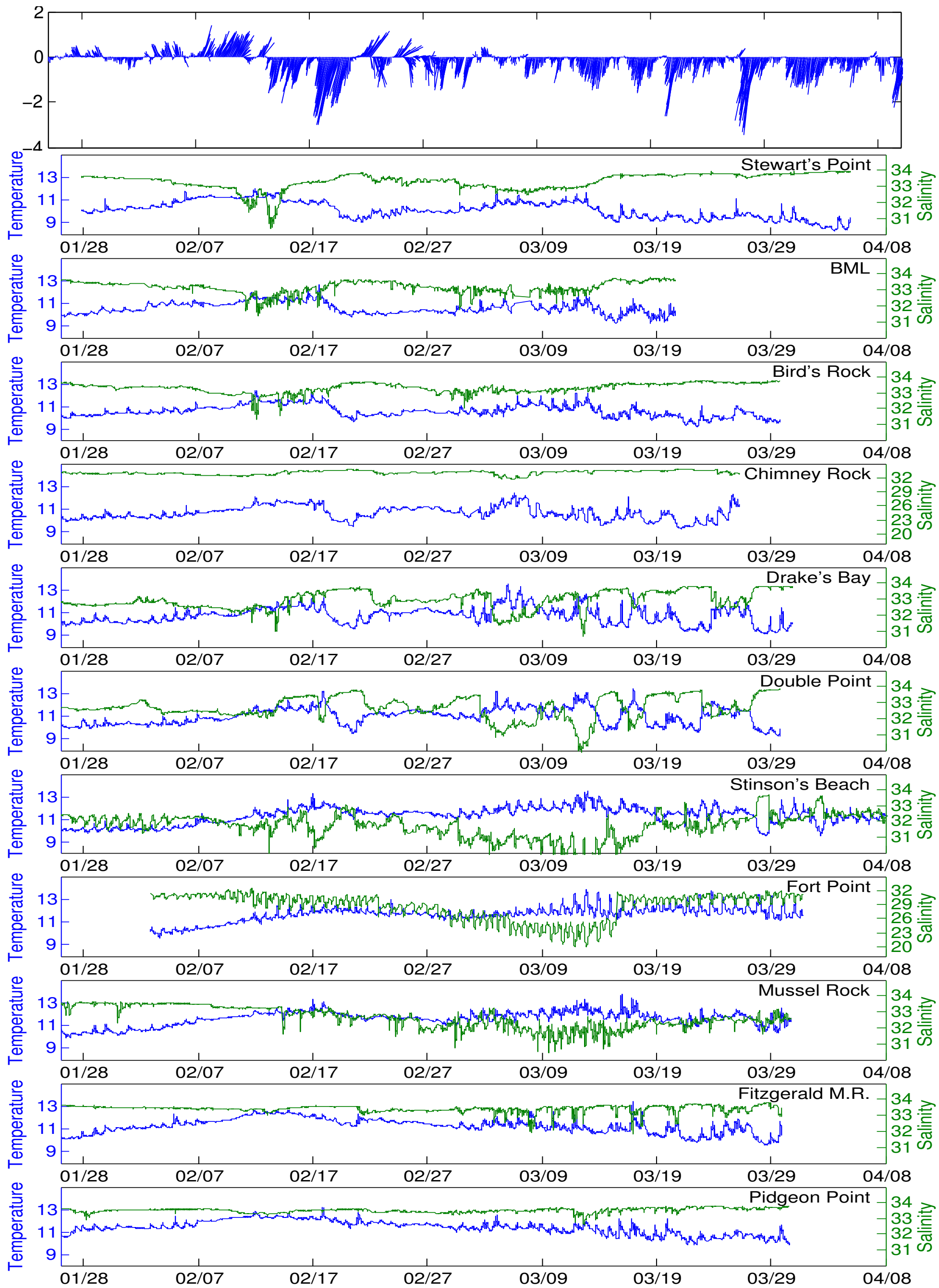

Figure 5. *Surface salinity and temperature observed in February-March 2007 at eleven sites. The plots are arranged north to south, and labeled. The uppermost panel is wind recorded at offshore NDBC Buoy 46013 – downward sticks indicate southward winds (e.g., 17-19 February) and upward sticks indicate upwelling-favorable northward winds (e.g., 9-11 February).*

Widespread rainfall is evident in low salinities at Stewart's Point on 11-13 February, due to local plumes from the Russian and Gualala Rivers. Salinity decreases of about 1ppt are also seen at BML, Bird Rock and Stinson Beach, likely due to runoff from other local creeks (Salmon Creek, Lagunitas Creek and Walker Creek in Tomales Bay, and Redwood Creek). At other sites, removed from local creek effects, there is little salinity signal, e.g., Chimney Rock, Drakes Bay, Fitzgerald, Pigeon Point, and even Fort Point at the mouth of San Francisco Bay. Soon after the rain, northerly winds drive upwelling along much of the coast, with full-strength salinity and sub-10^{o}C waters evident around 20 February both along the open coast north of Point Reyes and in the Gulf at sites north of Golden Gate and removed from the tidal influence (i.e., Chimney Rock, Drakes Bay and Double Point).

In contrast, as freshwater outflow from the Bay increases following the late-February upwelling event, salinity at Fort Point decreases in late February and early March, with outflowing salinity minima as low as 20ppt by 12 March. This 3-week decrease in salinity is also seen at Stinson Beach and weakly at Mussel Rock. However, this low-salinity water only appears at Double Point on 4 March and at Drakes Bay on 5 March, and finally a weak salinity drop is observed at Chimney Rock on 7 March. These latter three sites are beyond a tidal excursion from the mouth of San Francisco Bay and show the northward expanding influence of low-salinity Bay outflow when northward currents set up in the northern Gulf of Farallones. A second pulse is seen at Double Point on 12 March and at Drakes Bay on 13 March, but not at Chimney Rock. No similar low-salinity signal is seen more than a tidal excursion southward of the mouth (i.e., at Fitzgerald or Pigeon Point sites) – illustrating the asymmetrical influence of Bay outflow on the shoreline and nearshore waters in the Gulf.

Decreases in salinity are also evident as low-salinity, bay-influenced waters reconnect with the shore as upwelling winds weaken, e.g., a drop in salinity at Double Point on 21 February is followed by salinity drops at Drakes Bay and Chimney Rock on 22 February. Similarly, as upwelling on 21-22 March weakens, low-salinity water appears at Double Point, Drakes Beach and Chimney Rock on 23-24 March. Upwelling returns again on 28 March.

In addition to salinity variability due to runoff and upwelling, a strong tidal signal is evident at Fort Point and also Stinson Beach and Mussel Rock at times. This represents a back-and-forth advection of the strong spatial gradients between low-salinity Bay waters and high-salinity ocean waters.

A boat survey of nearshore salinity on 4 March illustrates the tendency for Bay outflow to remain attached to the shore north of Golden Gate, but not to the south (Figure 6) – even while northerly winds drive southward transport (23-35 cm/s) past Point Reyes (Figure 7). While salinity is ~33.0 on the north side of Point Reyes, salinity is less than 32.0 along the Gulf shoreline north of Golden Gate, and below 31.0 south of Double Point. This northward attachment is also evident in data collected in this region by Wilkerson et al (2002) – associated with separation of the southward flow past Point Reyes and a tendency for anti-clockwise circulation in the northern Gulf (Figure 2) – discussed further in Section 5.

