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The potential influence of abiotic conditions on mussel species abundance in San Francisco Bay

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ABSTRACT

Climate change has negatively altered seawater conditions, which may have severe implications for marine ecosystems. Mussels are susceptible to environmental changes since they are primary consumers and filter-feeding bivalves. Two species of particular interest to the West Coast of the U.S. are *Mytilus galloprovincialis* and *M. trossulus*. *M. trossulus* is native to the California Coast and was historically prevalent from Southern California to Washington. However, with increased shipping and rising seawater temperature, *M. galloprovincialis*, an invasive species from the Mediterranean, pushed the species range of *M. trossulus* poleward. *M. trossulus* is more tolerant of cold seawater with variable salinity while *M. galloprovincialis* thrives in warmer, more saline water. Recent studies have shown zones of hybridization in Central California where both species co-exist. By understanding the dynamics of abiotic seawater conditions and how they have been altered by climate change, we can make better predictions of where *M. galloprovincialis* might take root next. Using publicly available data from NOAA, CeNCOOS, and SCOOS I characterized patterns in seawater temperature (ºC), salinity (ppt), oxygen concentration (mg O_2/L), and pH level at various sites throughout San Francisco Bay, CA from 2010 to 2020. My results show that San Francisco Bay is variable with site specific differences in salinity and temperature. Based on each species' environmental stress tolerance levels, *M. galloprovincialis* is likely the dominant species at Fort Point, Tiburon, and the East Bay, while *M. trossulus* is likely more prevalent at Carquinez.

INTRODUCTION

According to the Intergovernmental Panel on Climate Change (IPCC), as carbon emissions continue to rise so will global terrestrial and marine temperatures (Nakicenovic et al., 2000). In fact, by 2090 if current trends continue, ocean temperatures are predicted to rise by about 2.73°C (Bopp et al., 2013). In addition to rising ocean temperature, pH is predicted to drop by 0.33 pH units, oxygen saturation is predicted to drop by 3.45% (Bopp et al., 2013). Anthropogenic change of this magnitude will likely lead to a variety of negative consequences. (Bopp et al., 2013; Braby and Somero, 2006). Some of these consequences include poleward shifts in species' home ranges as global ocean temperatures warm up and thus allow organisms to move into regions previously outside of species' physiological limits (Cheung et al., 2009). These non-native encroaching species then begin competing with native species as they move further poleward (Cheung et al., 2009; Shien and Morgan, 2009). When non-native species successful dominate areas formerly dominated by native species, they become invasive and can cause all kinds of cascading damage within an ecosystem such as a loss in biodiversity as native species are displaced, consume different food sources, and cause over predation or overgrazing of certain species (Cheung et al., 2009; Dimitriadis et al., 2021).

While anthropogenic changes have been shown to adversely affect many different kinds of marine life, mussels are particularly vulnerable to climate change due to their immobile lifestyle, their role as filter-feeding primary consumers, necessity for a calcium carbonate ($CaCO_3$) shell, and their inability to filter out pollution from their environment (Azizi et al., 2017; Jakubowska and Normant, 2015). Because mussels are sessile organisms and cannot emigrate away from adverse conditions, they must be equipped to cope with a wide range of stressors in order to survive, making them great indicators of environmental change (Azizi et al., 2017). For example, mussels can be used to monitor heavy metal pollutants and point researchers to areas with industrial toxins that need to be remediated (Azizi et al., 2017). Because mussels require calcium carbonate ($CaCO_3$) to develop their shells, mussels also can indicate changes in pH and ocean acidity as these shells will be disfigured and weaker in environments with lower pH (Kurihara et al., 2008).

In particular, the relationship between blue mussels *Mytilus galloprovincialis* and *M. trossulus* on the Pacific Coast of the United States models the impacts of anthropogenic changes on mussels. The invasive *M. galloprovincialis* originating in the Mediterranean has been shown to be much more heat tolerant with a thermal limit between 26℃ – 31℃ and are adapted to stable high salinity conditions, while *M. trossulus* prefers colder temperatures with a critical limit between 23℃ – 27℃ and is able to tolerate lower salinity with more frequent oscillations (Braby and Somero 2006a; Somero 2012). *M. galloprovincialis* is better able to combat protein denaturation via heat shock proteins such as Hsp70 (Tomanek and Zuzow, 2010). Yet due to increased global shipping, warmer oceans and higher salinity *M. galloprovincialis* has successfully invaded the southern California coastline and has become prevalent as far north as Bodega Bay, CA displacing the native species *M. trossulus* (Lockwood and Somero, 2011). Currently the region from Monterey Bay to Bodega Bay is characterized as a hybrid region where both *M. trossulus* and *M. galloprovincialis* coexist and thus are ideal areas for investigating differences between each species (Lockwood and Somero 2011; Braby and Somero, 2006a; Braby and Somero, 2006b).

One hybrid site of particular interest is San Francisco Bay. Not only is San Francisco Bay a major global shipping hub, but it also has numerous microclimates making it ideal for better understanding which species might be more or less successful under a variety of conditions

(Braby and Somero 2006b). While there is an abundance of research on how water temperature and salinity affect mussel survival, few consider pH, and oxygen concentration and none to our knowledge consider how all four variables impact population distributions. Therefore, in this study we will characterize water temperature, salinity, pH, and oxygen concentration at two sites within the San Francisco Bay in order to construct a more complete understanding of the abiotic trends in this area and then use these analyses to predict which species will be more or less successful within San Francisco Bay. [insert your hypotheses here. And then finish with 1 sentence as the why this research is important]

METHODS

The data for this study was collected from publicly available research stations managed by National Oceanic and Atmospheric Administration (NOAA) and the Central and Northern California Ocean Observation System (CeNCOOS). The data was downloaded in csv. files and manipulated in excel. The time period analyzed began on May 19th 2010, and continued to May 18th, 2020. The locations selected for data acquisition were chosen due to their position throughout the San Francisco Bay as well as the type of sensors the stations were equipped with (Figure 1).

The data collected from NOAA included water temperature (°C) at the Redwood City Station. CeNCOOS data stations include the SFSU Carquinez Station, the SFSU Tiburon Station, the Fort Point Station and the DMB Station. Water temperature (°C), salinity (ppt), pH, and dissolved oxygen concentration (mg of O_2/L) data were collected from SFSU Carquinez Station and SFSU Tiburon station. At Fort Point only water temperature (°C) and salinity (ppt) data were available and at DMB station only salinity data was collected. Redwood city and the DMB station were grouped together to estimate the water temperature and salinity of the larger East

Bay region. This was necessary because the Redwood City station from NOAA only had water temperature data but no salinity data. To supplement this gap, data from the DBM station was used in conjunction with the Redwood City water temperatures. However, it is important to note that DMB only collected salinity from 2006 – 2009 as the salinity sensor was either removed or damaged after 2009. There are no other salinity sensors in the East Bay and thus we were forced to use DMB as a best approximation of current salinity measurements. The water temperature (°C) at each station was measured hourly (both NOAA and the CeNCOOS). The pH, salinity (ppt), and oxygen concentration (mg of O_2/L) were measured every 6 minutes for ten years (CeNCOOS). Additionally, some stations had data gaps due to sensor damage or maintenance and therefore in some instances data is not continuous for the 10-year period.

