COASTWIDE REFERENCE MONITORING SYSTEM (CRMS)

ANALYTICAL NOTES FOR CRMS COASTWIDE TRENDS IN HYDROLOGY AND WETLAND SURFACE ELEVATION (2008-2023)

APPENDIX B - BOUNDARY CONDITIONS, HYDROLOGY GROUPINGS, AND ACCRETION RATE CALCULATIONS

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COASTWIDE REFERENCE MONITORING SYSTEM (CRMS)

This document features data collected through Louisiana's Coastwide Reference Monitoring System (CRMS), a network of 390 coastal monitoring sites that provide comprehensive information on coastal trends necessary to plan, implement and assess coastal restoration projects and in support of CPRA's Coastal Master Plan. The CRMS network was established in 2005 to provide a complete suite of monitoring data for Coastal Wetland Planning, Protection and Restoration Act (CWPPRA) projects. CRMS monitoring is conducted by the Coastal Protection and Restoration Authority (CPRA) and the U.S. Geological Survey (USGS) and is currently funded by the CWPPRA program, the Louisiana Trustee Implementation Group for the Deepwater Horizon Natural Resource Damage Assessment (NRDA) Trustees, and the State of Louisiana. CRMS data are publicly available from CPRA's Coastal Information Management System (CIMS; link) and derived data are available through USGS's CRMS website (link).

CITATION

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This work was funded, in part, by the Louisiana Trustee Implementation Group as part of the effort to restore natural resources injured by the 2010 *Deepwater Horizon* oil spill.

EXECUTIVE SUMMARY

This document is an appendix to the 2008-2023 CRMS Data Synthesis. It features analytical notes related to boundary conditions, hydrology groupings and accretion rate calculations.

Sea level varies cyclically in coastal Louisiana with decades of relatively high sea level followed by decades of relatively low sea level. The timing of these cycles aligns with processes that drive the Jet Stream including the North Atlantic Oscillation, El Nino Southern Oscillation, and the 18.6 year lunar nodal cycle. The location of the Loop Current and of warm core eddies that have been shed from the Loop Current directly impact coastal Louisiana and effectively define what is possible from a water management perspective. Understanding and anticipating these cyclical drivers should benefit CRMS data users and coastal planners as they interpret trends in water level and salinity.

The 2008-2023 CRMS Synthesis Report features hydrology groups that were defined by tidal connectivity and wetland type. Notes related to the discriminant analysis used to confirm group differences are provided.

The CRMS accretion sampling approach has been to regularly deploy new feldspar marker horizons while systematically sampling the older plots. There are now eight different sets of accretion plots established and sampled at different times during the CRMS monitoring timeframe (since 2006). The relationship between accretion rates from plots of different ages is examined to show that short term rates over-estimate accretion until the plots are about 15 years old.

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LIST OF ABBREVIATIONS

CIMS .... COASTAL INFORMATION MANAGEMENT SYSTEM
CO-OPS .... CENTER FOR OPERATIONAL OCEANOGRAPHIC PRODUCTS AND SERVICES
CPRA .... COASTAL PROTECTION AND RESTORATION AUTHORITY
CRMS .... COASTWIDE REFERENCE MONITORING SYSTEM
CWPPRA .... COASTAL WETLANDS PLANNING, PROTECTION, AND RESTORATION ACT
DWH .... DEEPWATER HORIZON
ENSO .... EL NINO SOUTHERN OSCILLATION
EPA .... ENVIRONMENTAL PROTECTION AGENCY
NAO .... NORTH ATLANTIC OSCILLATION
NOAA .... NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NRCS .... NATURAL RESOURCES CONSERVATION
NRDA .... NATURAL RESOURCE DAMAGE ASSESSMENT
PS .... PLOT SET
TIG .... TRUSTEE IMPLEMENTATION GROUP
USACE .... U.S. ARMY CORPS OF ENGINEERS
USFWS .... U. S. FISH AND WILDLIFE SERVICE
USGS .... U. S. GEOLOGICAL SURVEY SERVICE
VA .... VERTICAL ACCRETION

1 - HYDROLOGY BOUNDARY CONDITIONS

SEA LEVEL VARIATION

Gulf sea level rise shows a consistent increasing trend through cycles of flood and drought with decades spent above and below the rising trend (Figures 1 and 2). Over the CRMS monitoring timeframe, sea level transitioned from relatively low (2006 to 2011) to very high (2015-2020) back to relatively low (2022 to present).