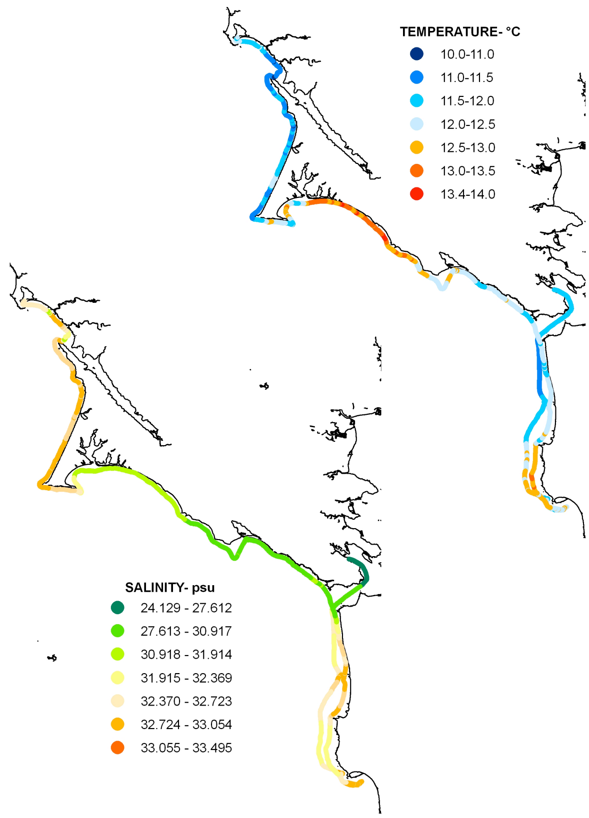

Figure 6. *Underway sampling of nearshore surface temperature and salinity on 4 March 2007.*

While some proportion of Bay outflow is retained south of Point Reyes and attached to the shoreline during upwelling-related southward flows, this low-salinity water is observed north of the headland during relaxation events (calm winds) and most strongly during southerly winds (i.e., following winter storms). This extended "zone of impact" for San Francisco Bay is evident as a decrease in salinity at Bird Rock 7-19 February and at BML 8-19 February, following southerly winds (Figure 5) and northward currents (Figure 7) from 5 to 12 February. The marked low-salinity events at Stewarts Point on 11 and 13 February (Figure 5) are due to northward transport of waters from the Russian River and other small rivers in the region north of Bodega Bay.

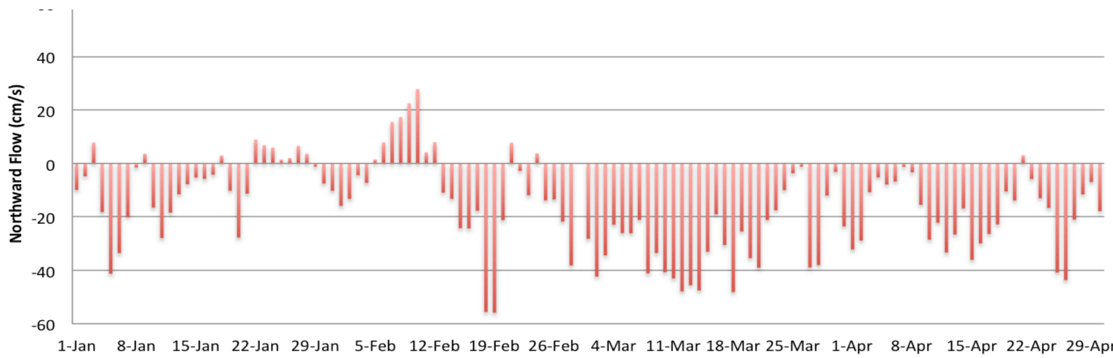

Figure 7. *Daily average surface current: northward flow past Point Reyes (January-April 2007). Data are from a high-frequency radar network (bml.ucdavis.edu/boon/currents.html), averaged over an area that extends 15km west and 20km north of Point Reyes. A strong northward flow event occurs from 5 to 12 February (during persistent southerly winds), with a weaker event 22-28 January, and brief events on 9 and 18 January, 21 and 24 February and 21 April.*

3.1.2 Summer data

Sensors were also deployed in May 2007, during stronger and more persistent upwelling. Salinity variability is best understood in terms of a weaker but steady outflow from San Francisco Bay, which is pushed offshore during active upwelling (7 to 12 June, 22 June to 5 July, 25 July) and can reattach to the shore north of Golden Gate during relaxation (mid-June, early July) – as evident in Figure 8.

Low-salinity, bay-influenced waters appear at Double Point on 13 June as wind forcing weakens and subsequently at Chimney Rock on 16 June, however a second pulse arriving at Chimney Rock on 17 June is subsequently observed at Bird Rock and BML on 19 June following northward transport past Point Reyes (Figure 8). A similar event starts at Double point on 4 July, appearing also at Chimney Rock, but it is the second pulse starting at Double Point on 7 July that is transported north of Point Reyes where it is observed at Bird Rock on 9 July and at BML on 10 July. The record of surface currents provided by HF radar shows these northward flow events past Point Reyes (Figure 9), and the influence of coriolis forcing keeps the buoyant low-salinity waters attached to the shore.

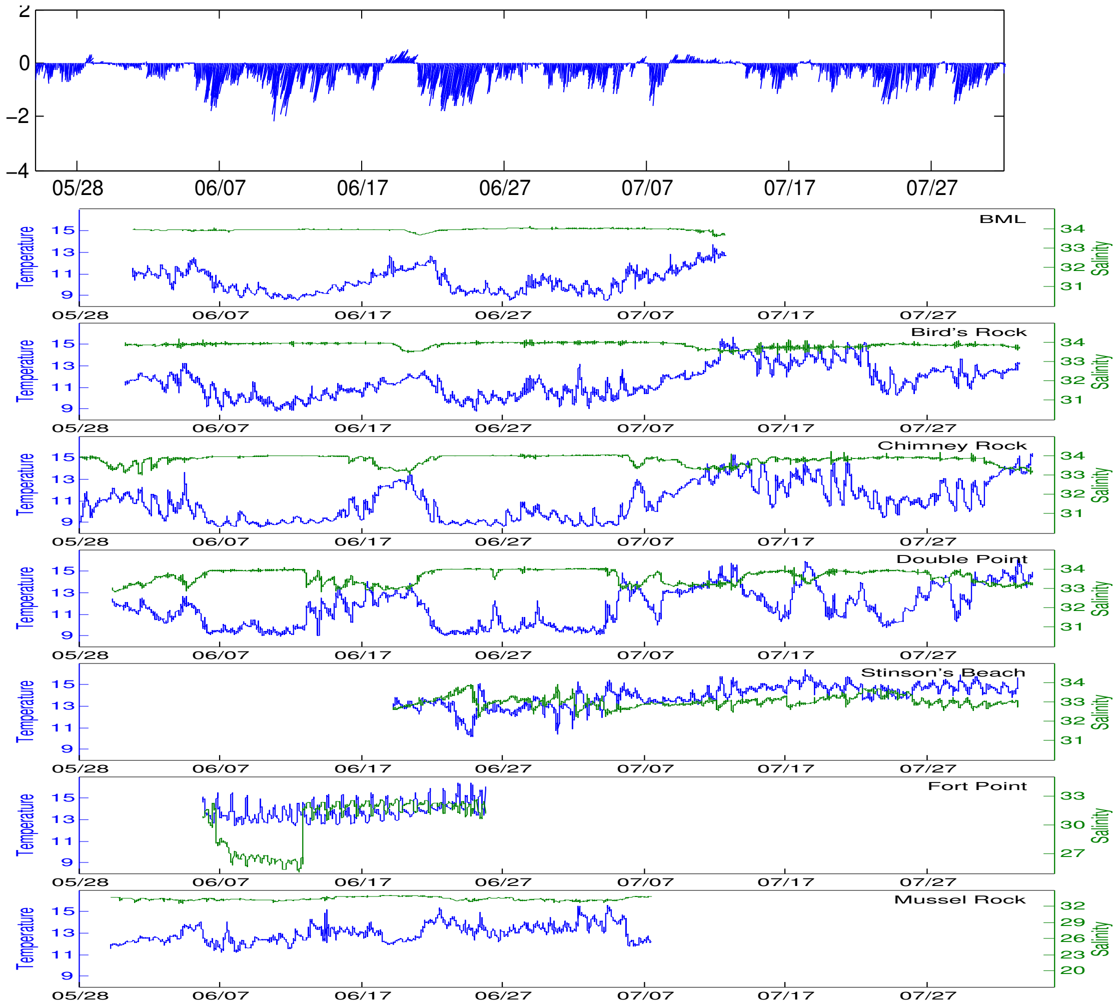

Figure 8. *Surface salinity and temperature observed June-July 2007 at seven sites. Plots are arranged north to south, and labeled. The uppermost panel is wind recorded at offshore NDBC Buoy 46013 – downward sticks indicate southward winds, which prevail.*