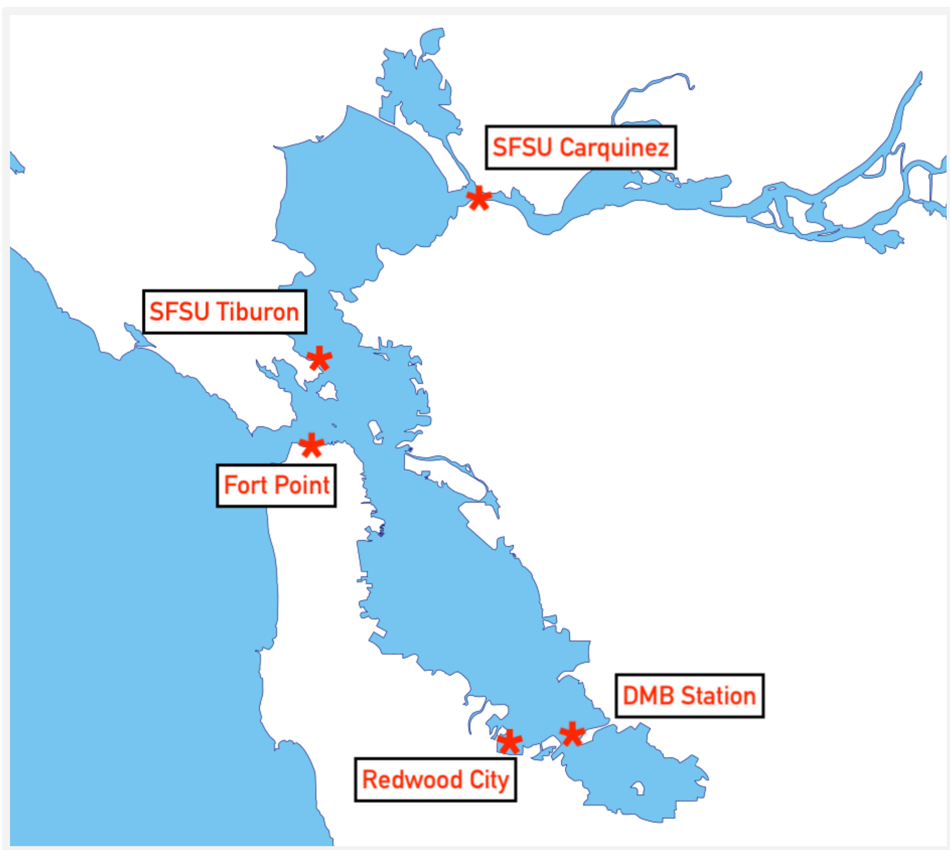


Figure 1: Map of the five CeNCOOS and NOAA data station locations distributed throughout San Francisco Bay. The water temperature (°C) was measured hourly while water pH, salinity (ppt), and oxygen concentration (mg of O_2/L) were measured every 6 minutes for ten years.

Analysis: All abiotic parameters were visualized using scatter plots in Excel. For all abiotic parameters we calculated mean, standard deviation, maximum and minimum values for the 10-year period.

RESULTS

SFSU Tiburon Station: Water temperature averaged approximately 14.9 °C over the ten-year period analyzed. SF Tiburon Station had modest seasonal temperature variation ranging with a standard deviation of ±3.29°C and range of approximately 7°C in the winter and all the way to 50°C in the summer. Salinity fluctuations included conditions reaching lower than 9 ppt a total of 22,249 times over ten years and maximum of 33.23 ppt, while the average salinity remained at 25.8 ppt. The ten-year pH average was 7.91 and the oxygen saturation averaged 7.81 mg O_2/L (Table 1, Fig. 2).

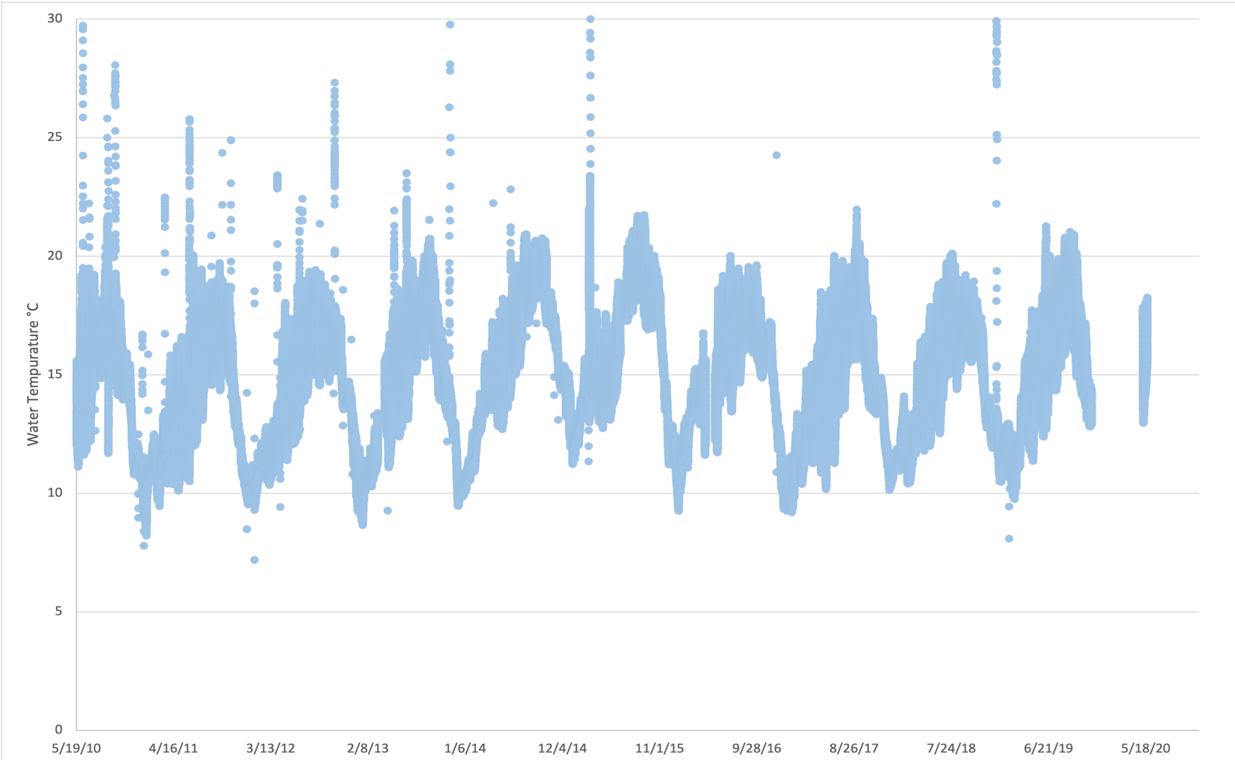
SFSU Carquinez Station: The average water temperature at the Carquinez station was similar to the Tiburon station (16.3°C) but Carquinez had a broader temperature range with a minimum near 6°C and a maximum around 24°C. Salinity was dramatically different from Tiburon, dropping lower than 9 ppt a staggering 152,343 times in ten years and then also peaking at 43.6 ppt with an average 14.8 ppt. Average pH is also depressed compared with the Tiburon station, averaging 7.54 pH units while oxygen concentration was slightly higher than Tiburon at 8.24 mg of O_2/L. Additionally, there are some extreme outliers displayed in these graphs likely due to sensors not working properly or being miscalibrated (Fig. 3 & Table 1).