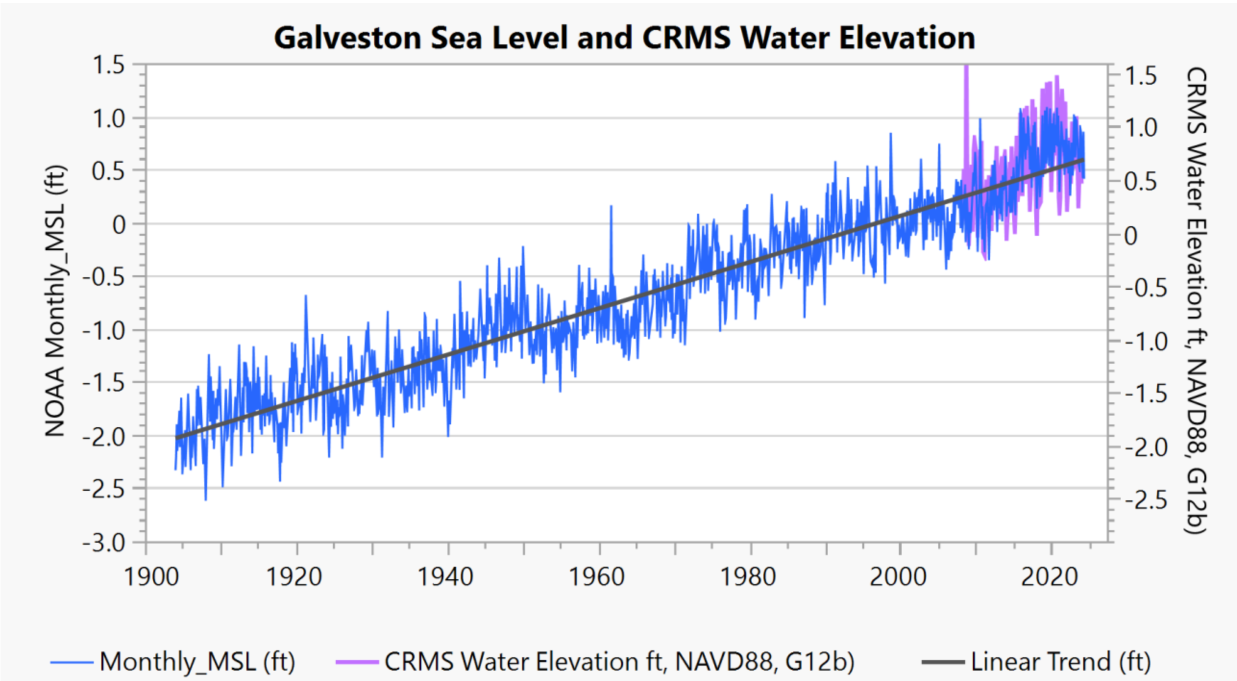


Figure 1. Monthly mean sea level (ft) at Galveston, TX's Pier 21 from 1904 through 2024 (Source: Center for Operational Oceanographic Products and Services (CO-OPS)), and CRMS monthly mean water elevation (ft, NAVD88 G12b). Note NOAA data have seasonality removed and CRMS data are as observed.