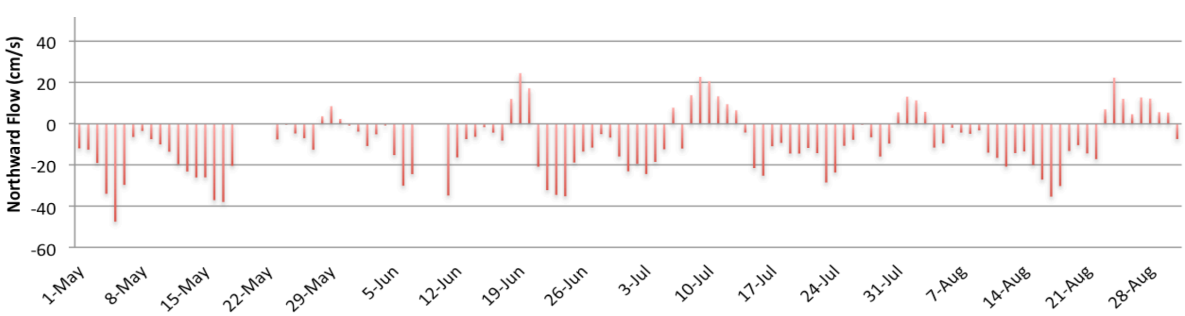

Figure 9. *Daily average surface current: northward flow past Point Reyes (May-August 2007). Data from high-frequency radar network (bml.ucdavis.edu/boon/currents.html), averaged over an area that extends 15km west and 20km north of Point Reyes. Northward flow events occur 28-30 May, 18-20 June, 6-13 July, 31 July to 3 August, and 23-30 August during periods when upwelling winds weaken ("relaxation events").*

3.2 Calculated freshwater fraction.

3.2.1 Winter data

The salinity data presented above can be re-plotted as freshwater fraction, following equation (1), given in Section 2. For values less than 1%, the error is large and limited confidence can be placed in the precision of the values, but the primary pollution zones of impact are represented by values that are greater than 3%.

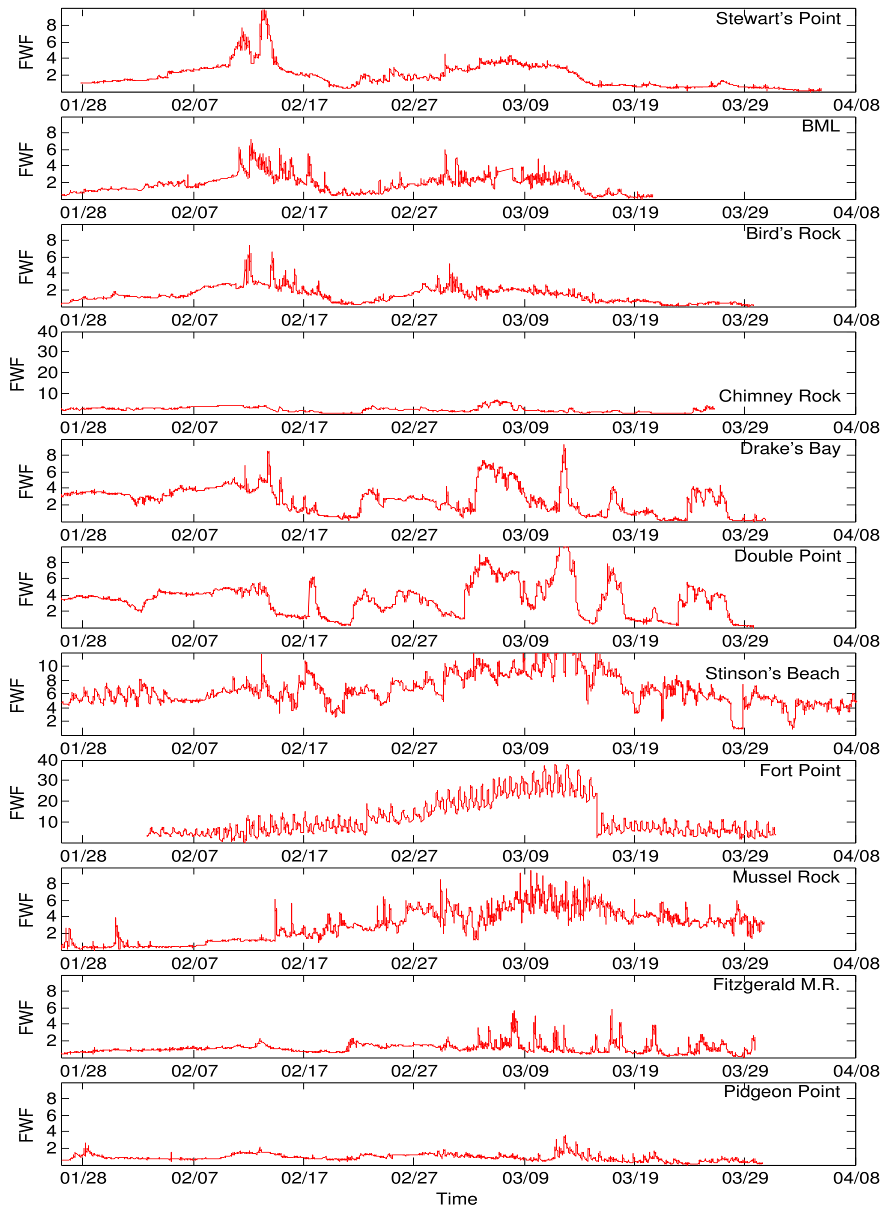

Figure 10. *Time series of freshwater fraction (Equation 1, with S_{oc}=34.0) for all sites in winter, given as a percentage for each of the eleven winter sites.*

These data provide site-specific quantification of the levels and probability of exposure to Bay waters (Figure 10). During the downwelling event in mid-February, freshwater fraction of 6 to 8% extends up to Bodega Head (BML). However, during the strong Bay outflow in early March, freshwater content is about 30% (a third) at Fort Point, mixing with sea water and reducing to about 10% up to Drakes Bay. North of Point Reyes, levels are only 2 to 4% and similar to what was observed on the north coast during the relaxation event at the end of February.

The probability of exposure to freshwater, and thus to the pollutants associated with runoff at a given site, is best shown as a distribution of freshwater fraction percentages (Figure 11). There are few values at or near zero, because salinity in the Gulf is seldom as high as 34.0 in winter – even during upwelling events. Choosing a value of 33.9 or 33.8 fills in the likelihood of zero-freshwater content, but makes little change to the values at the modes – each being associated with the specific events observed in February and March 2007.