Fort Point Station: Fort point was the coldest location averaging 13.5 °C over the ten-year period studied. It also showed least variability ranging from approximately 0°C to 54.69°C. Fort Point Station had the highest salinity averaging 28.5 ppt with a maximum salinity of 33.05

ppt. No pH or oxygen concentration data was available at Fort Point and therefore was not included (Fig. 4; Table 1; Table 2).

East Bay: For the East Bay region, Redwood City had the highest average water temperature in the San Francisco Bay at 17.8°C (±4.08). Water temperature was also highly variable between winter and summer ranging between 8.2°C - 25°C. DMB also showed a high average salinity at 25.1 ppt and reaching a maximum of 33.97ppt (Fig. 5; Table 1; Table 2) However, because the only salinity data available from the DBM station was collected between 2006-2009, these descriptive are likely an underestimate of current salinity measurements.

A.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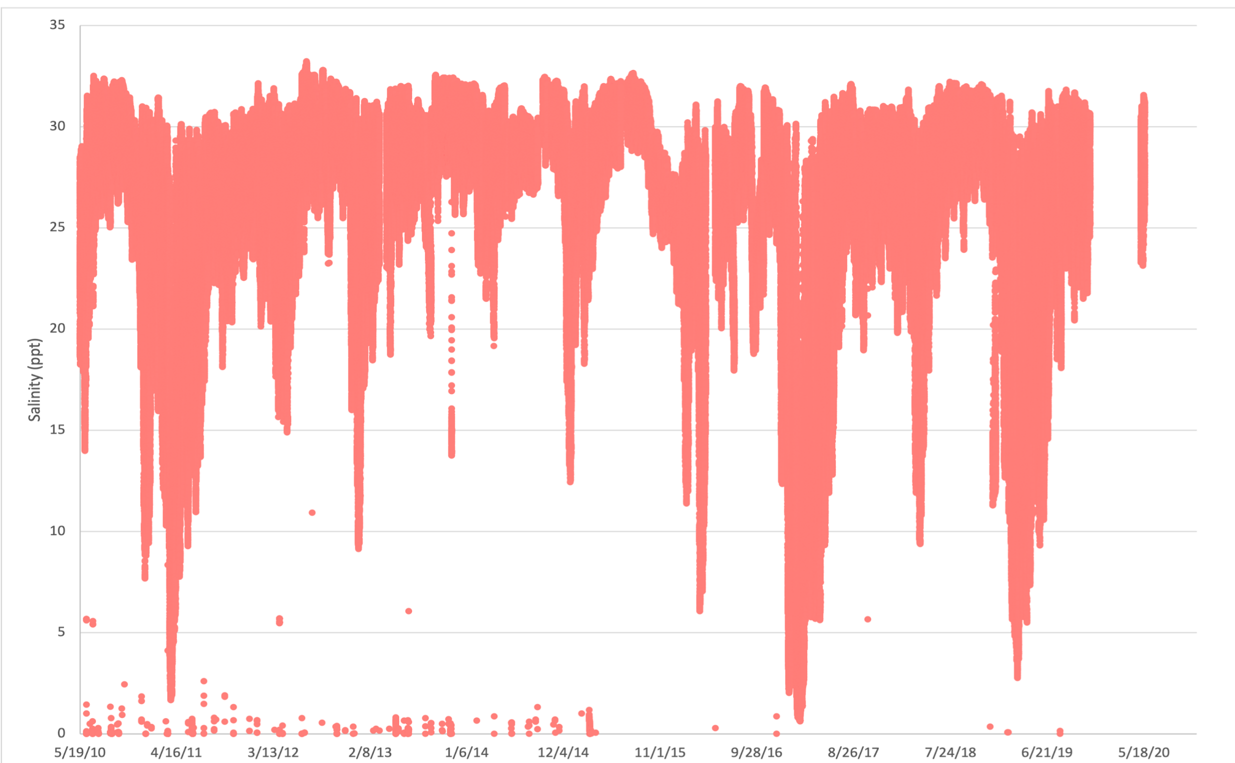
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Salinity (ppt)
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C.

