RELATIONSHIPS BETWEEN FRESHWATER DISCHARGE, SALINITY, AND LARGE-SCALE CLIMATE PATTERNS IN GALVESTON BAY, TEXAS

An Undergraduate Research Scholars Thesis

by

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RESEARCH COMPLIANCE CERTIFICATION

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This project did not require approval from the Texas A&M University Research Compliance & Biosafety office.

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ABSTRACT

Relationships Between Freshwater Discharge into Galveston Bay and Large-Scale Climate Patterns

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Freshwater input into an estuary is one of the most important factors that affect various aspects of the estuarine ecosystem. The goal of this study was to develop a correlation of the variations of climatic patterns to annual river discharge levels and salinity regimes, and to denote the differences in dry versus wet years in Galveston Bay. This was accomplished through a time-series analysis developed in R-studio of freshwater discharge data from the US Geological Survey (USGS), the salinity data from the Texas Water Development Board's (TWDB's) Water Data for Texas, and National Oceanic and Atmospheric Administration's (NOAA's) climate indices. Data was collected and run through a series of regressions to develop the average salinity, freshwater discharge, and El Niño/La Niña Southern Oscillation (ENSO) and Atlantic Multidecadal Oscillation (AMO) index values that were then denoted as "normal conditions"

during analysis from which comparisons could be made. I hypothesized the following: 1) higher rainfall and thus more freshwater discharge into Galveston Bay will be seen in times of El Niño and opposite trends will be shown in La Niña, and 2) positive AMO conditions to correspond to trends of higher precipitation, and the reverse shown for negative trends in AMO. This understanding will aid in the prediction of ecological and biophysical responses of the Galveston Bay estuary due to climate change. Current analysis indicates that significant correlation exists between freshwater discharge and salinity values around regionally around the bay. A similar correlation between discharge and the climate indices has been found, leading us to conclude that, climate regimes are important factors in predicting the ecological and biophysical responses in Galveston Bay. However, local factors have larger impacts on the observed scale. I hope that further analysis will be carried out to finalize the relationship between the three factors and develop a model of Galveston Bay.

DEDICATION

To my friends, mentors, families, faculty and peers who supported us throughout the research process. I could not have achieved this without you.

ACKNOWLEDGEMENTS

Contributors

I would like to thank my faculty advisors, Dr. Park and Dr. Kaiser for their guidance and support throughout the course of this research.

Thanks also go to my friends and colleagues and the department faculty and staff for making my time at Texas A&M University a great experience.

Thank you to my family for their encouragement and love in my academic path to pursue my degree.

And finally, a huge thank you goes to my colleague and friend Paul Goza for all the work he did with the climate indices and data analysis. I wish him nothing but success in his journey in both academia and career.

The data analyzed/used for Relationships Between Freshwater Discharge into Galveston Bay and Large-Scale Climate Patterns were provided by Dr. Park and Dr. Kaiser from the USGS databases, the Texas Water Development Board's Water Data, and NOAA's Climate indices. The analyses depicted in Relationships Between Freshwater Discharge into Galveston Bay and Large-Scale Climate Patterns were conducted in part by Department of Marine Sciences and are currently unpublished.

All other work conducted for the thesis was completed by the student independently.

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No funding was awarded or received for this project.

1. INTRODUCTION

1.1 Freshwater Discharge

In the global hydrological cycle, water is perpetually moved throughout various components of the global system. One of the components to this cycle is freshwater discharge, which is the movement of freshwater from land into the oceans. The freshwater discharge is controlled by many factors such as temperature or weather (Labat, 2010). One important freshwater source is river discharge, through which continental-derived materials are introduced into an estuary and have a direct impact on the estuary and in some cases even the local ocean's freshwater budget. There are several minor sources of freshwater discharge into an estuary, including groundwater, surface runoff, and direct precipitation. (Dai & Trenberth, 2002; Lorhenz et al., 2013).

Freshwater discharge plays a vital role in functioning estuaries (Fonseca & Seixas, 2016; Kolar & Dennison, 2018). The amount of freshwater introduced to the system can have critical impacts on the physiochemical characteristics. These characteristics drive estuarine ecosystem dynamics through variations of freshwater flux into mixing and circulation regimes (Zhou et al. 2018; Wang et al. 2019). Changes in freshwater input can occur via natural variability due to climate change or anthropogenic activities such as dam construction. These variations alter the freshwater input due to the subsequential sediment and nutrient loading from both terrestrial and anthropogenic sources into an estuary that would not be naturally derived there otherwise from the freshwater flux (Kim et al., 2017). Consequently, this is further shown by the particulate organic material and other biogeochemical variability in materials found in an estuary that have not been documented prior to recent years (Lohrenz et al., 2013). Additionally, freshwater discharge helps replenish the water volume and maintain overall hydrodynamics of the estuarine system. Differences in inflow rates can cause alterations in stratification, water circulation, and residency time (Azevedo et al., 2010). Inflow rates are thusly critical to development of hypoxia formation events, impacting the health of any specific estuary (Sheldon & Alber, 2013; Sheldon & Burd, 2014).

Direct precipitation from climate patterns is a non-negligible secondary source to consider for an estuary's water budget. Large-scale climate patterns throughout a substantial portion of Earth, including El Niño/La Niña Southern Oscillation (ENSO) and Atlantic Multidecadal Oscillation (AMO), are known to not only influence river discharge, but impact the estuary directly through changes in direct precipitation. For instance, a noticeable reduction of early winter precipitation is likely to occur during the El Niño phase in the Northern Hemisphere, with a corresponding increase in precipitation during the La Niña phase (Daniel & Robert, 1992). These patterns can also cause variability to areas at the watershed scale, the impact of which is far less noted than the large-scale impacts (Tolan, 2007). However, it is the local scale where effective water resource management decisions are critically relevant. For instance, coastal and estuarine communities in Texas have been experiencing dynamic population increases. These human populations rely on the health of the estuarine and coastal environments. Therefore, it is important to consider the impact of climate on freshwater discharge on the local estuarian ecosystems (Tootle et al., 2005).

1.2 Salinity

Salinity refers to the amount of dissolved salts in seawater. It is measured in parts per thousand solids in a liquid (Boyer et al., 2006). Estuarine salinity levels can range from oligohaline (0.5 ppt) to polyhaline (30 ppt). Salinity is frequently used to define estuarine water because it characterizes the brackish water intermediate zone found between rivers and tributaries and the mouth that extends out into the ocean. This makes the salinity of an estuarine ecosystem dependent on the amount of freshwater inflow and seawater intrusion. The size of an estuary is determined by the depth of the slope and the size of the rivers that feed into its upstream end (Marshall, 2012). Larger estuaries can be on the order of a million hectares, with small streams inputting into the estuary being less than a hectare. Estuarine waters can be well mixed or stratified on a horizontal or vertical gradient depending on additional factors where energy is exerted, such as shear stress from weathering events onto the surface waters (Simons et al., 2010)

In estuarine systems, evaporation and precipitation can be a form of regulation to freshwater discharge into the estuary (Montagna et al., 2012) and can impact total salinity values. The net input can be either positive or negative, depending on whether precipitation exceeds evaporation or evaporation exceeds precipitation, and can vary seasonally. As an example, estuaries are expected to increase in salinity during the summer due to a decrease in freshwater inflow, which is controlled by rising temperatures that correlate to higher evaporation rates. In this case, the system is classified as a negative estuarine system (Montagna et al., 2012). Another factor that influences salinity levels is proximity to coastal water. The Gulf of Mexico's influence on areas near the bay's mouth is a more important controller of salinity levels than precipitation events occurring in the bay's center (Habib et al., 2008). From another viewpoint, freshwater diversion into the bay from rivers such as Trinity River is likely to have more influence on levels of salinity in Trinity Bay, a northeastern region of the Galveston Bay system, causing the upper regions of the bay to be dominated by amounts of freshwater discharge (Das et al., 2012).

Salinity is an important parameter in the estuary because it affects water solubility, resulting in a decrease in dissolved oxygen level as salinity increases. Because of the inverse connection between salinity and oxygen level in water, organisms can only tolerate particular salinity ranges. Oysters, mollusks, and other benthic species that are unable to leave the substrate are likely to experience increased stress as a result of salt levels that exceed or drop below the tolerable range. This can have a harmful effect on their reproduction and survival (Palmer et al., 2008). Salinity is directly impacted by freshwater discharge. Therefore, being able to forecast future estuarine conditions allows estuarine management teams to develop expected results for economically important organisms.