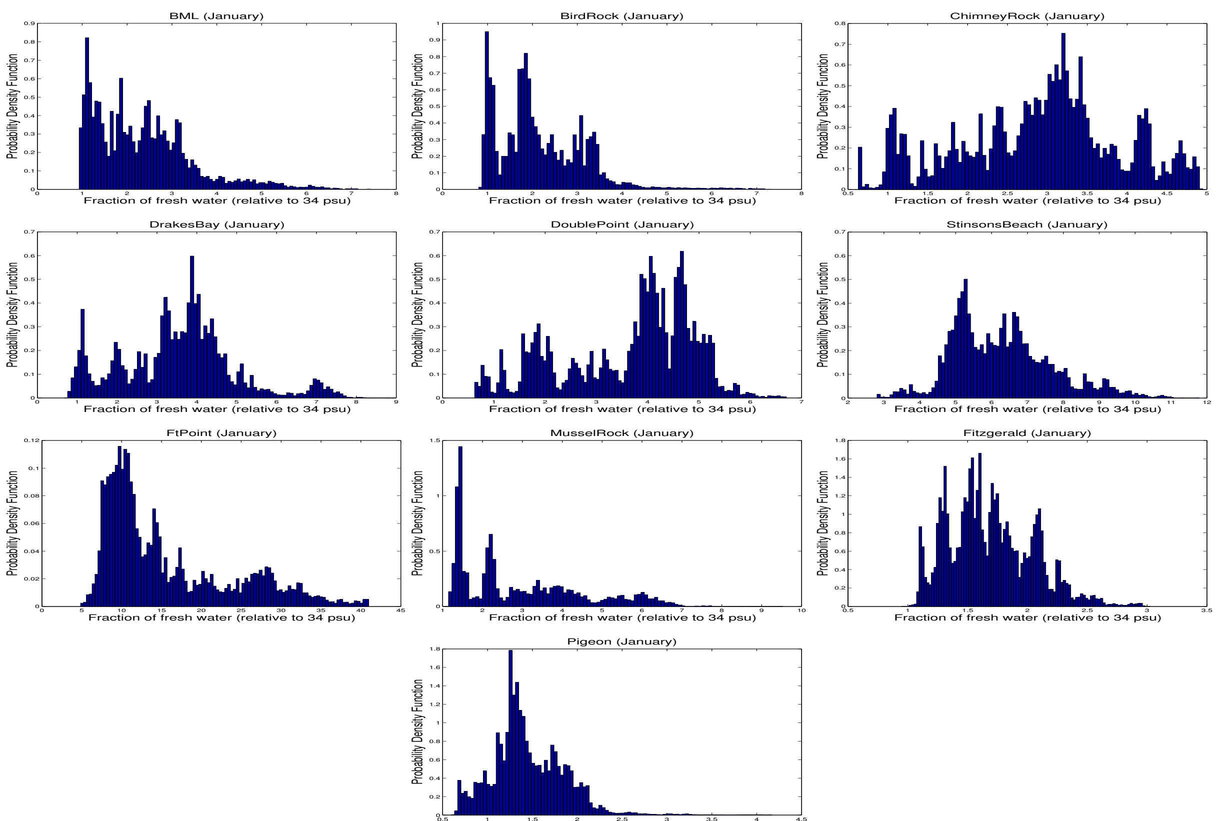

Figure 11. *Probability density functions for fraction of freshwater percentage at ten sites in winter: BML, Bird Rock, Chimney Rock, Drakes Bay, Double Point, Stinson Beach, Fort Point, Mussel Rock, Fitzgerald Marine Reserve, and Pigeon Point.*

Alternatively, one can plot cumulative probability (Figure 12), which allows one to directly read off the probability of a specific value being exceeded. For example, in Figure 12 a dashed line marks the 5% freshwater level – corresponding to 1 part freshwater and 19 parts seawater. At Fort Point this level is exceeded 75% of the time, but at Drakes Bay it is exceeded less than 10% of the time, and it was not exceeded at all at Pigeon Point.

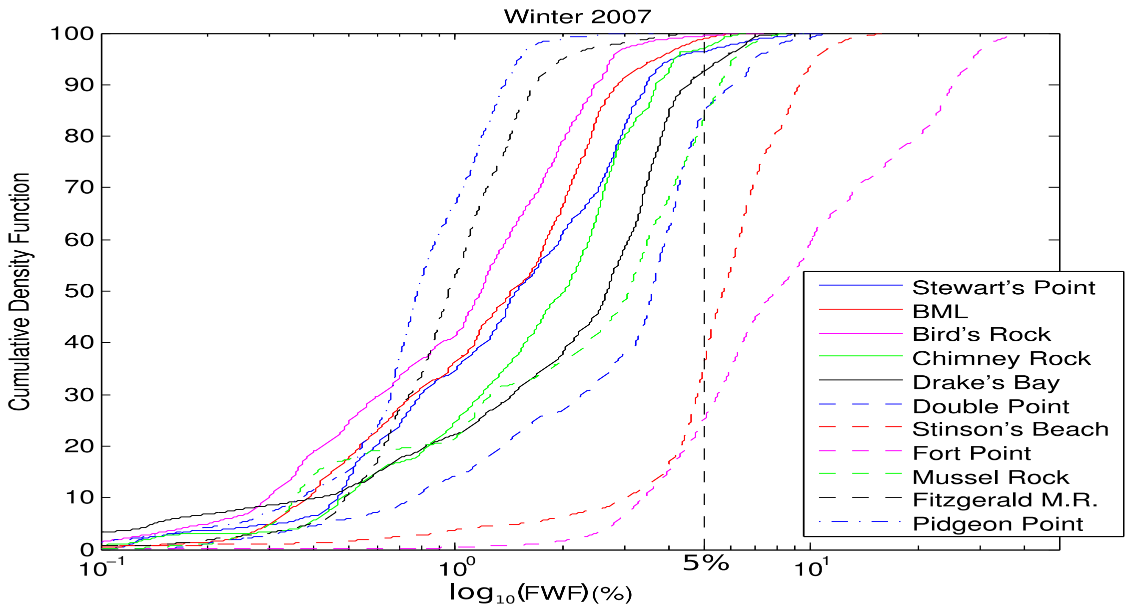

Figure 12. *Cumulative probability for fraction of freshwater – percent of time freshwater fraction is below a given level, e.g., Double Point site is exposed to levels below 5% freshwater for 84% of the time and it is never exposed to levels above 10% freshwater.*

3.2.2 Summer data

Summer salinity data can also be re-plotted as freshwater fraction (Figure 13). Similarly probability density functions (Figure 14) and cumulative probability curves (Figure 15) can be plotted. Other than in the outflow (Fort Point), freshwater fraction is below 5% at all sites (Figures 13 and 15).