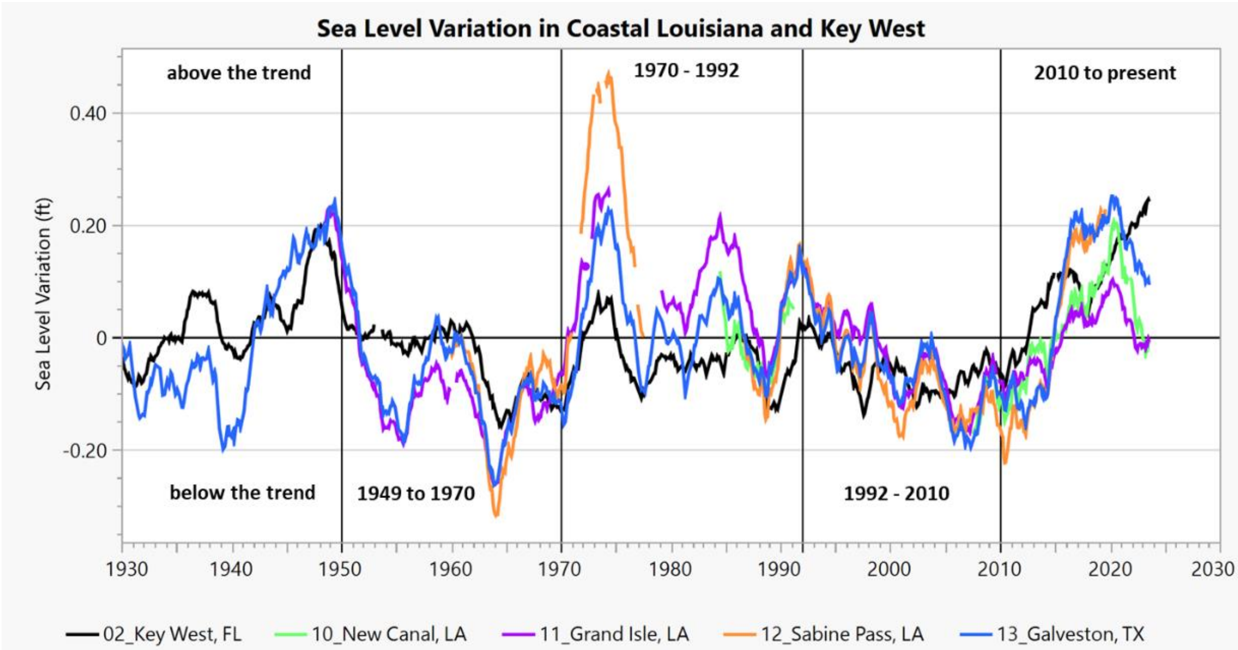


Figure 2. Sea level variation at Key West, New Canal, Grand Isle, Sabine Pass and Galveston gauges. All stations represented by a 36 month moving average.

NORTH ATLANTIC OSCILLATION (NAO)

The North Atlantic Oscillation (NAO) influences Jet Stream dynamics (Figure 3) and causes relatively high sea level in the Gulf along with higher rainfall in the Mississippi River watershed when in its positive phase and relatively low sea level and lower rainfall when in its negative phase (Figures 4 and 5).

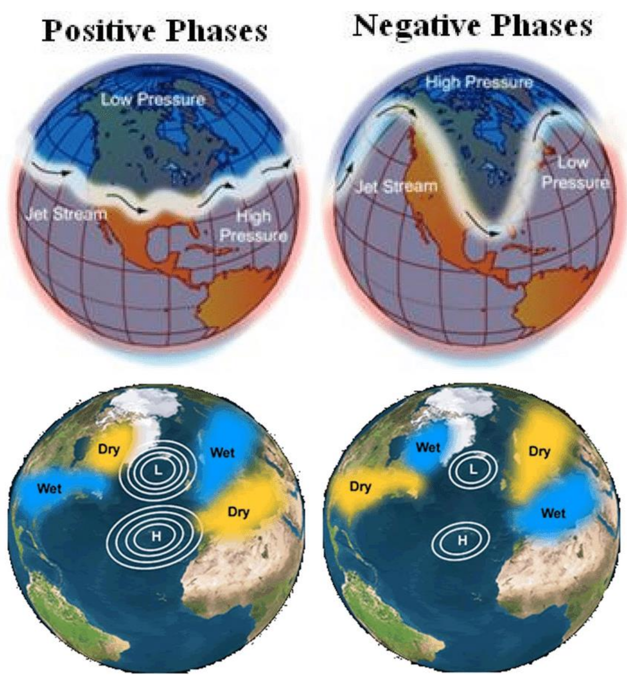


Figure 3. NAO diagram showing jet stream, pressure and precipitation patterns in the Positive and Negative phases. Sea level, rainfall and Mississippi River levels are all higher in coastal Louisiana in the positive phase of the NAO.