1.3 Large-Scale Climate Patterns

Large-scale climate patterns throughout a substantial portion of Earth, such as ENSO and AMO, are known to influence river discharge. Therefore, it is important to consider the impact of these climate patterns on river discharge into estuarine ecosystems (Tootle et al., 2005). ENSO is one of the large-scale climate oscillations in the equatorial Pacific Ocean, affecting both the atmospheric circulation and the distribution of warm water in the ocean. In a neutral year, the Pacific Equatorial currents, driven by global wind patterns, cause a buildup of warm water in the Western Pacific Ocean, called the Pacific Warm Pool (Picaut et al., 1996). This warm pool causes the formation of a low-pressure zone over the Western Pacific as the air is warmed by the waters below, driving an atmospheric pressure gradient between the Eastern and Western Equatorial Pacific, resulting in atmospheric circulation known as the Walker Circulation Cell, which results in further easterly trade winds (Lau, 2003).

Occasionally, the pressure gradient between the Eastern and Western Equatorial Pacific weakens, causing the trade winds driving the warm water westward to weaken. This results in the Pacific Warm Pool flowing back eastward, driven primarily by pressure gradient forces caused by surface slope, and causing a rise in the sea surface temperature (SST) of the East Pacific (Bjerknes, 1966). This rise of SSTs in the Eastern Equatorial Pacific is known as the El Niño phase, and generally lasts between 12 and 18 months, typically starting in November-December. In contrast, La Niña is the revitalization of the Walker Circulation Cell to an extreme extent following an El Niño event, such that the pressure gradient between the low pressure over the Western Equatorial Pacific Warm Pool and the resultant high pressure over the Eastern Equatorial Pacific is greater than the neutral case (Fig. 1) (Bjerkness, 1966).

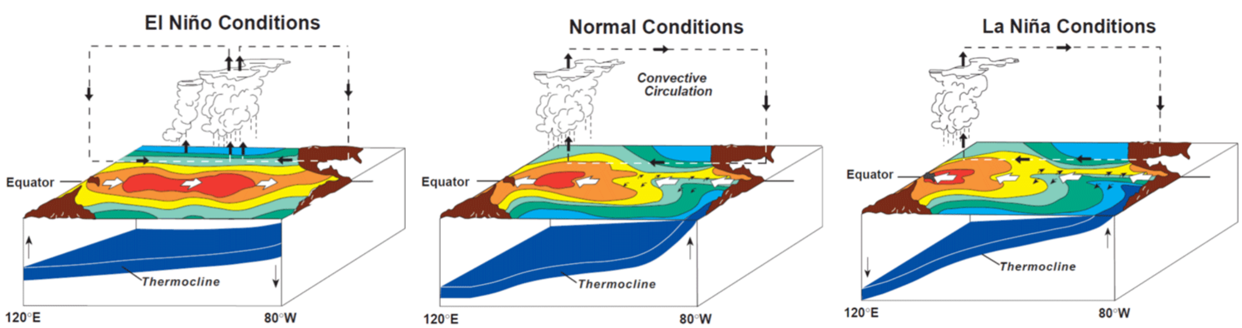

Figure 1: Diagrams showing surface temperatures, winds, areas of ascending/descending air, and the thermocline (blue surface) in the tropical Pacific during El Niño, normal, and La Niña conditions. Source: NOAA/PMEL/TAO Project Office, Dr. Michael J. McPhaden, Director.

During the negative phase of the ENSO pattern (El Niño), higher precipitation in the southeastern region of North America is expected, which contributes to more freshwater discharge into the bays along the Gulf Coast (Daniel & Robert, 1992). It can also contribute to more hurricane activity due to factors like decreased wind shear, which can lead to increased freshwater discharge into estuarine bay systems. During the positive Southern Oscillation phase (La Niña), less precipitation is expected in the southeast of North America, which contributes to lower freshwater discharge along the Gulf Coast.

The Southern Oscillation Index (SOI) is the measured atmospheric pressure gradient between Papeete (Tahiti, French Polynesia) and Darwin (Northern Territory, Australia) (Ropelewski & Jones, 1987). The SOI is calculated as the anomaly departure from the mean, calculated from a base period from 1981 to 2010. The Tahiti anomaly is the mean sea level pressure (SLP) subtracted from the measured SLP. The standardized Tahiti values are then calculated as the Tahiti anomaly divided by the standard deviation calculated from the base period. With the data from Darwin treated in the same manner, the resultant SOI equation is the standardized Darwin data subtracted from standardized Tahiti data, all divided by the monthly standard deviation, which is calculated by summing the difference between the Tahiti and the Darwin data multiplied by two (Climate Prediction Center Internet Team, 2007).

The Oceanic Niño Index (ONI) is the three-month running mean of the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed SST (ERSST.V5) anomalies in the Niño 3.4 region (5°N-5°S, 120-170°W). These anomalies are based upon a changing base period, consisting of multiple centered 30-year base periods, used to calculate the anomalies of successive 5-year periods in the record. The combination of both indices, noting both the changes in the atmospheric pressure gradient and the changes in the SST across the equatorial Pacific work together to provide a more complete understanding of ENSO.

AMO is the multidecadal oscillation of average SSTs in the North Atlantic Ocean, and its impacts are global, but most intense in the North Atlantic. The cause of the oscillation is currently unknown but may be related to fluctuations in the Atlantic thermohaline circulation (Enfield et al., 2001). During the negative phases, or the warm periods, less rainfall is expected in the United States, thus less freshwater discharge is expected into bay systems along the US coast. During positive phases, the reverse is expected, more rainfall and precipitation, thus more freshwater discharge along the coast into bays and estuaries. The AMO index data are calculated from the Kaplan SST Dataset, which are gridded global SST anomalies derived from UK Met Office SST data, provided by the NOAA Physical Science Laboratory (PSL). The area weighted average of the SST data is computed for the North Atlantic, from 0° to 70°N. The time series is then detrended and smoothed with a 121-month smoother.

Another large-scale multidecadal climate oscillation in the Pacific Ocean is the Pacific Decadal Oscillation (PDO). Like AMO, PDO is a measure of SST anomalies across the North Pacific Basin (Mantua, 2002). During the PDO positive phase, SSTs in the interior North Pacific are anomalously cool and anomalously warm along the North American Pacific coast, resulting in below average sea level pressures over the North Pacific. During the negative phase, the reverse is seen, with warm SSTs in the interior, and cooler SSTs along the North American coast, and above average pressures over the North Pacific (Mantua, 1999). The NOAA PSL PDO index is based on the ERSST.V5 dataset, constructed by regressing the ERSST anomalies against the Mantua PDO index. The anomalies are then projected onto a PDO regression map, calculated from the regression, in order to compute the index.

Arctic Oscillation (AO), a large-scale climate oscillation in the Arctic Ocean, was originally defined as the leading empirical orthogonal function (EOF) of monthly SLP anomalies poleward of 20° N during the winter (Deser, 2000). AO highly resembles North Atlantic Oscillation (NAO), though is distinguished from the more regional pattern by its distinct barotropic structure and barotropic structure. At the NOAA Climate Prediction Center (CPC), AO index is constructed by projecting the daily SLP anomalies poleward of 20°N onto the AO loading pattern, obtained using year-round monthly mean anomaly data. It is also noted that because AO has the largest variability during the winter months, the loading pattern primarily reflects the cold season AO pattern.

1.4 Research Site

Freshwater input into an estuary is one of the most important factors that affect various aspects of the estuarine ecosystem. This research aimed to investigate these relationships between large-scale regional climate oscillations and the freshwater discharge into Galveston Bay. Salinity levels are dependent on these discharge levels and therefore by climate oscillations. I examined correlations of the variations of climatic patterns to annual river discharge levels and salinity regimes and denoted the differences in dry versus wet years in Galveston Bay. This was completed through a time-series analysis of freshwater discharge data from the U.S. Geological Survey (USGS) in comparison to the variations in climate indices such as SOI and AMO.

Galveston Bay is the largest of seven estuaries on the coast of Texas. The bay is approximately 50 km long, 27 km wide, has a mean depth of 2.5 m, and has an area of 1,500 km^2 (Quigg et al., 2007). Inputs of freshwater can be derived mainly from the Trinity and San Jacinto rivers, while seawater enters through the inlets from the Gulf of Mexico. The shallow nature of the bay makes the community more susceptible to changes. This project looked at the impact of regional weather oscillation on the river discharge into Galveston Bay. This was done through a time-series analysis of river discharge data provided by USGS in comparison to the presence of ENSO and AMO conditions derived from NOAA’s climate indices, and salinity Data provided from the Texas Water Development Board (TWDB).