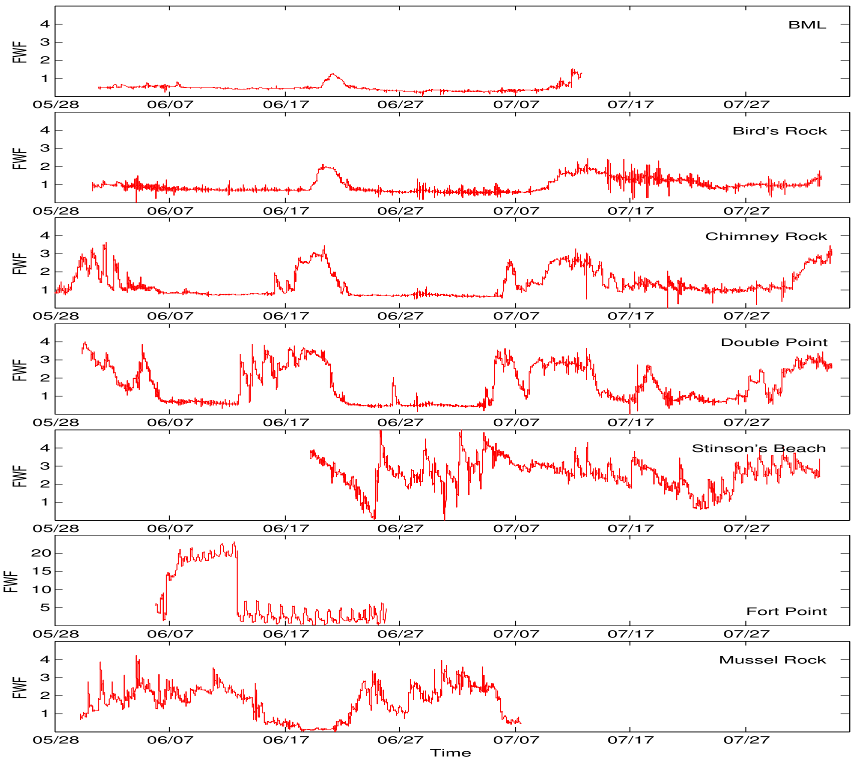

Figure 13. *Time series of freshwater fraction (Equation 1, with S_{oc}=34.0) for all sites in summer, given as a percentage for each of the eleven winter sites.*

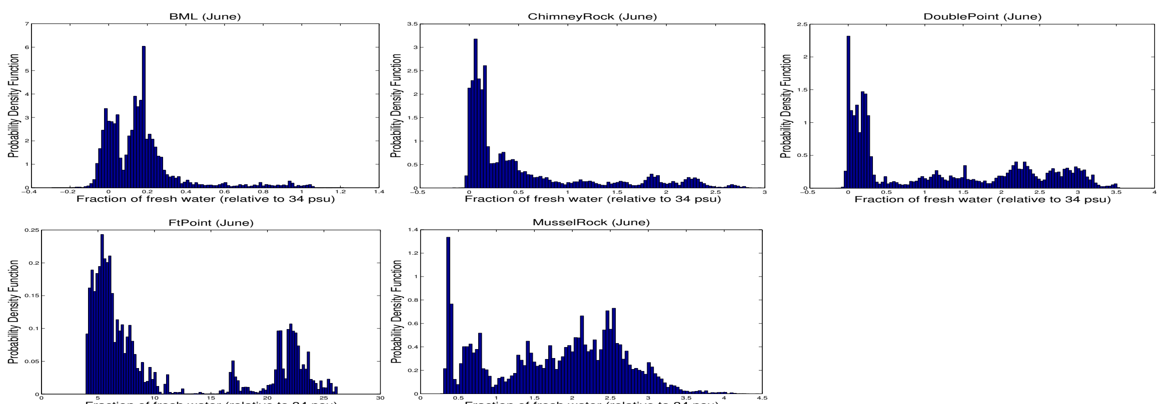

Figure 14. *Probability density functions for fraction of freshwater percentage at five sites in summer: BML, Chimney Rock, Double Point, Fort Point, and Mussel Rock.*

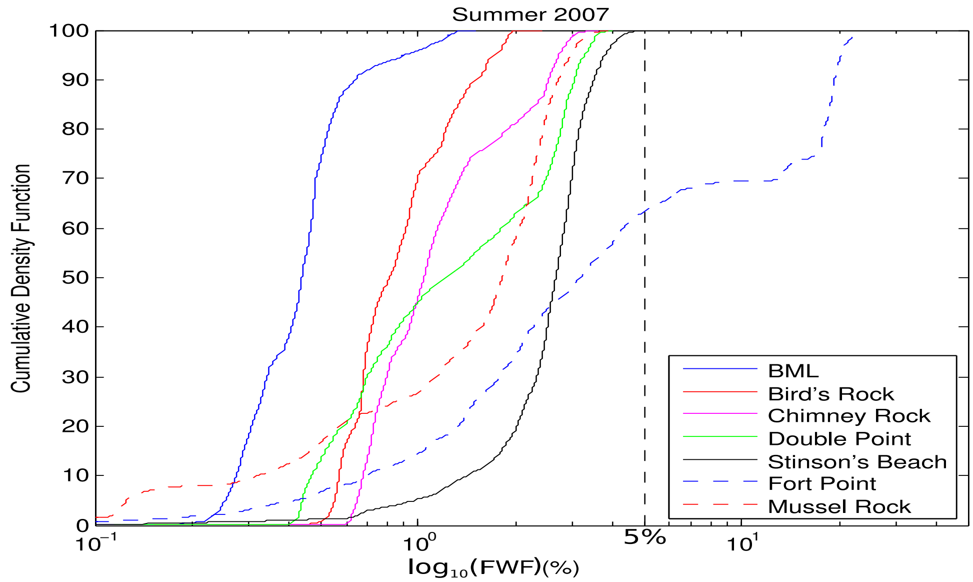

Figure 15. *Cumulative probability for fraction of freshwater – percent of time freshwater fraction is below a given level, e.g., Double Point site is never exposed to levels above 5% freshwater, but some freshwater influence (>3%) is seen 1/3 of time.*

3.3 Transport scenarios.

Combining the conceptual model outlined in Section 1, and the data shown in Section 3, it is clear that there are specific flow scenarios related to wind conditions that in turn determine the key transport scenarios: upwelling, relaxation and downwelling. With a longer time series that captures several of each type of events, one could develop characteristic statistics for each scenario. Here, with just one or two events of each kind, typical freshwater fraction values (i.e., plume dilution) are estimated more subjectively – see Table 1.

	Upwelling	Relaxation	Downwelling
	mid-Feb & late-Mar	*late-Feb & early-Mar*	*early-Feb*
BML	33.9	33.0	32.5
Bird R.	33.9	33.0	33.0
Chimney R.	33.9	32.0	32.0
Drakes Bay	33.9	32.0	32.0
Double Pt	33.9	31.0	32.0
Stinson B.	33.0	30.0	32.0
Fort Pt	32.0	22.0	30.0
Mussel R.	33.2	32.0	33.0
Fitzgerald	33.5	33.0	33.2
Pigeon Pt	33.7	33.2	33.2

Table 1. *Typical daily-minimum-salinity values for each site observed during upwelling, relaxation, downwelling events in winter. Maximum observed ocean salinity S_{oc} ~ 33.9*

4. PROJECTED POLLUTANT EXPOSURE

Pollutant concentration in Central Bay provides initial condition for outflow from San Francisco Bay. Salinity-based dilution model (Section 2) requires concurrent pollutant concentration and salinity in the outflow. For this preliminary assessment, we reviewed data available from USGS monthly cruises and also from the Regional Monitoring Program coordinated by SFEI. As an example, a scatter plot of ammonium levels versus salinity levels is shown in Figure 16 and a histogram plot from the CD3 database for the Regional Monitoring Program is shown in Figure 17.