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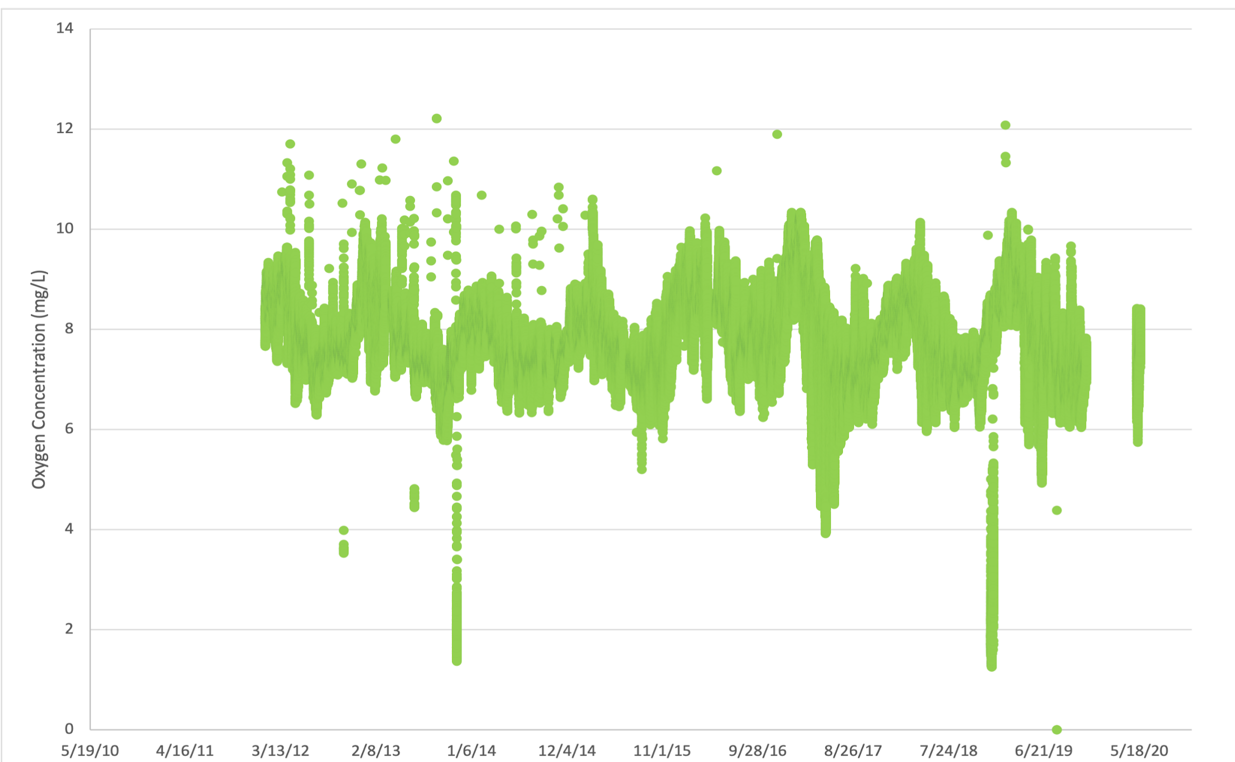
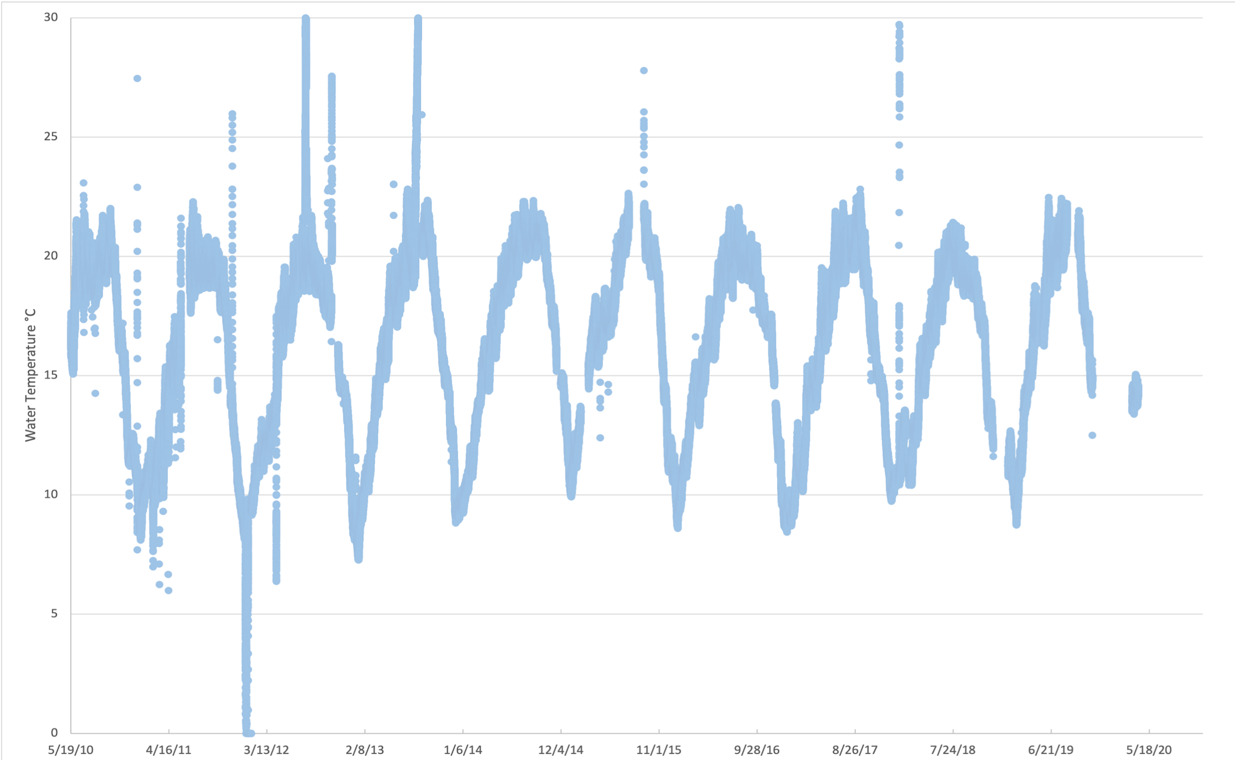


Figure 2: Water temperature (ºC) (A) salinity (ppt) (B), pH (C) oxygen concentration (mg O_2/L) (D) data from the SFSU Tiburon station between May 2010 - May 2020. Data was obtained from online databases CENCOOS (https://data.cencoos.org/#metadata/103547/station).