I first characterized the freshwater discharge into Galveston Bay compared to salinity values, and then determined the relationship between the freshwater discharge and regional weather indices, e.g., ENSO and AMO. Then, I developed a hypothetical “normal” year for Galveston Bay freshwater discharge to be used in future modeling of the Bay in-between fluxes and deficits of freshwater for future estuary management. Therefore, it was hypothesized there would be more precipitation and thus more freshwater discharge into Galveston Bay in times of El Niño and less precipitation and thus less freshwater discharge in times of La Niña. Additionally, it is also hypothesized positive AMO conditions to correspond to trends of higher precipitation, and negative trends in AMO will correspond to lower levels of precipitation. This understanding will aid in the prediction of ecological and biophysical responses of the Galveston Bay estuary due to climate change.

2. METHODS

2.1 Characterization of Freshwater Discharge

2.1.1 Data sources

There are three main sources of freshwater discharge for Galveston Bay: Trinity River, Lake Houston (San Jacinto River), and Buffalo Bayou. To characterize freshwater discharge into Galveston Bay, data was collected through the USGS water data table. The four gauging stations of interest were: Trinity River at Wallisville TX (USGS 08067252), Trinity River at Romayor, TX (USGS 08066500), Lake Houston near Sheldon, TX (USGS 08072000), and Buffalo Bayou at West Belt Dr, Houston, TX (USGS 08073600) (Fig. 2). The Lake Houston station will act as a marker for freshwater discharge data from the San Jacinto River system. The Buffalo Bayou station will provide data on input from the tidal river that flows through urbanized Houston, dumping into Galveston Bay. The Wallisville gauging station is close to the mouth of Trinity River, however it is lacking in data. Therefore, a regression was used from data collected from the Romayor station to estimate discharge data at Wallisville prior to Wallisville's initial collection time of 2014.

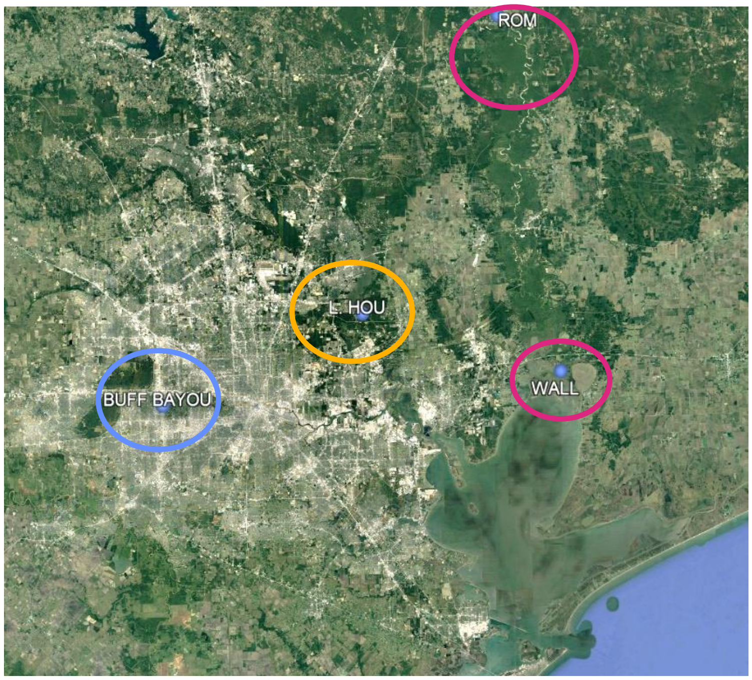

Figure 2: The four USGS gauging station locations used to characterize freshwater discharge into Galveston Bay.

2.1.2 Data Analysis

Data collected from each station had a time range from origin of gauge beginning collection to the date of file extraction from the USGS website (September 2022). All data was inserted into R-Studio from a txt-file, then run through filtration for approved status (indicated with A), so only the processed numbers that had been reviewed by USGS for publication were included in the analysis (Figs. 3 and 4). After all raw data was processed in R-studio statistical metrics, e.g., long-term discharge, percentiles (25, 50, 75-percentiles, etc.) and a long-term mean from the daily discharges over one mean year were then developed on all USGS station data to be used for analysis in characterization of a "mean" year in Galveston Bay.

```
################################
Buff_RAW_Select <- Buff_RAW%>%
  select(datetime,Mean_Disch,Mean_Disch_code) %>%
  #now we are only looking at the datetime,
  #Mean discharge and the code, I can now filter
  #this for Buff to only show us Mean discharge
  #if A has been evaluated for the number
  filter(Mean_Disch_code == 'A')%>%

  select(datetime,Mean_Disch)
#this has now been filtered to only include approved variables
######################################
```

Figure 3: A sample code created in R-studio to filter for approved data from the USGS 08073600 gauging site in Buffalo Bayou.

R ▾ Global Environment ▾

Data	
Buff_RAW	11660 obs. of 11 variables
Buff_RAW_Select	11283 obs. of 2 variables

Figure 4: Sampled data from the USGS 08073600 gauging site in Buffalo Bayou filtered for approved (indicated with A) data depicted in Buff_RAW_Select.

For the USGS Lake Houston site, the gauging station does not have a measurement for freshwater discharge, only recording daily water level means. By determining the relationship between mean water level and freshwater discharge rates of other USGS gauging stations inputting into Galveston Bay, extrapolation to fill in the missing data may be possible to understand the Lake Houston impact on Freshwater input into Galveston Bay. The relationship between water level and discharge, developed by the TWDB, is denoted in the following equation when supplied with mean water values. For any mean water values on 2009-10-01 or later that is below 44.8 ft,

$$Q_f\left(\frac{ft^3}{sec}\right) = 86.76 * (\mathrm{wl} - 44.5)/0.3 \qquad (1a)$$

For any mean water values on 2009-10-01 or later that is above 44.8 ft,

$$Q_f\left(\frac{ft^3}{sec}\right) = 5418.31 * (wl - 44.5)2 - 1366.29 * (wl - 44.5) \qquad (1b)$$

where Q_f represents the unknown freshwater discharge ($\frac{ft^3}{sec}$), and wl is the mean water height (m). Currently, there is no other equation we have developed for dates prior to 2009-10-01.

2.1.3 Conditions of Categorization

The averaged long-term total discharge was used as a method of modeling to determine how each year between 1980-2022 in Galveston Bay would be categorized. The conditions of categorization were the following: if the discharge for the year was consistently fluctuating between the mean and the long-term 75th percentile or above, the year would be categorized as "wet;" if the year showed modest fluctuation between the 25th and 75th or stabilized near the long-term mean the year would be considered "normal"; and if the year had consistent values below the mean or fluctuating around 25th percentile or lower, the year would be considered "dry".

2.2 Salinity Characterization

2.2.1 Salinity Gauge stations

The TWDB and other agencies such as NOAA have been collecting time-series salinity data from multiple stations in Galveston Bay. To find relationships between freshwater discharge and salinity in Galveston Bay, all salinity data was collected from the TWDB's Water Data for Texas (Fig. 5). Some sites were inactive or destroyed over the timeline, so all data was considered for full representation of values found in Galveston Bay. Data points were extracted from the initial date of origin the station began recording until the ending date of September 2022.