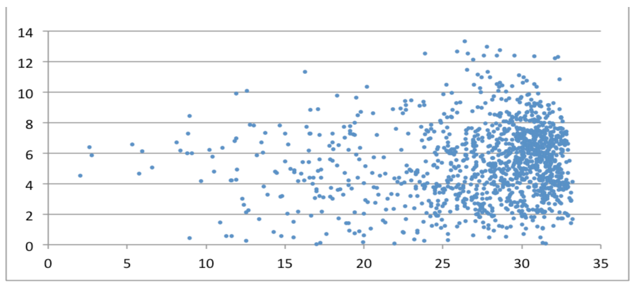

Figure 15. *Scatter plot of ammonium levels (µM) versus salinity for data collected in Central Bay. A representative value of S~30 waters is 6µM. Data from the CD3 database could not be cross-referenced to salinity values, but corroborated similar ammonium levels in Central Bay sampling.*

For the 4 primary nutrients (ammonium, nitrate, phosphate, silicate), we determined typical, high and low values in Central Bay waters as an estimate of likely concentrations in the outflow. Using equation (5), an apparent freshwater concentration is determined for each.

		Low	Typical	High
Ammonium	Central Bay (S~30)	2.0	6.0	8.0
	Apparent FW	18.2	54.5	72.7
Nitrate+Nitrite	Central Bay (S~30)	10.0	17.0	25.0
	Apparent FW	90.9	154.5	227.3
Silicate	Central Bay (S~30)	30.0	50.0	70.0
	Apparent FW	272.7	454.5	636.4
Phosphate	Central Bay (S~30)	1.5	2.8	4.5
	Apparent FW	13.6	25.5	40.9

Table 2. *Observed nutrient levels in Central Bay and calculated "apparent freshwater concentration" according to equation (5).*

The estimated pollutant levels at monitoring sites are obtained from the typical freshwater fraction and the apparent freshwater concentration (Table 2), following equation (5). The freshwater fraction is calculated from typical daily-minimum-salinity data (Table 1), using equation (1) and S_{oc}=33.7. For all scenarios where salinity equals or exceeds 33.7, it is interpreted as the presence of upwelled water (and absence of Bay waters). No estimates are made for Fort Point when observed salinities are lower than 30, which is the salinity used to obtained apparent freshwater concentration from Central Bay nutrient data.

		ESTIMATED AMMONIUM CONCENTRATIONS		
	Bay loading scenario	Upwelling events	Relaxation events	Downwelling events
	High	0.00	1.51	2.59
BML	**Typical**	**0.00**	**1.13**	**1.94**
	Low	0.00	0.38	0.65
	High	0.00	1.51	1.51
Bird Rock	**Typical**	**0.00**	**1.13**	**1.13**
	Low	0.00	0.38	0.38
	High	0.00	3.67	3.67
Chimney R.	**Typical**	**0.00**	**2.75**	**2.75**
	Low	0.00	0.92	0.92
	High	0.00	3.67	3.67
Drakes Bay	**Typical**	**0.00**	**2.75**	**2.75**
	Low	0.00	0.92	0.92
	High	0.00	5.83	3.67
Double Pt	**Typical**	**0.00**	**4.37**	**2.75**
	Low	0.00	1.46	0.92
	High	1.51	7.98	3.67
Stinson B.	**Typical**	**1.13**	**5.99**	**2.75**
	Low	0.38	2.00	0.92
	High	3.67		7.98
Fort Pt	**Typical**	**2.75**		**5.99**
	Low	0.92		2.00
	High	1.08	3.67	1.51
Mussel R.	**Typical**	**0.81**	**2.75**	**1.13**
	Low	0.27	0.92	0.38
	High	0.43	1.51	1.08
Fitzgerald	**Typical**	**0.32**	**1.13**	**0.81**
	Low	0.11	0.38	0.27
	High	0.00	1.08	1.08
Pigeon Pt	**Typical**	**0.00**	**0.81**	**0.81**
	Low	0.00	0.27	0.27

Table 3. *Estimated ammonium concentrations in the Gulf of Farallones based on Central Bay concentrations and dilution rates in the outflow plume from San Francisco. Shading indicates values that exceed 2.0 and 5.0 µM.*

Similar tables for other silicate, phosphate and nitrate illustrate the same spatial patterns, with highest levels within a tidal-excursion distance of the mouth of the Bay (Table 3) – north to Stinson Beach and south to Mussel Rocks. The impact is greater to the north during relaxation and downwelling conditions when high nutrient values may extend northward through the Gulf to Chimney Rock at Point Reyes. These scoping estimates are intended to identify places where high nutrient levels may be observed, and likely values, which can be the basis for discussion and further work.

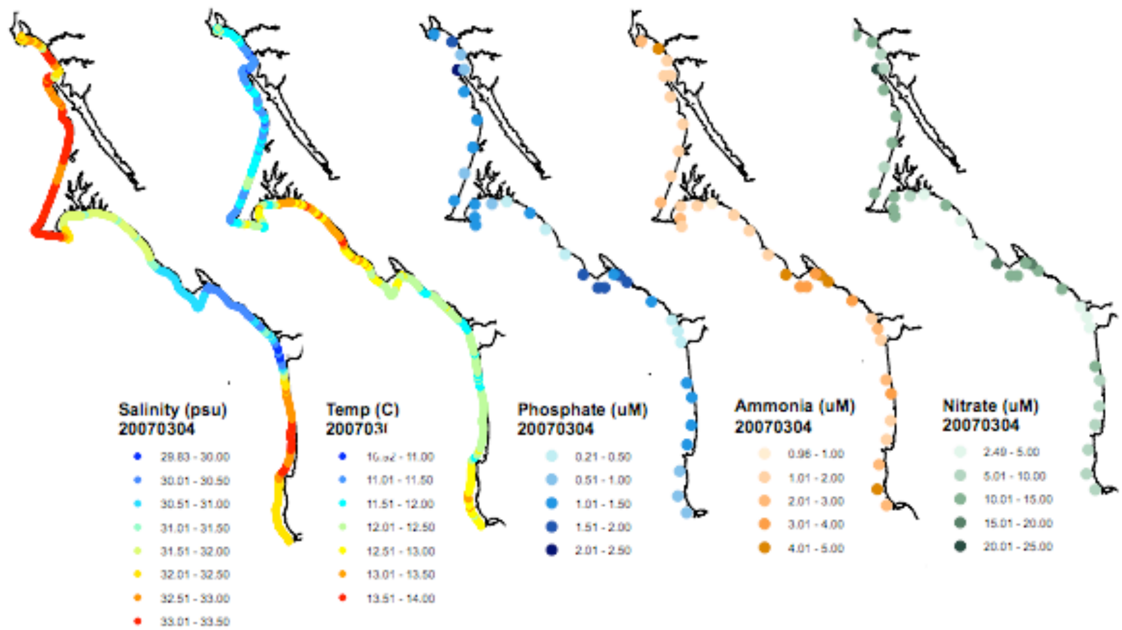

Figure 16. *Rapid underway sampling of nearshore nutrient concentrations on 4 March 2007, showing a high-ammonia zone north of the Bay mouth, as suggested by estimates reported in Table 3. This zone also exhibits high phosphate and nitrate values, all due to Bay outflow.*

By assuming conservative behavior at short times, one can look at nutrients but also other pollutants, e.g., metals. Figure 17 provides a distribution of copper values in Central Bay (collated from Regional Monitoring Program data). Similarly, the freshwater fraction method can provide estimates of copper levels along the open coast – assuming no rapid chemical reactions.

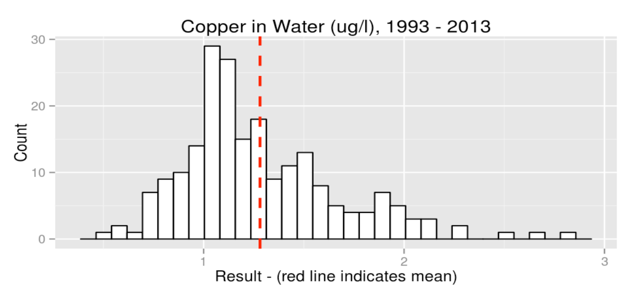

Figure 17. *Rapid underway sampling of nearshore nutrient concentrations on 4 March*

5. DISCUSSION OF CIRCULATION AND FRESHWATER EXPOSURE

The patterns of salinity and freshwater content – and thus potential pollutant exposure – can be understood in terms of water circulation in the coastal ocean off San Francisco Bay.