A.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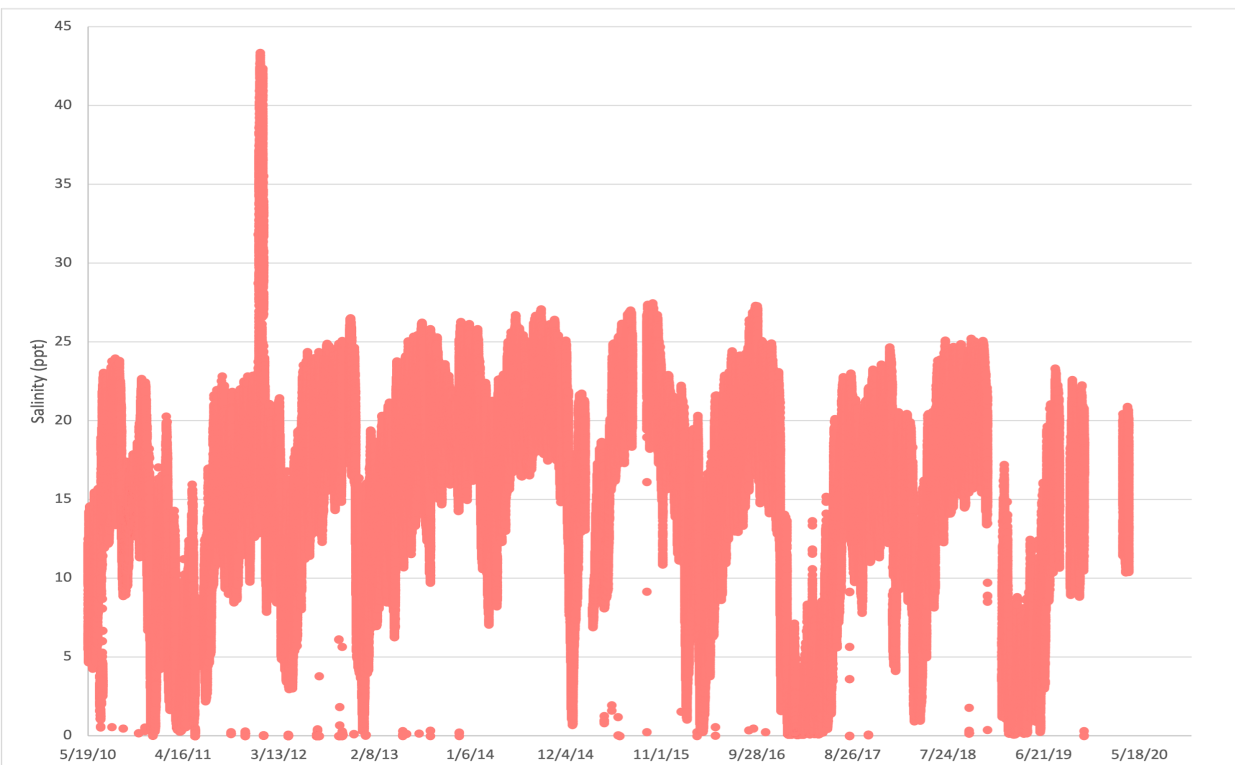
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Salinity (ppt)
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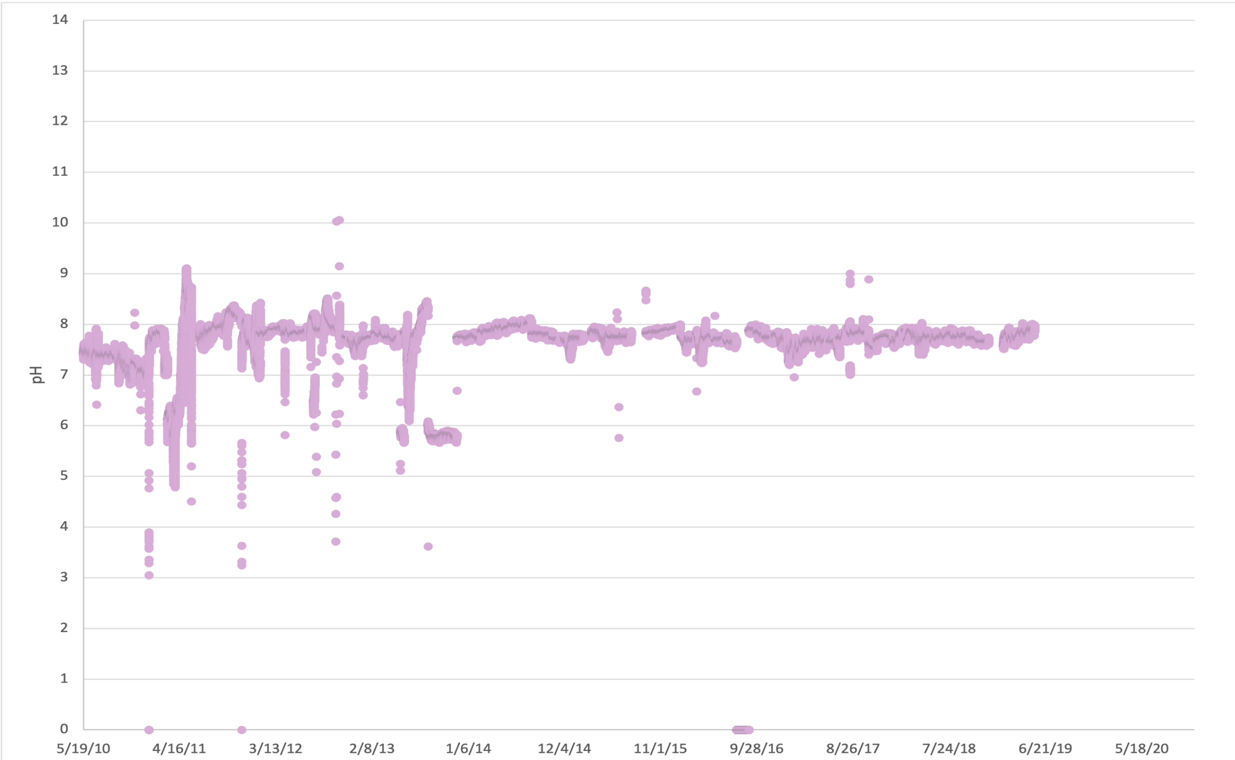
C.



D.

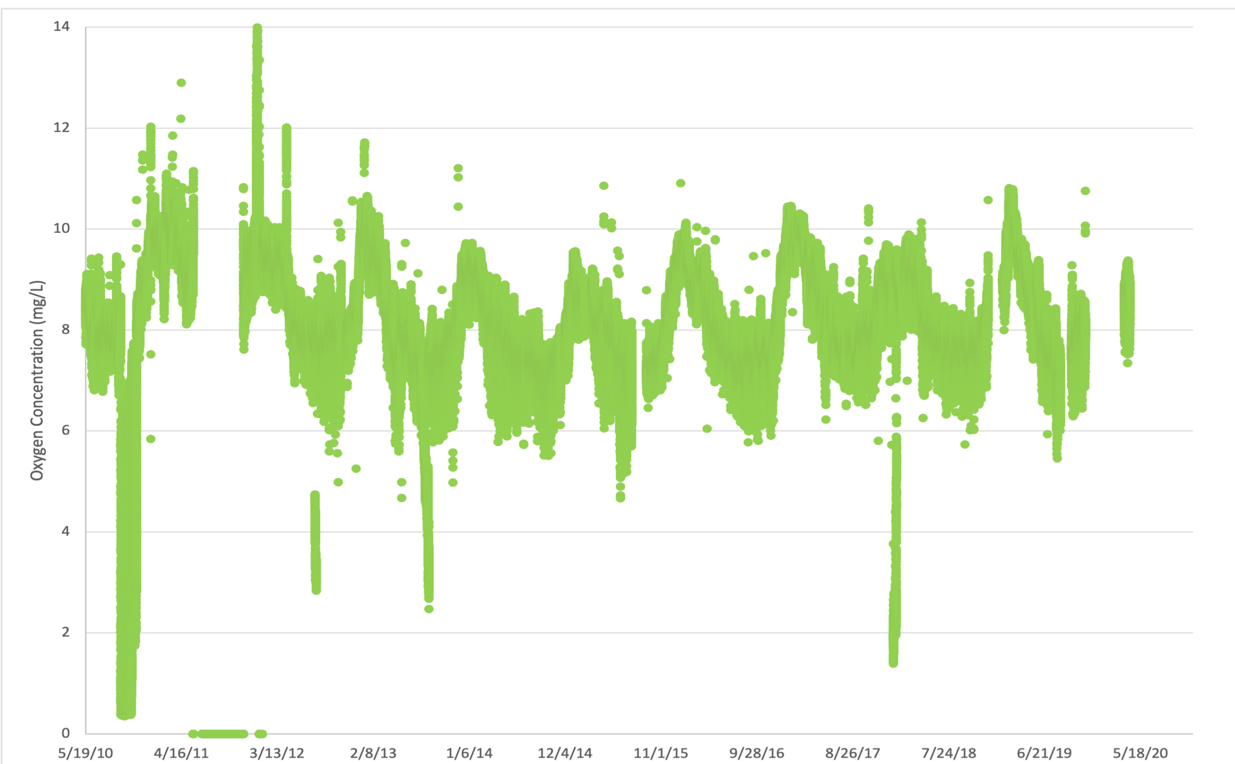
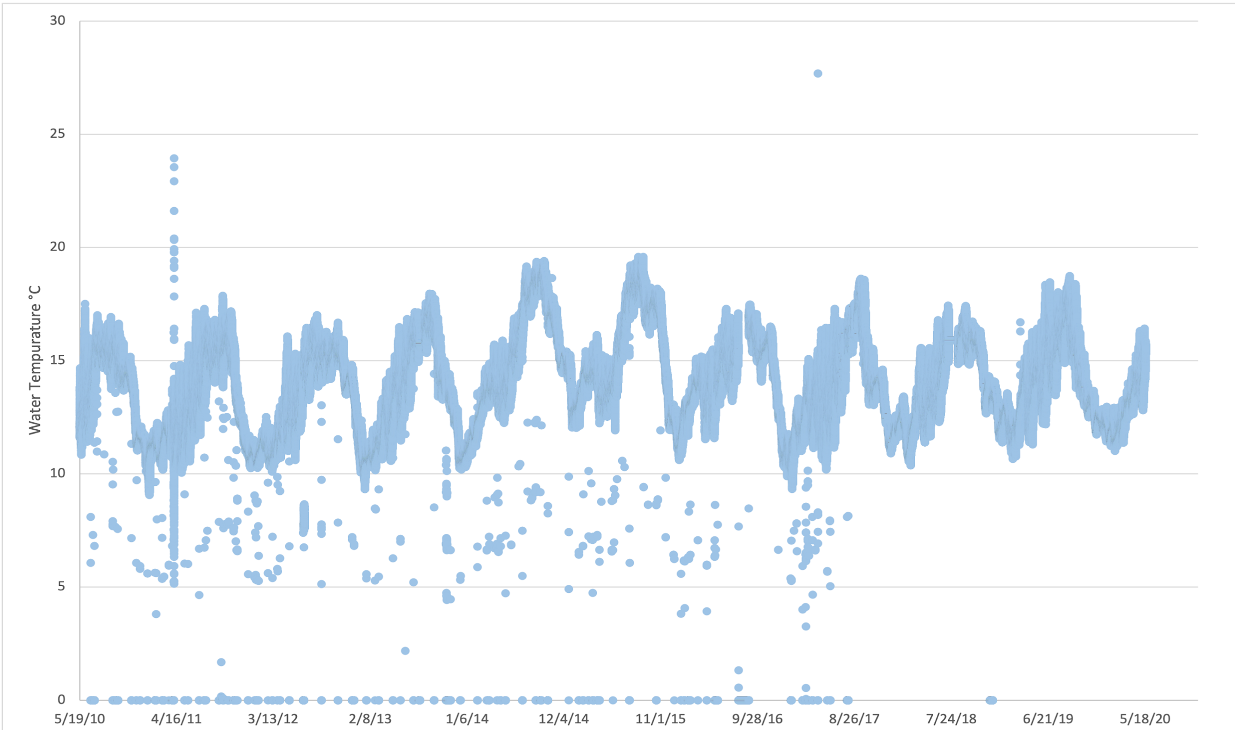