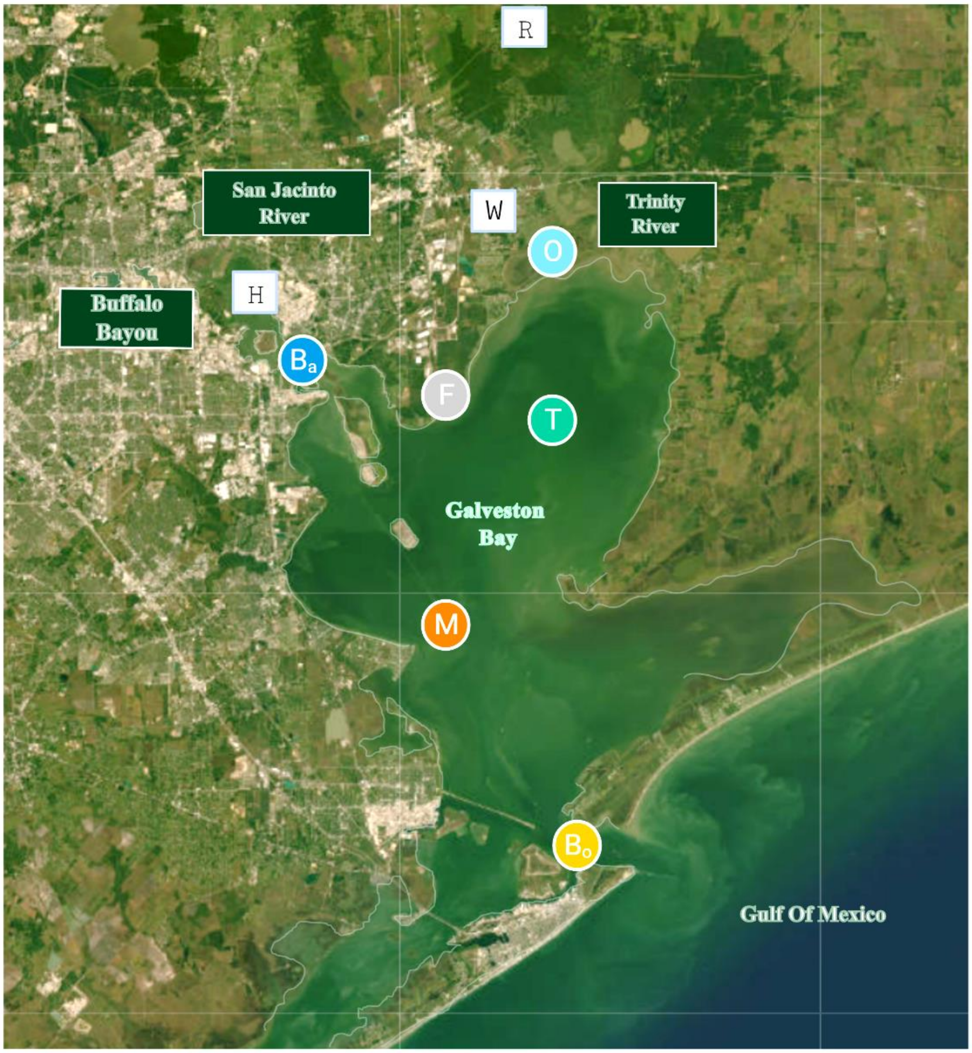

Figure 5: Locations of all salinity stations values were taken from to establish time-series relationships between USGS freshwater discharge values and TWBD salinity Data. Pink denotes inactive salinity site, yellow represents currently active salinity stations, and blue shows the USGS discharge gauging stations used for comparison of freshwater discharge values to salinity values in Galveston Bay between January 1982, to September 2022.

2.2.2 Salinity Data Analysis:

This data was then processed using the same metrics defined in the freshwater discharge characterization. All data was already defined and approved and published, so no filtration needed to be considered.

2.3 Freshwater versus Salinity Relationships

The salinity data was analyzed in conjunction with the freshwater discharge data to find potential correlations between the two sets of data. This was done by merging the USGS and TWDB data into one table based on "datetime". TWBD only began collection in 1982, so USGS was filtered to "datetime" ≥ 1982-10-01 before merging occurred. Initially, scatterplots were used for initial visualization of salinity levels to freshwater discharge relationships at each of the six TWBD salinity stations (Fig. 6). This form of analysis didn't show any patterns of significance ($r^2 < 0.30$), so another approach was implemented. Indexing the discharge data in R-studio constituted the next step in further exploring the relationships between freshwater discharge and salinity. Statistical analyses were carried out in order to determine the 95th percentile of discharge values at each station. Any data that exceeded these limits was considered an outlier and was not processed further. The remaining values were then binned into freshwater discharge ranges and displayed on bar graphs to provide a more accurate representation of the statistical distribution of salinity and freshwater discharge. A linear regression was then run on the averaged salinity values found in each freshwater discharge range to find correlation with the p-value set to be <.05 for significance.

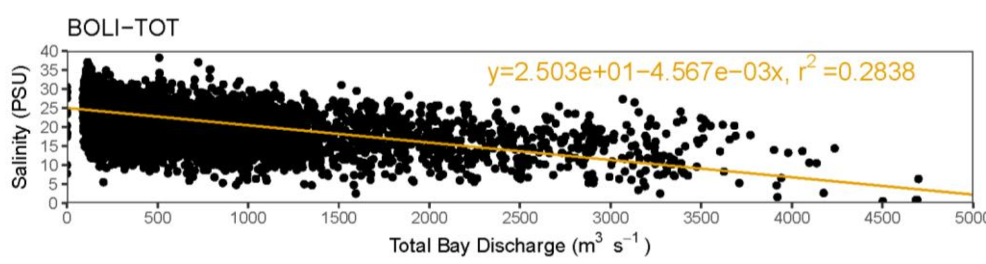

Figure 6: An example of initial data as a scatterplot and showing low correlation before further processing implemented in R-studio. This example looked at salinity measurements taken at the TWDB Boli station in conjunction to total freshwater discharge (m^3/s^{-1}) in Galveston Bay from 1982-2022.

2.4 Climate Index Characterization

Multiple indices have been used to represent ENSO. Among them, we will examine the Southern Oscillation Index (SOI) and NOAA Oceanic Nino Index (ONI). Monthly data from both indices as well as monthly AMO, AO, and PDO data were collected from the Climate Indices page from the NOAA Physical Sciences Laboratory. The data was collected from the index start date to 2022.

First, the correlation between the different climate indices were drawn using the "cor_test" function in R, which gave both the correlation coefficient and the p-value for the correlation coefficient. This was done in order to eliminate as many climate indices as possible to reduce the number of correlations performed between climate indices and the average monthly freshwater discharge. The data were already in monthly averages, so there was no need for further filtration.

The freshwater discharge data were then lagged monthly, and correlations were drawn between the lagged data and the lagged freshwater discharge. The lagging was performed under the assumption that large scale climate patterns do not have an immediate impact on any region outside of the region that is used to index the patterns. It may take time for each of the patterns' effects to reach the Galveston Bay area, thus the climate data are compared to discharge data from a range of lagged time frames. Statistical (e.g., time-lagged regression and correlation) and time-series (e.g., spectral analysis) analyses were performed with the data. This provides more information as to the indicators of a "normal," "wet," or "dry" year in Galveston Bay.

3. RESULTS

3.1 Visualization of Freshwater Discharge into Galveston Bay

USGS Freshwater Discharge values were plotted using R-studio ggplot2 to look at initial trends of Freshwater input between the four identified stations (Fig. 7). The values from each location varied from 0 to over 5,000 $m^3 s^{-1}$. This data was used to identify average freshwater discharge input into Galveston Bay.

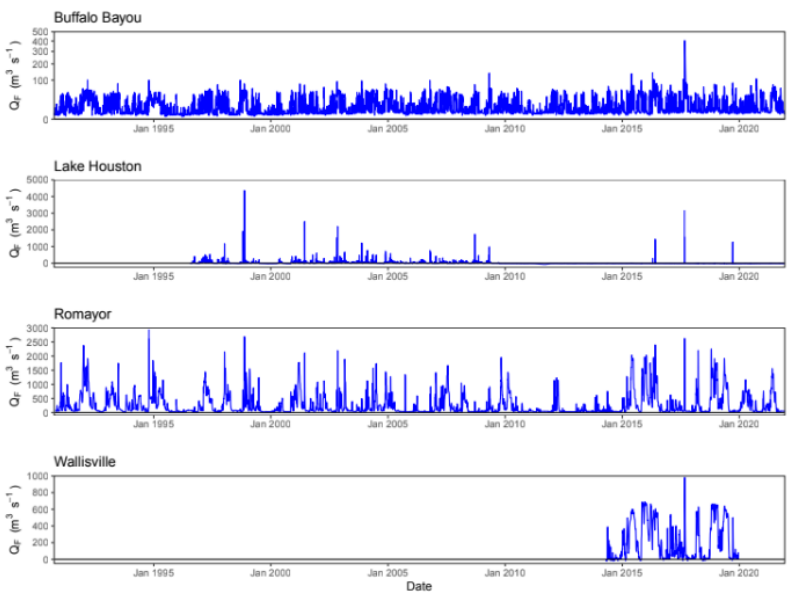

Figure 7: Time series analysis of freshwater discharge rate (Qf) from four sampled USGS gaging sites. Positive values imply positive values of freshwater discharged into Galveston Bay.

3.2 Extrapolation on Wallisville Data

Following equations 1a and 1b, Romayor data from the USGS gauging site was run through a regression so multidecadal data could be used for analysis to establish true Trinity River freshwater discharge input into the Bay (Fig. 8).