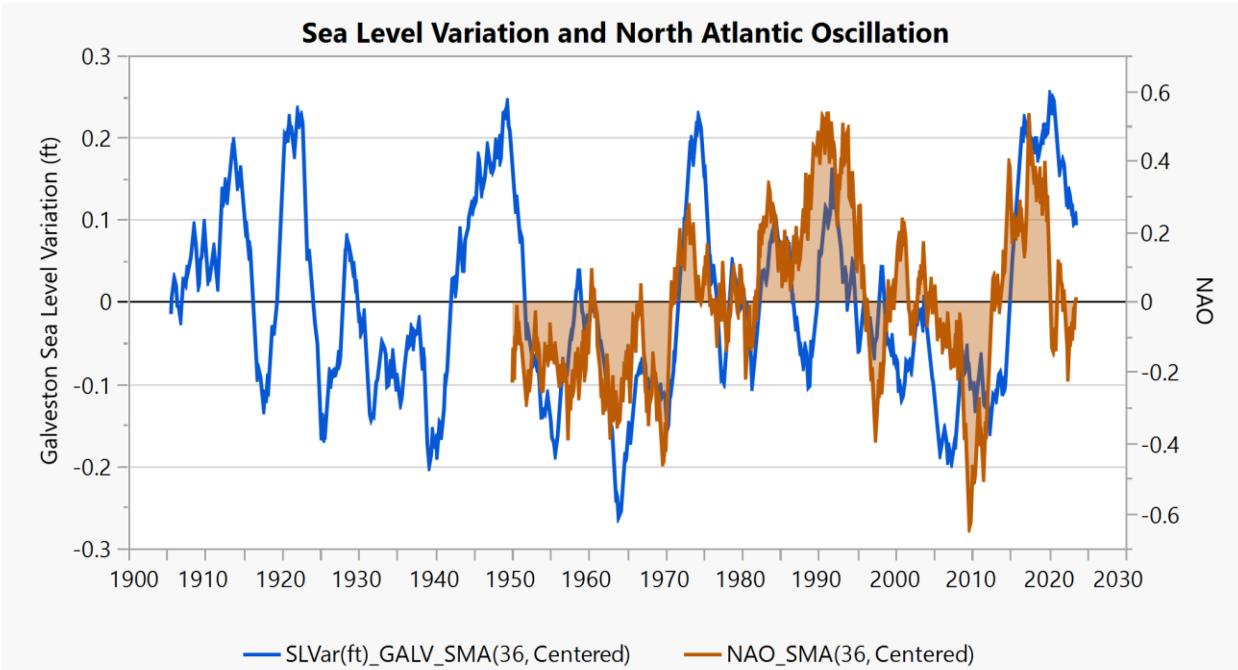


Figure 4. Galveston sea level variation and NAO. Both monthly datasets were smoothed with a 36 month moving average (centered).