Figure 3: Water temperature (ºC) (A) salinity (ppt) (B), pH (C) oxygen concentration (mg O_2/L) (D) data from the SFSU Carquinez station between May 2010 - May 2020. Data was obtained from online databases CENCOOS (https://data.cencoos.org/#metadata/103546/station).

A.



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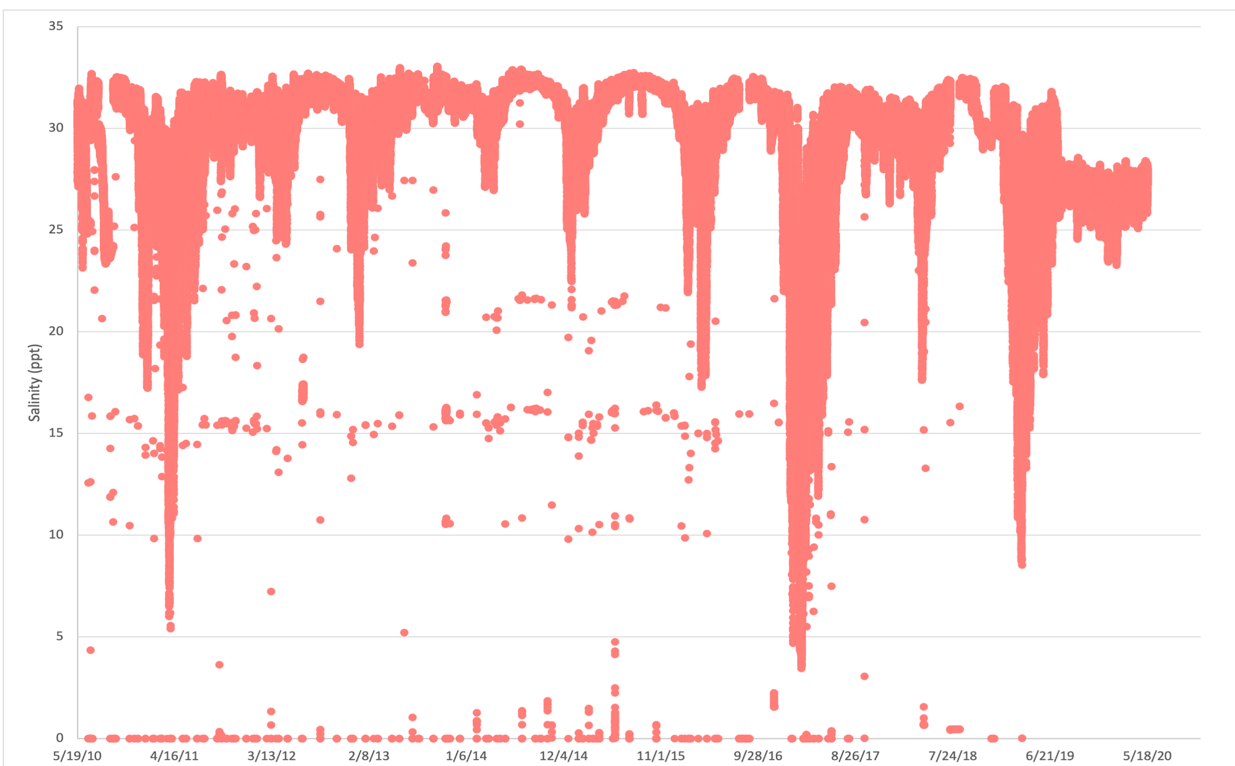
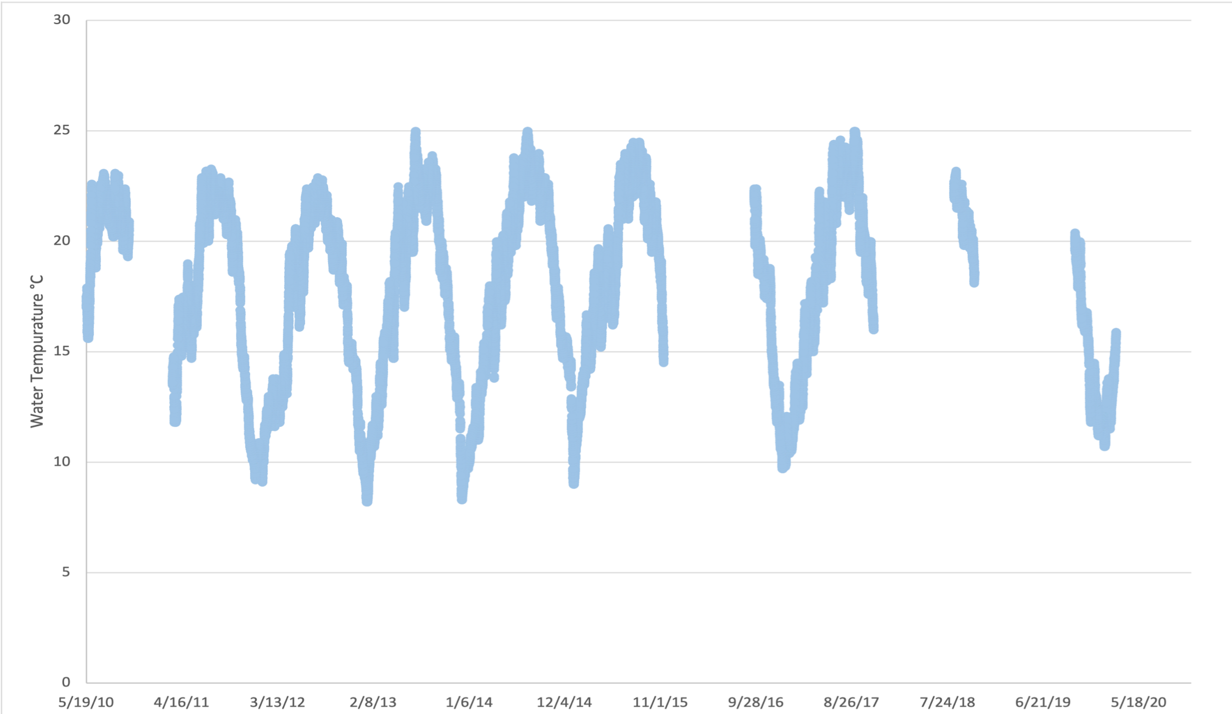