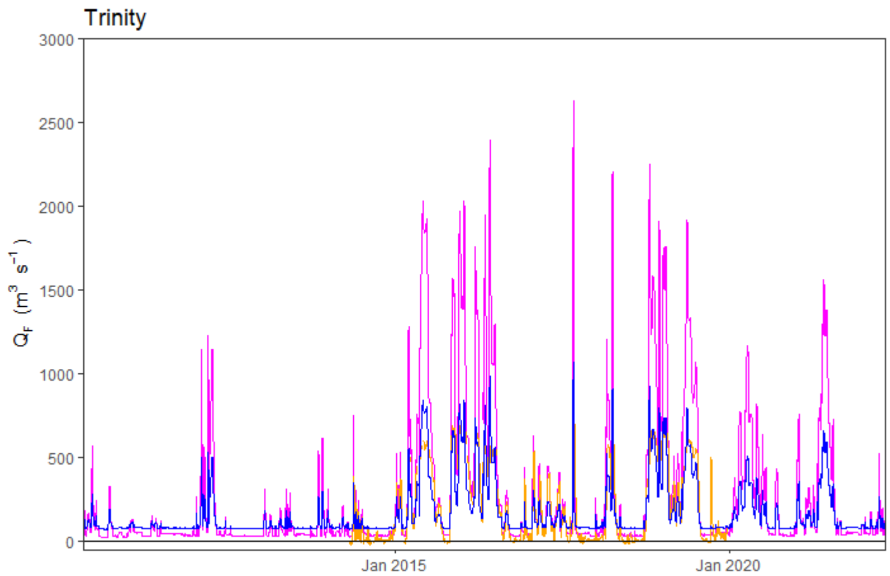

Figure 8: Extrapolation on Wallisville data through a regression series was run on Romayor values; where Romayor is denoted by the pink, yellow represents the initial Wallisville data, and blue is a representation of the new calculated values of Wallisville to be used in analysis.

3.3 Total Freshwater Discharge to Salinity Values in Galveston Bay

TWDB salinity station data was filtered to USGS total discharge inputs on a case-by-case basis based on proximity to freshwater input sources. The MIDG and BOLI stations that were the furthest away from fresh-water input sources had higher average salinity values ranging from 0 to 35 PSU. OLDR, TRIN, and FISH are salinity stations found close mouth of Trinity River. Trinity River freshwater input was summated and compared to the values derived from each station (Fig. 9). BAYT salinity station is closer to San Jacinto input, and was compared to the values of that source. OLDR, BAYT, and TRIN stations had the lowest average salinity range of 0-15 PSU. The salinity range of the FISH station was 0-23 PSU. R^2 values greater than 0.95 with p-values less than 0.001 indicate a strong correlation between salinity levels and freshwater discharge into the Galveston Bay region (Fig. 9). The values for freshwater discharge ranged from 0 to 750 (m^3s^{-1}).

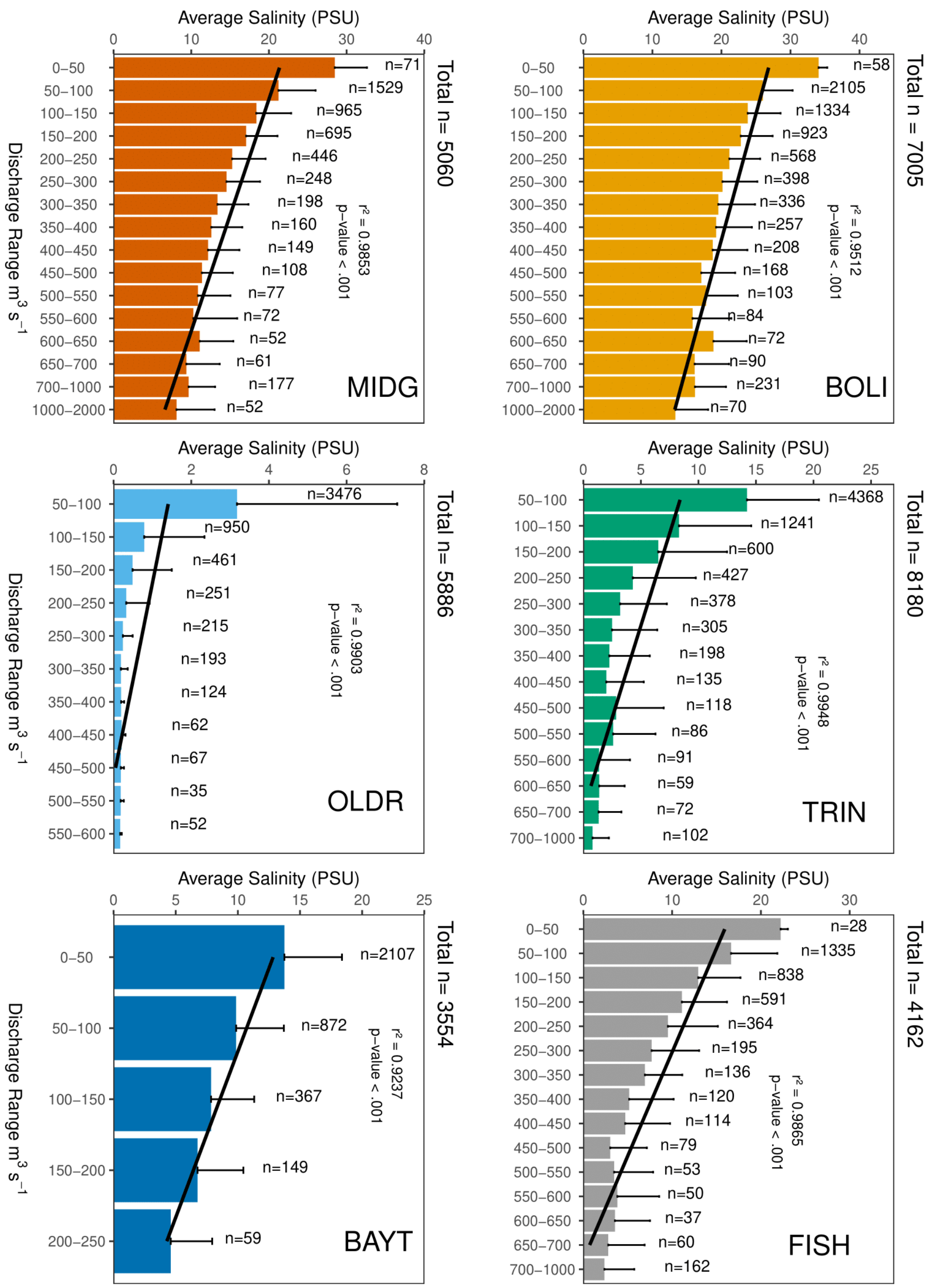

Figure 9: The relationship between freshwater discharge into Galveston Bay and the TWDB salinity station values from 1982-2022. n refers to the total count of salinity found at each station below the 95th percentile Freshwater discharge ranges were represented by either total, San Jacinto input, Buffalo Bayou input, or Trinity River input. Due to proximity TRIN, OLDR and FISH were compared to Trinity input; BAYT salinity levels were compared to Buffalo Bayou and San Jacinto input; and BOLI and MIDG stations were assessed on to the total input from all three systems between January 02,1982 to September 1, 2022.

3.4 Categorization Of Freshwater Discharge into Galveston Bay from 1980-2021

From 1980 to 2021, the USGS daily discharge data were collected and filtered for annual mean years (Table 1). Statistical analysis of the data revealed that the 25th percentile was 290.6 (m^3 s^{-1}), the mean was 435.1 (m^3 s^{-1}), and the 75th percentile was 586.0 (m^3 s^{-1}). Eleven years fell below the 25th percentile range and were classified as "Dry," twenty of the forty-two years were classified as "Average," and eleven years were greater than the 75th percentile of annual freshwater discharge into Galveston Bay. These were classified as wet years (Table 2).