5.1 Tidal outflow

High levels of freshwater content and Bay pollutants are expected in a tidal outflow zone that extends from Golden Gate to beyond the bar, and with a tendency for northward tidal flow following tidal outflow, as illustrated in drifter tracks (Figure 18) and sea surface temperature data (Figure 19). This clockwise turning of tidal outflow is also seen in HF radar data in this region (Gough et al 2010).

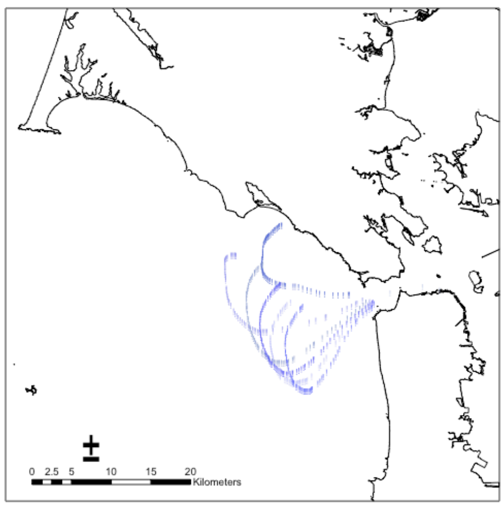

Figure 18. *Drifter positions shown as blue dots provide tracks for 5 drifters released immediately west of Golden Gate Bridge in November 2006 during an outflowing tide – following the westward jet flow, the drifters move north to Stinson Beach.*

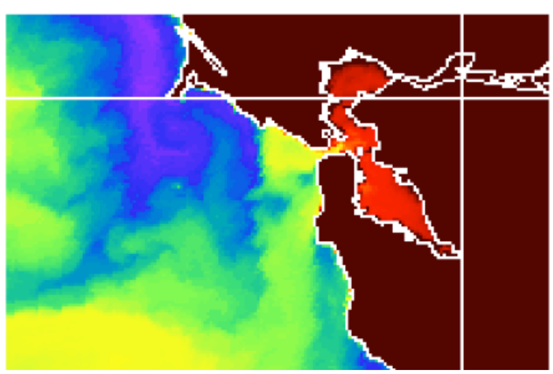

Figure 19. *Sea surface data showing the filling in of warm water north from Golden Gate to Stinson Beach, due to tidal flows.*

5.2 Gulf circulation in summer.

Beyond the tidal flow effects, Bay outflow is mostly advected away to the south by wind and current forcing, but held away from the coast by active upwelling along the shores south of the mouth of the Bay. However, for much of the summer period, an anti-clockwise circulation is observed in the northern Gulf driven by flow separation at Point Reyes and several other possible reasons. This circulation was evident during a drifter study in 2008 during calm winds, when the drifters closest to Stinson Beach were entrained in a northward flow up to Point Reyes (Figure 20). Other drifters have also exhibited this circulation (e.g., Kaplan & Largier 2006). This pattern is also evident in satellite imagery (Figure 2) and HF radar data on currents.

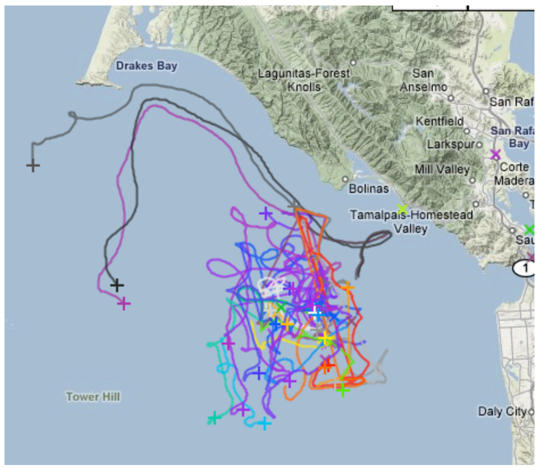

Figure 20. *Drifter tracks in Gulf of Farallones showing northward transport into Drakes Bay.*

Further, when upwelling winds stop, a relaxation flow transports Gulf waters northward past Point Reyes – and a general northward flow through the Gulf transports Bay outflows up to Point Reyes and around it. Low-salinity water is typically seen at Bodega Head 2-3 days after winds stop blowing (e.g., Largier et al 2006). These northward flows are observed in HFR data at Point Reyes (Figure 9) and in the Gulf (Gough et al 2010).

5.3 Gulf circulation in winter

In winter, the zone of impact increases and also extends more to the north. This is partly due to the increased runoff and the coriolis tendency for large-scale outflows to turn to the right in the northern hemisphere. And it is partly due to the southerly winds that drive string northward flows – but these winds also induce onshore Ekman transport, which holds the low-salinity waters close to the shore and reduces further dilution. A strong northward flow past Point Reyes and separation eddy is evident in satellite turbidity patterns (Figure 21) and also in HF radar data (Kaplan & Largier 2006). Drifters deployed at the mouth of San Francisco Bay on 25 January 2008 were recovered off Fort Bragg two days later. During the upwelling season in 1983, following heavy rains and concurrent with northward flow associated with an El Nino, the monthly mean salinity at Bodega Head was 30.5 – indicating a persistent northward transport in that year (Figure 22). In other years, there are several events during with similarly low salinity water (or lower) is transported from San Francisco Bay to Bodega Head, but usually less persistent.

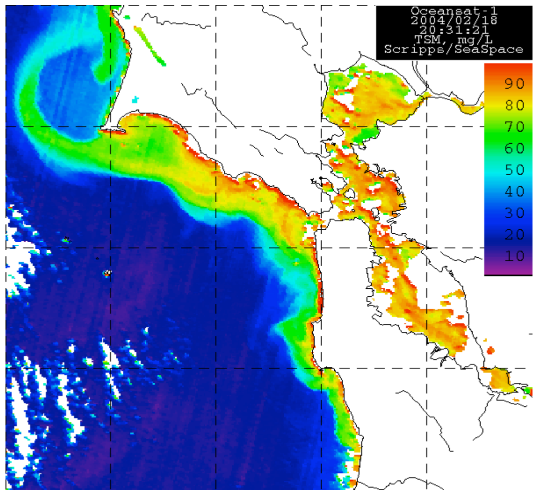

Figure 21. *Turbidity pattern outlining strong northward flow past Point Reyes during a winter storm on 18 February 2004.*

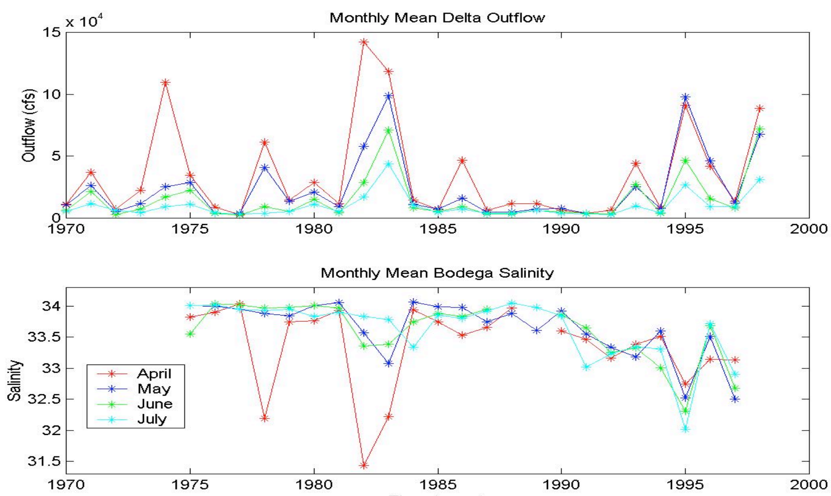

Figure 22. *Monthly mean Delta Outflow (upper panel) and monthly mean salinity at BML (lower panel) for months of April, May, June and July from 1970 to 1998.*

5.4 Seasonal and interannual variability in circulation

There is much oceanographic variability evident at seasonal and interannual time scales, but the best summary is provided by the 15-year record of surface flow past Point Reyes (Figure 23). Similar flows are expected through the outer Gulf. Southward flow is seen in spring and summer, with weak northward flow in fall and winter in some years. Given the tendency for offshore transport of plume waters when flow is southward, and onshore when northward, it is the northern Gulf and the coast north of Point Reyes that appears most exposed to outflows from San Francisco Bay.