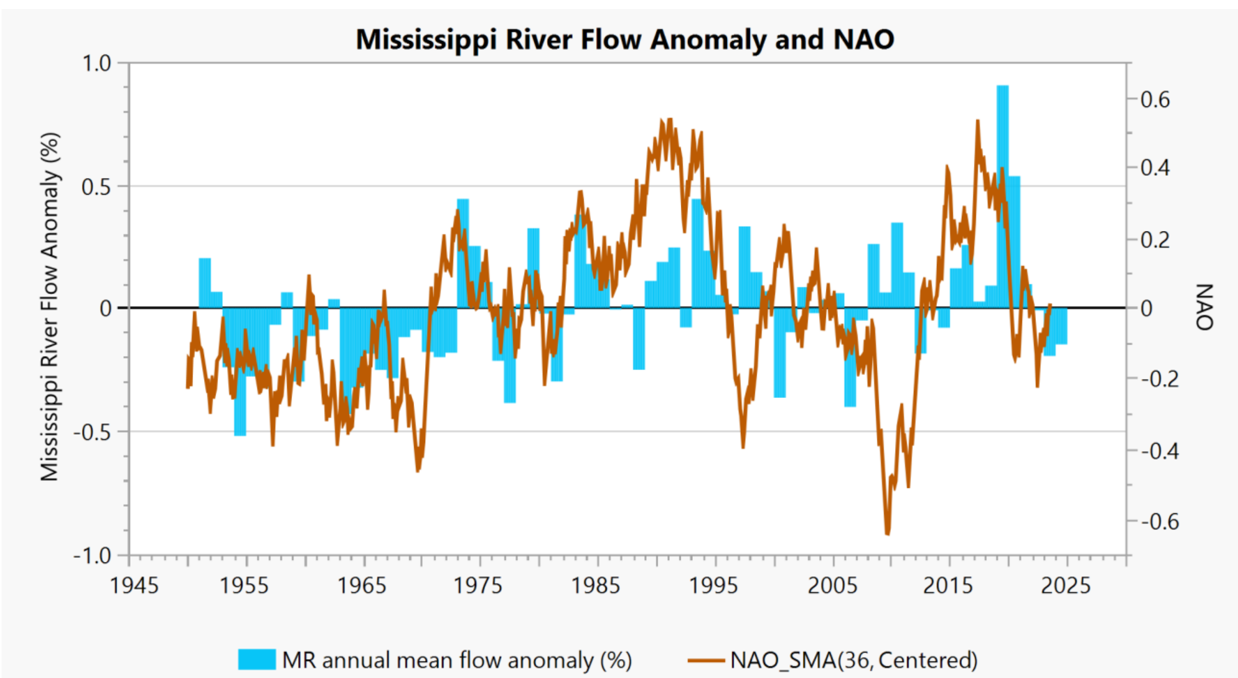


Figure 5. Mississippi River flow anomaly and NAO (smoothed with 36 month moving average).

LUNAR NODAL CYCLE

The 18.6 year lunar nodal cycle causes variation in sea level and tide range in the northern Gulf where tidal energy is lower when the moon is further from earth and higher when the moon is closer. The duration of each peak is around three years and it takes 18.6 years to complete a full cycle so we experience three years of relatively low tidal energy followed by a transition to the opposite phase and three years of relatively high tidal energy nine years later. We are currently at the peak of the relatively low water phase (2024-2026). The last high water phase began around 2015 and did align with an increase in sea level and associated flooding (Figure 6).

The effect of the lunar nodes on Gulf sea level does seem to be ramping up (Figure 7). The last full cycle saw large departures from the rising trend in both directions with very low water transitioning to very high water and back to very low water (current conditions).