Table 1: Annual average freshwater discharge into Galveston Bay from 1980-2021

Year	Annual Avg.	Percentile Range	Category	Year	Annual Avg.	Percentile Range	Category
1980	257.9706	<25%	Dry	2002	444.6532	25-75%	Average
1981	364.1965	25-75%	Average	2003	290.5478	<25%	Wet
1982	426.6399	25-75%	Average	2004	570.6145	25-75%	Average
1983	307.2733	25-75%	Average	2005	290.8793	25-75%	Average
1984	272.4248	<25%	Dry	2006	176.3373	<25%	Dry
1985	396.2157	25-75%	Average	2007	641.3134	>75%	Wet
1986	443.5383	25-75%	Average	2008	297.4769	25-75%	Average
1987	345.2446	25-75%	Average	2009	397.4737	25-75%	Average
1988	170.1574	<25%	Dry	2010	391.5818	25-75%	Average
1989	468.3021	25-75%	Average	2011	137.1091	<25%	Dry
1990	688.2529	>75%	Wet	2012	278.646	<25%	Dry
1991	610.2166	>75%	Wet	2013	193.0943	<25%	Dry
1992	771.7669	>75%	Wet	2014	191.8787	<25%	Dry
1993	575.2988	25-75%	Average	2015	1225.0452	>75%	Wet
1994	589.558	>75%	Wet	2016	1044.1975	>75%	Wet
1995	535.0967	25-75%	Average	2017	457.207	25-75%	Average
1996	162.9218	>75%	Wet	2018	895.1587	>75%	Wet
1997	546.3339	25-75%	Average	2019	966.3318	>75%	Wet
1998	633.6502	>75%	Wet	2020	464.0215	25-75%	Average
1999	305.0678	25-75%	Average	2021	497.0388	25-75%	Average
2000	257.608	<25%	Dry				
2001	668.7365	>75%	Wet				

Table 2: Summary of statistical findings and categorization of annual average freshwater discharge into Galveston Bay from the years 1980-2021

q25	q50	q75	Total observations	Dry	Average	Wet
290.6	435.1	586.0	42	11	20	11

3.5 Freshwater Visualization

All years between 1980 through 2021 were manually categorized as being a “Dry,” “Average,” or “Wet” year in Galveston Bay based on statistical analysis (Fig. 10)

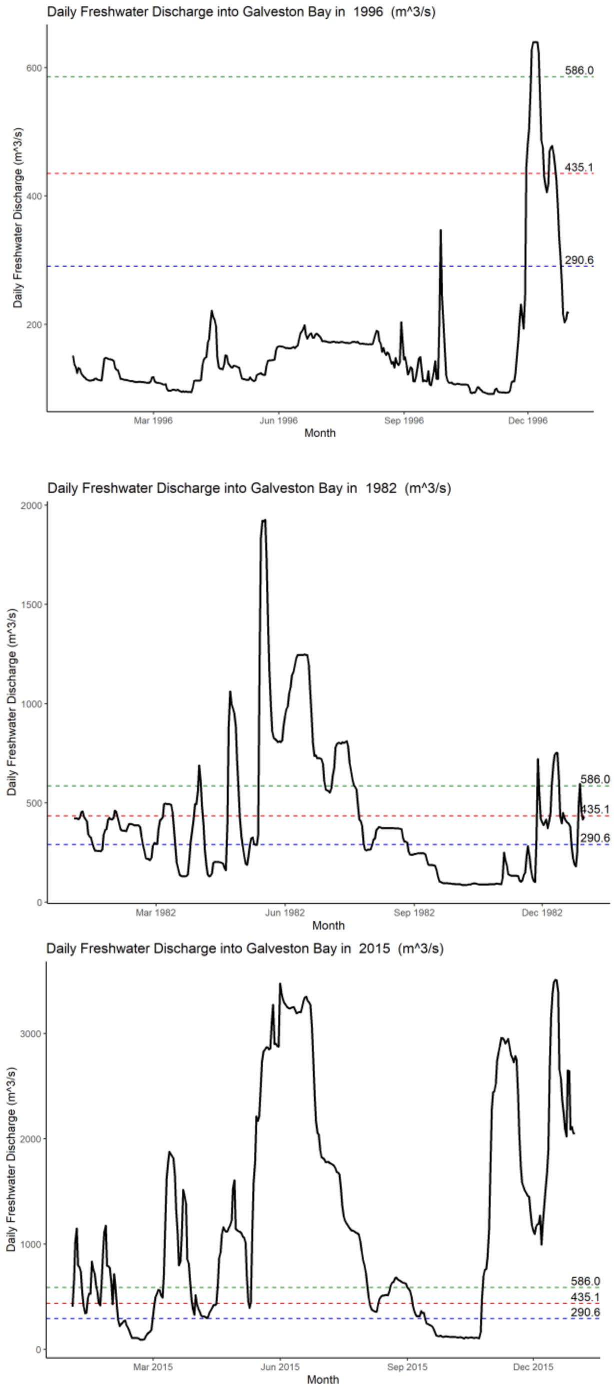

Figure 10: Sample freshwater discharge data from USGS from the year 1996 showing an example of a "Dry" year on Galveston Bay based on freshwater discharge, The year1982 showing an "Average" year, and 2015 showing an example of a "Wet" year in Galveston Bay. The black line represents daily discharge from Jan 1980 to Jan 1981. The horizontal lines indicate respectfully; the 25th, 50th, and 75th percentile values from overall freshwater discharge into Galveston Bay between 1980 to 2021.

3.6 Lagged Correlation Outputs and Climate Correlation Outputs

Correlations between each of the climate indices were drawn, and the outputs are shown in Table 3. The only correlations that had no statistical significance were those drawn between SOI and AMO, AO and AMO, and AMO and ONI. Because ONI and SOI are so well correlated, with a correlation coefficient of -0.73 and a p-value of less than 0.0001, as they are both measures of ENSO, it is expected that if a climate index is not correlated with SOI, it should also have no correlation with ONI.

Table 3: Correlation coefficients and p-values for correlation tests between the five climate indices.

Indexes	correlation_coefficient	p_value
SOI_PDO	-3.78E-01	1.03E-30
SOI_AO	9.23E-02	6.65E-03
SOI_AMO	3.68E-02	2.98E-01
SOI_ONI	-7.31E-01	6.17E-145
PDO_AO	-9.56E-02	4.61E-03
PDO_AMO	-1.04E-01	2.44E-03
PDO_ONI	4.13E-01	1.85E-37
AO_AMO	-1.99E-02	5.70E-01
AO_ONI	-9.99E-02	3.10E-03
AMO_ONI	-6.16E-03	8.61E-01

Correlation tests were also drawn between the lagged average monthly freshwater discharge data and each of the climate indices (Table 4). The data are also represented in graph form as the correlation coefficients change with additional months lagged (Fig. 11). The change in the correlation coefficients is shown as the freshwater data indicate how long it takes for changes in the climate indices to reach and affect the local weather of the Galveston Bay area. The months lagged values for peaks in the correlation coefficients indicate the number of months between changes in the climate patterns and the climate patterns' effects reaching the Galveston Bay area.

Table 4: Correlation coefficients and p-values for the correlation test drawn between each of the climate indices and lagged average monthly freshwater discharge data.

months_lagged	SOI_coef	SOI_p_value	PDO_coef	PDO_p_value	AO_coef	AO_p_value	AMO_coef	AMO_p_value	ONI_coef	ONI_p_value
0	-1.30E-01	1.40E-04	2.14E-01	1.10E-10	1.75E-02	6.06E-01	1.33E-01	1.11E-04	1.79E-01	1.14E-07
1	-1.07E-01	1.71E-03	2.51E-01	2.73E-14	2.11E-02	5.35E-01	1.35E-01	8.59E-05	1.63E-01	1.43E-06
2	-1.13E-01	8.66E-04	2.44E-01	1.39E-13	2.42E-02	4.75E-01	1.37E-01	7.11E-05	1.42E-01	2.53E-05
3	-1.18E-01	5.43E-04	2.22E-01	1.68E-11	-4.20E-03	9.02E-01	1.38E-01	6.16E-05	1.19E-01	4.46E-04
4	-1.18E-01	5.50E-04	1.87E-01	1.64E-08	3.11E-02	3.59E-01	1.36E-01	7.81E-05	9.77E-02	3.86E-03
5	-6.76E-02	4.74E-02	1.36E-01	4.54E-05	4.90E-02	1.48E-01	1.29E-01	1.69E-04	8.11E-02	1.65E-02
6	-8.32E-02	1.45E-02	1.02E-01	2.17E-03	3.53E-02	2.97E-01	1.31E-01	1.42E-04	6.56E-02	5.23E-02
7	-6.28E-02	6.52E-02	7.81E-02	1.92E-02	2.59E-02	4.44E-01	1.32E-01	1.21E-04	5.09E-02	1.33E-01
8	-5.31E-02	1.19E-01	6.88E-02	3.90E-02	8.38E-03	8.04E-01	1.35E-01	8.74E-05	3.83E-02	2.58E-01
9	-5.12E-02	1.32E-01	5.92E-02	7.57E-02	2.08E-02	5.38E-01	1.36E-01	7.62E-05	2.43E-02	4.74E-01
10	-3.41E-02	3.17E-01	7.71E-02	2.06E-02	7.86E-03	8.16E-01	1.38E-01	5.70E-05	7.13E-03	8.33E-01
11	-2.14E-02	5.31E-01	9.44E-02	4.59E-03	4.69E-02	1.65E-01	1.39E-01	5.15E-05	-5.01E-03	8.82E-01
12	-1.41E-02	6.80E-01	1.02E-01	2.26E-03	9.43E-02	5.22E-03	1.40E-01	4.42E-05	-1.04E-02	7.59E-01