Figure 4: Water temperature (ºC) (A) salinity (ppt) (B), data from Fort Point between May 2010 - May 2020. Data was obtained from online databases CENCOOS (https://data.cencoos.org/#metadata/19947/station).

A.



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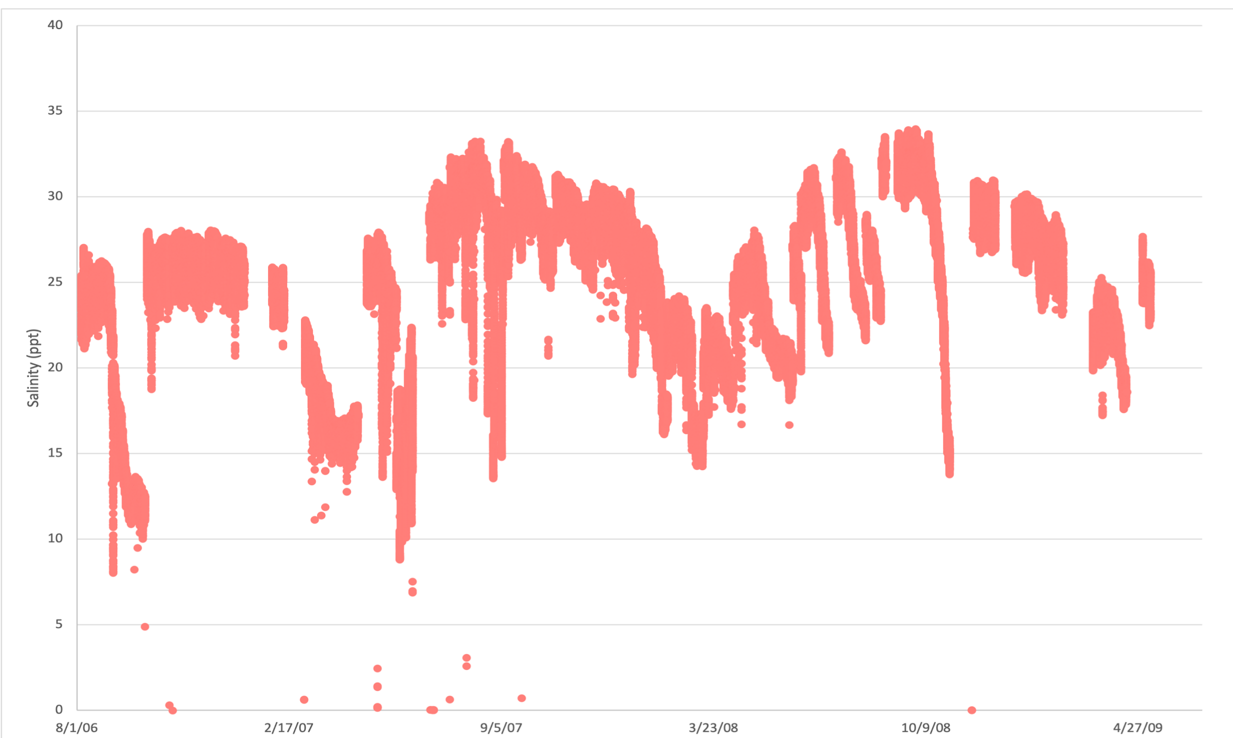

Figure 5: Water temperature (ºC) (A) at Redwood City (Station ID: 9414523) between May 2010 - May 2020 and salinity (ppt) (B) at the DMB station between 2006 – 2009. Data was obtained from online databases NOAA Tides and Currents (https://tidesandcurrents.noaa.gov/stationhome.html?id=9414523) and CENCOOS (https://data.cencoos.org/#metadata/20584/station).

Table 1: Descriptive statistics for water temperature (ºC), salinity (ppt), pH, and oxygen concentration (mg O_2/L) at each station location with standard deviation. In some instances no data was available and is indicated by nd.

Station	Avg. Water Temp (°C)	Avg. Salinity (ppt)	Avg. pH	Avg. Oxygen Concentration (mg/L)
SFSU Carquinez	16.29 (±4.45)	14.82 (±6.45)	7.54 (±1.02)	8.24 (±1.54)
SFSU Tiburon	14.89 (±3.29)	25.83 (±5.90)	7.91 (±0.33)	7.81 (±0.84)
Fort Point	13.53 (±2.99)	28.53 (±6.43)	nd	nd
Redwood City	17.77 (±4.08)	nd	nd	nd
DMB	nd	25.08 (±4.88)	nd	nd

Table 2: Minimum to maximum values for water temperature (ºC), salinity (ppt), pH, and oxygen concentration (mg O_2/L) at each station location. In some instances, no data was available and is indicated by nd.