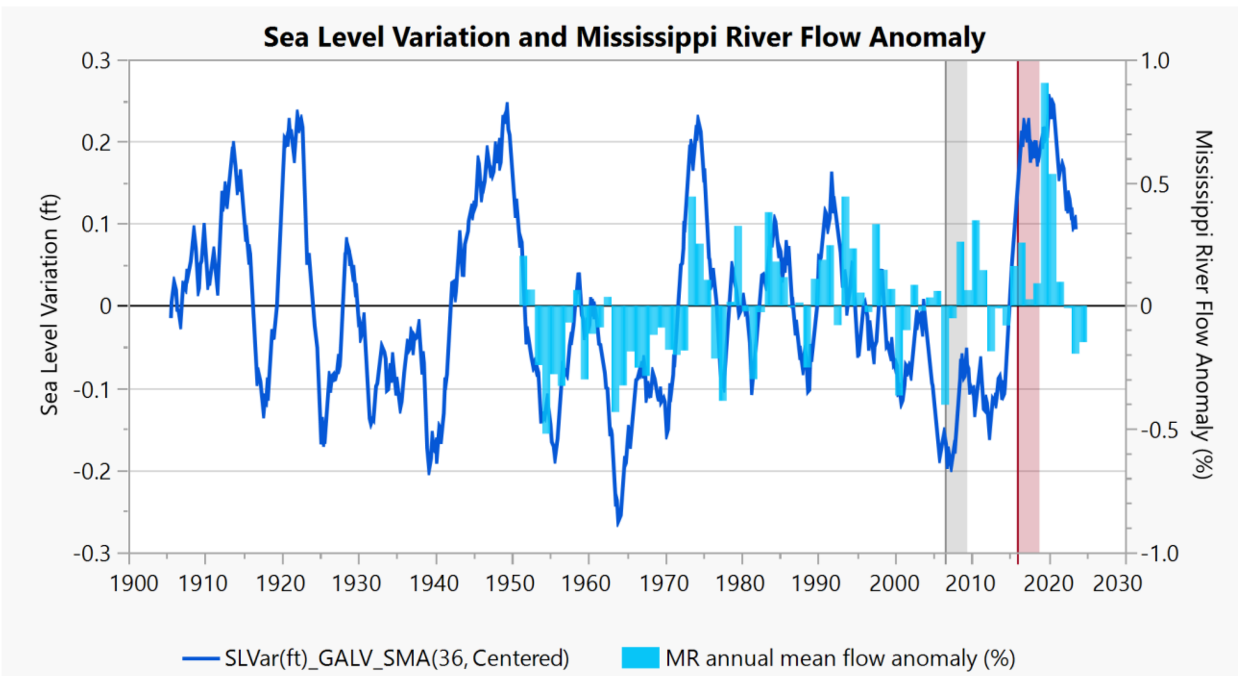


Figure 6. Galveston sea level variation, Mississippi River flow anomaly, and timing of the last lunar nodal cycle. Black line indicates when the last low water phase of the cycle began (2006.5) and the grey bar highlights the three years that followed. Red line marks the beginning of the most recent high water phase (2015.8) and the red bar highlights the three years that followed. We are currently in a low water phase that began on 2025.1. The next high water phase is expected to arrive in 2034.4.

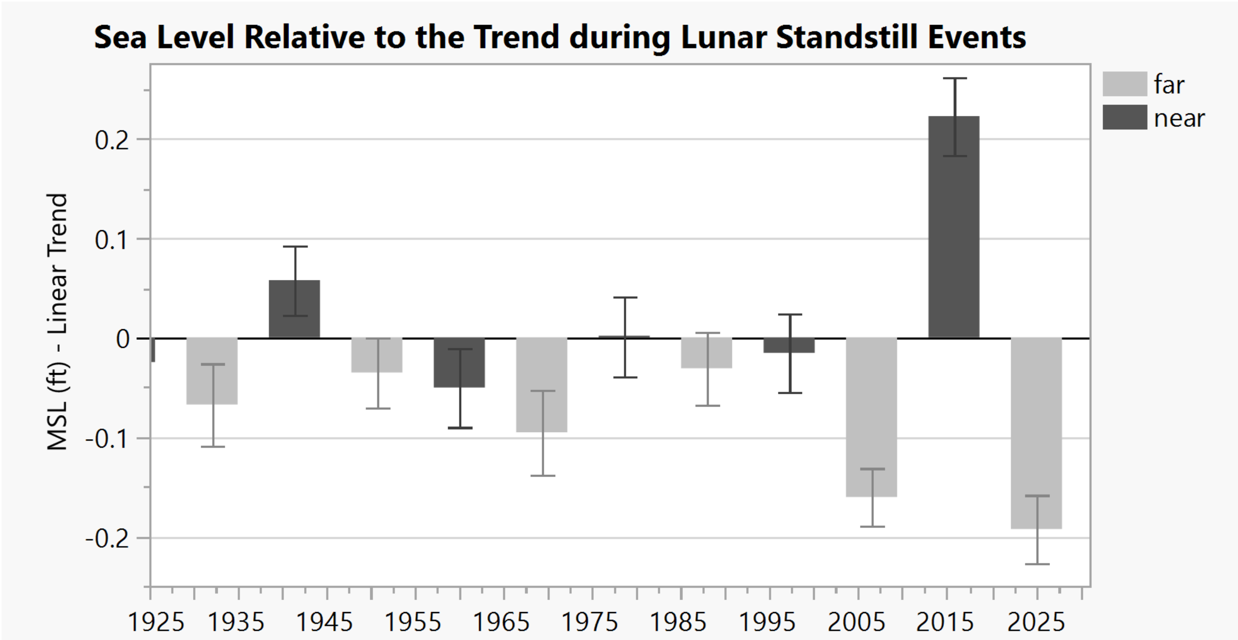


Figure 7. Average departure from the rising trend during the three years after each lunar nodal event using the NOAA Galveston Pier 21 dataset. Mean +/- Std Err. The last bar only includes one year of data (2025). The effect has been amplified for the last full cycle. It is reasonable to expect a strong departure from the mean in the next flood cycle that begins in 2034.