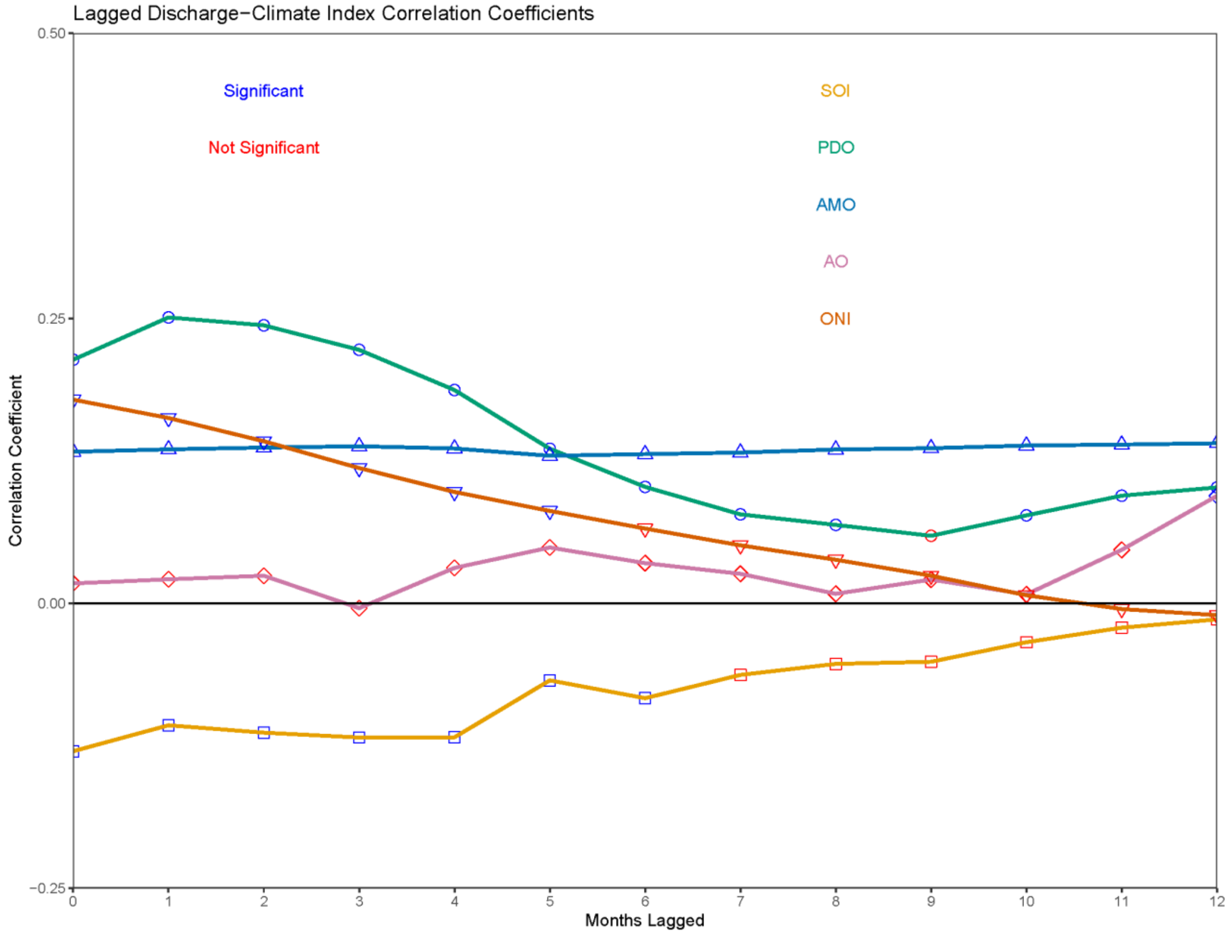

Figure 11: The change in correlation between the average monthly discharge and the various climate indices. The red points indicate coefficients that are not statistically significant, and the blue points represent the coefficients that are statistically significant.

4. CONCLUSION

4.1 Yearly Freshwater Conditions in Galveston Bay from 1980 to 2022

The trends observed in Galveston Bay from the USGS data between 1980 and September 2022 have provided context as to what a "dry", "average", or "wet" year in Galveston Bay look like (Table 1 and Fig. 10). As previously mentioned, amounts of freshwater in an estuarian environment determines species composition and is therefore crucial in understanding composition and abundance, as well trying to maintain an ecologically sound environment (Alber, 2002). In the last 40 years of data, there seems to be influencers causing the shifts from Wet-Average regimes to Dry-Average regimes to switch sooner. From 1980-2000, these shifts that are likely caused by large-scale weather patterns, were switching every decade. Because of climate change, the time for these shifts to occur began to shorten after 2000, shifting between regimes every five to seven years.

Research on this topic also suggests global precipitation intensification has been caused by the reduction in lag time observed between the AMO and SOI (Trenberth, 1998; Dykstra and Dzwonkowski, 2021). As global temperatures increase, the water-holding capacity of the atmosphere also increases. This implies an increase in atmospheric moisture is resultant with enhanced evaporation due to this hike in temperature. And since nature likes to be in balance, there must be an increase in precipitation events to follow these enhanced dry periods. Lag being reduced between AMO, and SOI has caused changes in river discharge, due to this higher advection of moist air during this time. Causing variability and drought conditions in Galveston Bay to be intensified. While the magnitude of these changes may vary depending on the location in the Bay and time period of interest, the overall trend is towards more frequent and severe hydrological extremes.

4.2 Salinity and Freshwater Discharge Relationships in Galveston Bay

As anticipated, a trend of salinity regional variations in Galveston Bay were established when analyzing the data of each TWDB salinity station to the USGS daily freshwater discharge of interest. At each station, the average salinity varied between 0 to 35 PSU, with most observed data points occurring between freshwater input of 0-200 (m^3 s^{-1}) at each station (Fig. 9).

With high r^2 values and low p-values established at each salinity station, there is a significance here worth discussing. What is being observed is fairly low freshwater influence from the three input sources, yet there is still such a variation regionally in Galveston Bay. There are likely multiple factors to consider causing this gradient. For one, Galveston Bay is a shallow estuary. Shallow estuaries are often influenced largely by tidal influences as opposed to the gradual freshwater input and are vulnerable to sea level rise (Khojasteh *et al.*, 2020) Therefore, future analysis of the Bay will likely need to examine tidal dynamics when considering the salinity dynamics in Galveston Bay. Wind shear and patterns are also another dynamic that can impact shallow estuaries. For instance, in the Pearl River Estuary, wind was shown to strongly adjust the longitudinal circulation during neap tide, while having less influence during spring tide (Lai *et al.,* 2018). Indicating that both tidal influence and wind shear can impact estuaries and how well mixed they are temporally. For the scope of this project, these dynamics were ignored. However, it would be wiser in future works to consider these influences on the salinity and freshwater relationship depicted into Galveston Bay.

4.3 Lagged Trends in Galveston Bay

There is generally higher correlation between SOI and ONI, the ENSO indices, and the average monthly freshwater discharge with fewer months lagged (Table 4). There is a general negative trend in the correlation between ONI and SOI, the ENSO indices, and the average monthly freshwater discharge (Figure 11). This negative trend in correlation indicates that the effect of ENSO is relatively immediate on the monthly freshwater discharge.

The correlation between PDO and the average monthly freshwater discharge peaks at 1 month lagged and then tapers off (Figure 11). This indicates that changes in the PDO index take about a month to see the effect of the climate oscillation on the freshwater discharge into Galveston Bay.

Conversely, the correlation between AMO and the average monthly freshwater discharge into Galveston Bay remains constant throughout the months lagged. This may be because of the relatively constant nature of AMO. Being a multidecadal oscillation, AMO has a very slow shift back and forth between the positive and negative phases. Determining correlation between AMO and freshwater discharge over time essentially asks whether the average discharge for a given multidecadal time period is less than or greater than the average discharge of an adjacent multidecadal time period (Enfield et al., 2001). Due to the multidecadal scale of AMO, the correlation between AMO and discharge should not vary with monthly lagging of the discharge data. Lastly, the correlation between AO and the average monthly freshwater discharge into Galveston Bay was statistically significant only once when the discharge data were lagged a full year. It is possible, however unlikely, that the effect of changes to the AO index take at least a full year to take effect. Continuing the time lagging process would give additional insight into how much time it takes for changes in AO to affect precipitation and freshwater discharge into Galveston Bay.

4.4 Future Works

Throughout this entire project, the end goal was to evaluate Galveston Bay water conditions to a baseline analysis. However, the overarching theme to this project focused on where this research can be used in the future. If there were more time given to this project, it is likely that wind patterns, tidal components, and other physical components would have been considered. And eventually, a model would be developed of Galveston Bay, that could predict future trends in water dynamics based on climate change. This model would optimally be able to provide estuarian management a resource in how to manage inflow rates to protect the oyster reefs and other vital species before it is too late.