Station	Min - Max Temp	Min - Max Salinity	Min - Max pH	Min - Max O_2
SFSU Carquinez	[0 – 50.00]	[0 – 43.36]	[0 – 10.06]	[0.36 – 40.01]
SFSU Tiburon	[7.20 – 50.00]	[0 – 33.23]	[0 – 14.00]	[0 – 12.22]
Fort Point	[0 – 54.69]	[0 – 33.05]	nd	nd
Redwood City	[8.20 – 25.00]	nd	nd	nd
DMB	nd	[0 – 33.97]	nd	nd

DISCUSSION

The purpose of our study was to characterize the abiotic conditions of San Francisco Bay and then use these measurements to make predictions about the distribution of *M. trossulus* and *M. galloprovincialis* throughout the Bay. We found that over the ten-year study period, the Carquinez station had the lowest average salinity at 14.82 ppt (± 6.45 ppt) and a fairly high average water temperature of 16.29°C (±4.45°C) (Table 1). While both the average temperature and average salinity are within the physiological limits of each species — *M. trossulus*: 23.0°C & 9.5 ppt and *M. galloprovincialis:* 26.0°C & 9.0 ppt — (Braby and Somero 2006a) the extreme changes in salinity (drops to nearly 0.0 ppt) and temperature (increases beyond 30ºC) make this San Francisco Bay region highly stressful for *Mytilus* mussels. Thus, it is unlikely that either species would be found in high abundance due to their physiological limits. However, we anticipate that *M. trossulus* may still be slightly more successful here due to their ability to better cope with extreme hypo-osmotic stress (Braby and Somero 2006a; Lockwood and Somero 2011). One study showed that *M. trossulus* maintained a higher average heart rate (13.95 beats/min) compared to *M. galloprovincialis* (11.21 beats/min) all the way until the salinity critical point (S_{crit}) around 9 ppt (Braby and Somero 2006a). Researchers theorize this elevated heart rate may allow *M. trossulus* to respond to acute salinity stress quicker than *M. galloprovincialis* by closing their shells earlier and thus isolating their internal fluids from the hypoosmotic environment (Braby and Somero 2006a). There is also speculation that an increased heart rate affects Mitogen Activated Protein Kinase activity (MAPKs) (Lockwood Somero 2011). MAPKs are responsible for substrate level phosphorylation and have been shown to increase cell survival in a variety of pathways such as upregulation of heat shock proteins, cell growth, and the inhibition of apoptosis (Evans and Somero 2010; Lockwood Somero 2011). Thus if *M. trossulus* is able to maintain a heart rate greater than *M. galloprovincialis* during hypoosmotic stress, substrate phosphorylation will also be elevated and thus *M. trossulus* will be able to better cope with the osmotic stress than *M. galloprovincialis*. Additionally, despite the Carquinez location being the second warmest location in the bay and seemingly favoring *M. galloprovincialis*, salinity has been shown to have a greater impact on distribution and survival than temperature differences (Braby and Somero 2006a).

Our data suggest that in the East Bay, the distribution of both mussel species is likely flipped, favoring *M. galloprovincialis* over *M. trossulus* due to both the high average salinity and high average water temperature. Here the average water temperature was 17.77°C (±4.08°C) and the salinity was 25.08ppt (±4.88ppt) (Table 1). While these averages are fairly moderate and are within the bounds of each species, the seasonal fluctuation between temperature and salinity is what also makes this location so physiologically stressful. In Redwood City, the surface temperature reached *M. trossulus's* limit of 23.0°C a total of 1571 times in the ten years, whereas it never reached beyond *M. galloprovincialis's* limit of 26.0°C (Fig. 5). This heat stress paired with high salinity strongly favors *M. galloprovincialis* survival over *M. trossulus*.

Fort Point Station and the SFSU Tiburon station are more difficult to characterize. Both of these stations had lower average temperatures at 13.53°C (±2.99°C) and 14.89°C (±3.29°C) and normal average salinities of 28.53 ppt (±6.43 ppt) and 25.83 (±6.15), as well as less extreme seasonal variability indicating both species could survive within the region (Table 1, Table 2). This is where additional factors such as basal thread strength and growth rates can help to further define species distributions (Newcomb 2015; Shien and Morgan, 2009).

Beyond heart rate and metabolic rate, increased temperatures have been shown to reduce the basal thread strength of multiple *Mytilus* species (Newcomb 2015). *M. trossulus* has been shown to have thinner basal thread strength than other *Mytilus* species such as *M. californianus* and *M. galloprovincialis* (Ball and Gosline, 1997). When water temperature surpasses 18°C this difference is disparity is further exacerbated as one study found that *M. trossulus* threads are not only 93% weaker than those of *M. galloprovincialis*, but also that *M. trossulus* produces fewer byssal threads when under heat stress (Newcomb 2015). This is particularly concerning to rocky intertidal areas which are constantly berated with waves. Experimental data shows that if the wave velocity exceeds 10 m/s the probability of *M. trossulus* dislodgment can be up to 0.65 and significantly decrease the chance of survival for *M. trossulus* (Ball and Gosline 1997). Thus, at locations such as Fort Point and Tiburon which are located closer to the mouth of the San Francisco Bay, there may be fewer *M. trossulus* simply because these locations are exposed to greater wave force than mussels residing in more protected sites such as Redwood City.

Growth rates may also have effects on distributions between these two species. *M. galloprovincialis* is known to grow quicker and larger than native *M. trossulus,* as well has been shown to clump together crowding out the more solitary *M. trossulus* (Shien and Morgan, 2009). One study tried to understand these relationships by investigating the competitive hierarchy between *M. trossulus*, M. *galloprovincialis*, and *M. californianus*. The experiment was set up with three treatments groups: Each species by themselves, two species mixed together, and all three species mixed together. Results showed that percent survival and per capita growth rate were very comparable between all treatments except when *M. trossulus* was mixed with *M. galloprovincialis*. In this treatment the percent survival and per capita growth rate of *M. trossulus* dropped significantly from about 95% survival to 70% survival and from 2.5 (µm/d) to less than 1 (µm/d), respectively, indicating that *M. galloprovincialis* is negatively affecting the survival of *M. trossulus* (Shien and Morgan 2009). Furthermore, within these polycultures it was found that *M. trossulus* emigrated the most frequently from the clumps of mussels and preferred to be dispersed from one another. This has direct effects on dislodgment probability. When *M. trossulus* is living in a tight bed experiencing a wave velocity of 10 m/s it is estimated that the dislodgment probability is approximately 20%, however when these mussels are alone and emigrate away from the mussel bed the risk of displacement jumps to 65% (Bell and Gosline, 1997). Therefore, not only do *M. trossulus* have thin basal threads that are getting even weaker with increasing water temperatures, but this dispersive behavior further reduces their fitness for survival in the intertidal zone. These competition mechanisms reinforce the likelihood that *M. galloprovincialis* will be the dominant species at Fort Point and Tiburon.

The next step is then to verify these distribution predictions by collecting samples from each station. Genomic analysis of these samples will allow for reliable distinction between the two species and thus determine if these predictions are accurate. Additionally, while oxygen concentration and pH data were collected in this study, both Tiburon and Carquinez locations had such similar averages it is difficult to attribute differences in the distribution of *M. galloprovincialis* and *M. trossulus* with these abiotic factors. Future studies investigating the effects of acidification and anoxia might be better studied in a laboratory setting where extreme pH and low oxygen concentration can be easily manipulated while also controlling for confounding variables such as salinity and water temperature and wave force.

In conclusion we found three major results: The Carquinez Station is unlikely to have a high abundance of either species, but may slightly favor *M. trossulus* due to very low salinity. The East Bay region will likely be dominated by *M. galloprovincialis* due to consistently high salinity as well as high surface temperatures. Fort Point and Tiburon Stations are more nuanced as abiotic conditions alone are favorable for both species. Yet because *M. trossulus* has thinner/weaker basal thread, prefers to be solitary or in small aggregates, and does not grow as large, *M. galloprovincialis* will likely dominate these two areas.

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