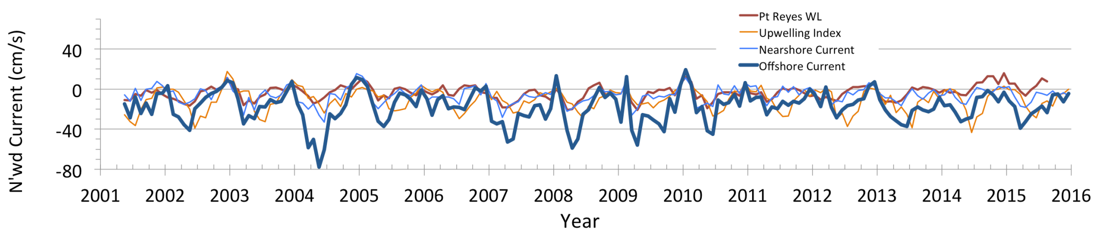

Figure 23. *Monthly average current flowing northward past Point Reyes. The heavy blue line indicates currents in waters far offshore, representing California Current. The fine turquoise line indicates currents in waters within several miles of the shore, which transports surface waters from the Gulf of Farallones to the north coast, as outlined here. During spring and early summer (March-July), flow is typically southward, but in fall the monthly mean is near-zero, indicating northward flow events being as likely as southward flow. In winter, northward flow may predominate, extending the Gulf zone of impact up the north coast.*

5.5 Coupling of the Gulf of Farallones with San Francisco Bay.

Outflow from San Francisco Bay may be retained in the northern Gulf, with retention times of a few days – based on drifter data and simple heat budget estimates. Also, retention of larvae in the northern Gulf has been addressed by Largier (2004). This is long enough for Bay nutrients to enhance primary production and phytoplankton blooms in the Gulf, which can subsequently be returned to the Bay. Although no published literature exists on Bay-Gulf coupling, over the last few decades there has been a growing appreciation that the northern Gulf may function as the outermost sub-embayment of the Gulf/Bay/Delta system – and the one part that remains little understood. While this report shows the outward linkage clearly, the plankton response and subsequent inward linkage requires a concerted effort.

Following Vander Woude et al (2006) and others, there is little doubt about the importance of the Gulf as a phytoplankton productivity and biomass hotspot. This is also evident in satellite data, e.g., June 2015 monthly mean sea surface temperature and chlorophyll (Figure 24).

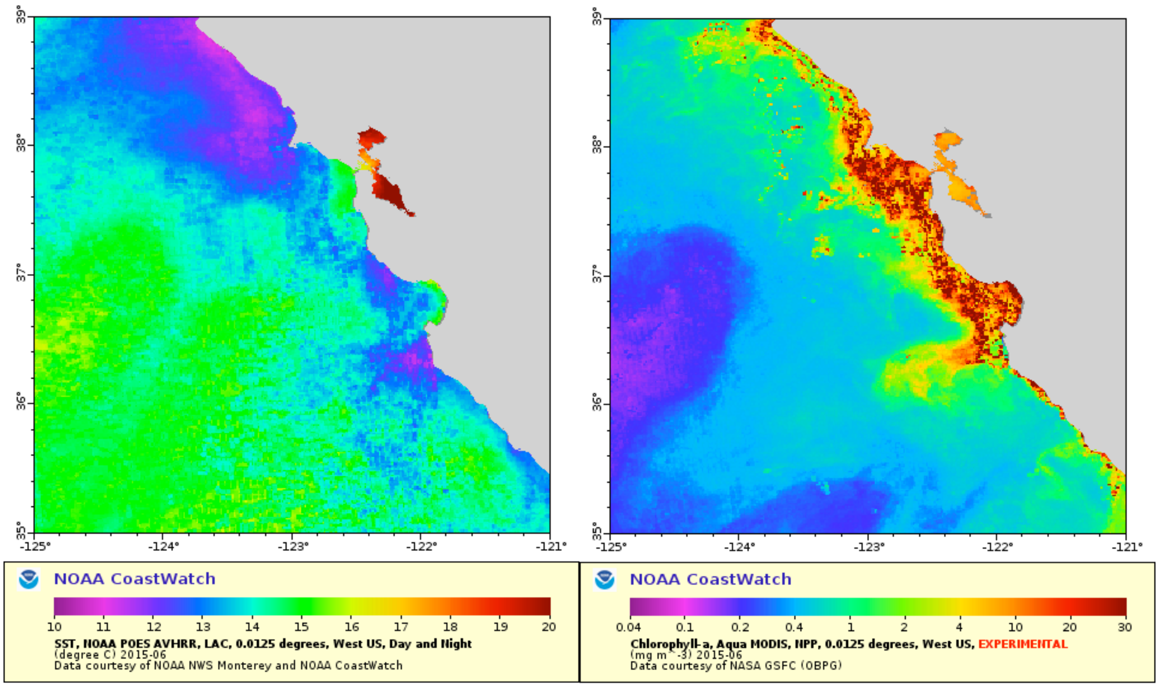

Figure 24. *Satellite sea surface temperature (left panel) and surface chlorophyll (right panel) averaged over June 2015.*

6. CONCLUSION

This study shows the value of using empirical data to determine the probability of exposure of open-coast shorelines to polluted outflow from San Francisco Bay. Key results include the greater exposure of the northern Gulf to Bay outflow and the clea differences between upwelling, relaxation and downwelling conditions.

This approach can be improved with longer-term data on salinity, which is easily obtained by deploying sensors, and concurrent sampling of pollutant levels and salinity in outflowing Bay waters. With more data in hand, a more statistical approach can be adopted, developing formal probability profiles for selected sites that in turn can be used to place limits on the concentration of pollutants in Bay outflow. The empirical approach has many advantages, including the possibility of tracking and reporting salinity and thus pollution risk in real-time.

In addition to monitoring directly, and development of an data-based management tool, outflow from the Bay can be modeled in a computer. There are several efforts underway that would be useful – specifically more recent model collaborations that include some biological/chemical reactions with water flow, transport and mixing. However, without a concerted data collection effort, modeling will provide mostly understanding of the system but may not be sufficiently constrained by data assimilation and validation to be useful as a forecast tool where small space and time scales matter.

Another empirical approach is to use HF radar data on surface currents, that are available hourly. Surface transport routes can be calculated in real-time using these HF radar data, yielding plume estimates continuously (as has been done for the Tijuana River plume in southern California).

More specific recommendations are best developed through dialog between researchers and managers, exchanging ideas on what is important and what is realistic. With this improved insight to the places and probability of pollutant impacts outside the Bay, our hope is that the ensuing dialog will be productive both for new insights and new operations.

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