REFERENCES

[1] Alber M (2002) A conceptual model of estuarine freshwater inflow management. *Estuaries 25*, 1246–1261.

[2] Azevedo, I. C., Bordalo, A. A., & Duarte, P. M. (2010). Influence of river discharge patterns on the hydrodynamics and potential contaminant dispersion in the Douro estuary (Portugal). *Water research*, *44*(10), 3133-3146.

[3] Bjerknes, J. (1966). Survey of El Niño 1957-58 in its relation to tropical Pacific meteorology.

[4] Boyer, T. P., Antonov, J. I., Garcia, H. E., Johnson, D. R., Locarnini, R. A., Mishonov, A. V., ..& Levitus, S. (2006). NOAA atlas NESDIS 60. *World Ocean Database 2005*

[5] Buzan D, Lee W, Culbertson J (2009) Positive Relationship between Freshwater Inflow and Oyster Abundance in Galveston Bay, Texas. Estuaries and Coasts 32:206–212. doi: 10.1007/s12237-008-9078-z

[6] Climate Prediction Center Internet Team. (2007, March 27). *Frequently Asked Questions Regarding CPC's Current Monthly Atmospheric and SST Index Values*. Climate prediction center - monitoring & data: Current monthly atmospheric and sea surface temperatures index values FAQs. Retrieved March 20, 2023, from https://www.cpc.ncep.noaa.gov/data/indices/Readme.index.shtml#SOICALC

[7] Dai, A. & Trenberth, K. E. (2002). Estimates of Freshwater Discharge from Continents: Latitudinal and Seasonal Variations. *J. Hydromet.* 3, 660-687.

[8] Daniel, R., & Robert, H. (1992). El Niño/southern oscillation and streamflow in the western United States. *El Niño: Historical and paleoclimatic aspects of the Southern Oscillation*, 29.

[9] Deser, C. (2000). On the teleconnectivity of the "Arctic Oscillation". *Geophysical Research Letters*, *27*(6), 779-782.

[10] Du J, Park K, Jensen C, Dellapenna TM, Zhang WG, Shi Y (2021). Massive oyster kill in Galveston Bay caused by prolonged low-salinity exposure after Hurricane Harvey. *Science of the Total Environment*, 774, 145132, doi:10.1016/j.scitotenv.2021.145132.

[11] Dykstra, S. L., & Dzwonkowski, B. (2021). The role of intensifying precipitation on coastal river flooding and compound river-storm surge events, Northeast Gulf of Mexico. *Water Resources Research*, *57*(11)

[12] Enfield, D. B., Mestas-Nuñez, A. M., & Trimble, P. J. (2001). The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental US. Geophysical Research Letters, 28(10), 2077-2080.

[13] Habib, E., Larson, B. F., Nuttle, W. K., Rivera-Monroy, V. H., Nelson, B. R., Meselhe, E. A., & Twilley, R. R. (2008). Effect of rainfall spatial variability and sampling on salinity prediction in an estuarine system. *Journal of Hydrology*, *350*(1-2), 56-67.

[14] Kaplan, A., M. Cane, Y. Kushnir, A. Clement, M. Blumenthal, and B. Rajagopalan, Analyses of global sea surface temperature 1856-1991, Journal of Geophysical Research, 103, 18,567-18,589, 1998

[15] Khojasteh, D., Hottinger, S., Felder, S., De Cesare, G., Heimhuber, V., Hanslow, D. J., & Glamore, W. (2020). Estuarine tidal response to sea level rise: The significance of entrance restriction. *Estuarine, Coastal and Shelf Science*, *244*, 106941.

[16] Kim, Y. H., Hong, S., Song, Y. S., Lee, H., Kim, H. C., Ryu, J., ... & Khim, J. S. (2017). Seasonal variability of estuarine dynamics due to freshwater discharge and its influence on biological productivity in Yeongsan River Estuary, Korea. *Chemosphere*, *181*, 390-399.

[17] Lai, W., Pan, J., & Devlin, A. T. (2018). Impact of tides and winds on estuarine circulation in the Pearl River Estuary. *Continental Shelf Research*, *168*, 68-82.

[18] Labat, D. (2010). Cross wavelet analyses of annual continental freshwater discharge and selected climate indices. *Journal of Hydrology*, *385*(1-4), 269-278.

[19] Larson CA, Belovsky GE (2013) Salinity and nutrients influence species richness and evenness of phytoplankton communities in microcosm experiments from Great Salt Lake, Utah, USA. *Journal of Plankton Research*, 35, 1154-1166.

[20] Lau, K. M., & Yang, S. (2003). Walker circulation. *Encyclopedia of atmospheric sciences*, *2505*(2510), 00450-4.

[21] Lester J, Gonzalez LA, Sage T, Gallaway A (2002). The state of the Bay: A Characterization of the Galveston Bay Ecosystem (2nd edition). GBEP T-7, Galveston Bay Estuary Program. TCEQ Publication No. AS-186/02.

[22] Lohrenz, S. E., Cai, W. J., Chakraborty, S., Gundersen, K., & Murrell, M. C. (2013). Nutrient and carbon dynamics in a large river-dominated coastal ecosystem: The Mississippi-Atchafalaya River system. *Biogeochemical Dynamics at Major River-Coastal Interfaces: Linkages with Global Change*, 448-72.

[23] Marshall, W. S. (2012). Osmoregulation in estuarine and intertidal fishes. In *Fish physiology* (Vol. 32, pp. 395-434). Academic Press.

[24] Montagna, P., Palmer, T. A., & Pollack, J. B. (2012). *Hydrological changes and estuarine dynamics* (Vol. 8). Springer Science & Business Media.

[25] Palmer, T. A., Montagna, P. A., & Kalke, R. D. (2008). Benthic indicators of the initial effect of opening a channel. *Environmental Bioindicators*, *3*(3-4), 205-206.

[26] Picaut, J., Ioualalen, M., Menkès, C., Delcroix, T., & Mcphaden, M. J. (1996). Mechanism of the zonal displacements of the Pacific warm pool: Implications for ENSO. *Science*, *274*(5292), 1486-1489.

[27] Quigg A, Davis SE, Roelke DF (2007). Final Report of the Coastal Coordination Council pursuant to National Oceanic and Atmospheric Administration Award No. NA05NOS4191064. pp. 47. Texas Coastal Management Program Cycle 10.

[28] Ropelewski, C. F., & Jones, P. D. (1987). An extension of the Tahiti-Darwin southern oscillation index. *Monthly weather review*, *115*(9), 2161-2165.

[29] Royer TC, Grosch CE, Mysak LA (2001). Interdecadal variability of Northeast Pacific coastal freshwater and its implications on biological productivity. *Progress in Oceanography*, 49(1-4), 95-111.

[30] Simons, R. D., Monismith, S. G., Saucier, F. J., Johnson, L. E., & Winkler, G. (2010). Modelling stratification and baroclinic flow in the estuarine transition zone of the St. Lawrence estuary. *Atmosphere-ocean*, *48*(2), 132-146.

[31] Sheldon JE, Alber M (2013). Effects of Climate Signals on River Discharge to Ossabaw, St. Andrew, and Cumberland Sounds. Georgia Coastal Research Council, Athens, GA, Prepared for the GA DNR-Coastal Resources Division.

[32] Sheldon JE, Burd AB (2014). Alternating effects of climate drivers on Altamaha River discharge to coastal Georgia, USA. *Estuaries and Coasts*, 37(3), 772-788.

[33] Thompson, D. W., & Wallace, J. M. (1998). The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. *Geophysical research letters*, *25*(9), 1297-1300.

[34] Tolan, J. M. (2007). El Niño-Southern Oscillation impacts translated to the watershed scale: Estuarine salinity patterns along the Texas Gulf Coast, 1982 to 2004. *Estuarine, Coastal and Shelf Science*, *72*(1-2), 247-260.

[35] Tootle GA, Piechota TC, Singh A (2005). Coupled oceanic-atmospheric variability and U.S. *streamflow. Water Resources Research*, 41, W12408, doi:10.1029/2005WR004381.

[36] U.S. Geological Survey, 2020, National Water Information System data available on the World Wide Web (USGS Water Data for the Nation), accessed September 8, 2022, at URL https://waterdata.usgs.gov/nwis/

[37] RStudio Team (2020). RStudio: Integrated Development for R. RStudio, PBC, Boston, MA URL http://www.rstudio.com/.