EL NINO SOUTHERN OSCILLATION (ENSO)

There are also associations between sea level, rainfall and ENSO cycles though the effects aren't as direct or easy to find and the relationship may be changing. In general, sea level variation had an inverse relationship with ENSO where sea level is lower during El Nino (ENSO positive) and higher during La Nina (ENSO negative). In recent decades, the relationship appears to have flipped (Figure 8).

The 2016 El Nino event was a strong one that co-occurred with the positive phase of the NAO. The resulting sea level rise was among the highest we've seen in coastal Louisiana. The 2022/2023 drought co-occurred with the negative phase of the NAO and the subsequent drought was also severe (Figure 9).

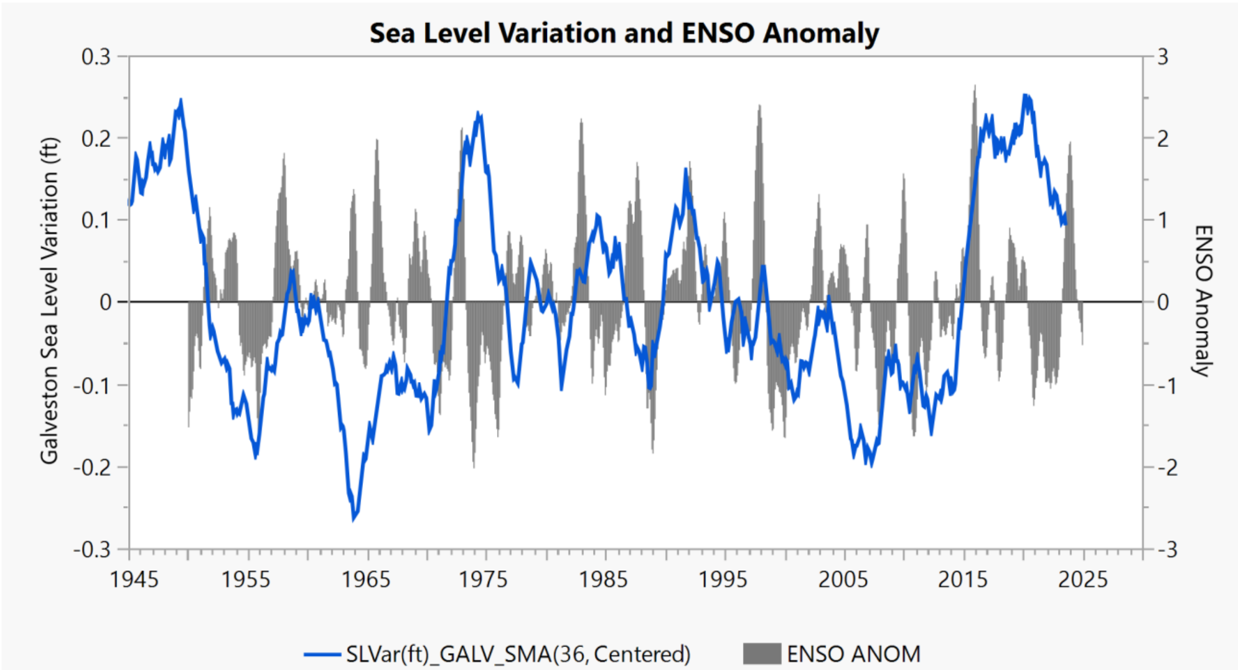


Figure 8. Galveston sea level variation and ENSO anomaly. Sea level has historically had an inverse relationship with ENSO though in recent decades the relationship appears to have flipped

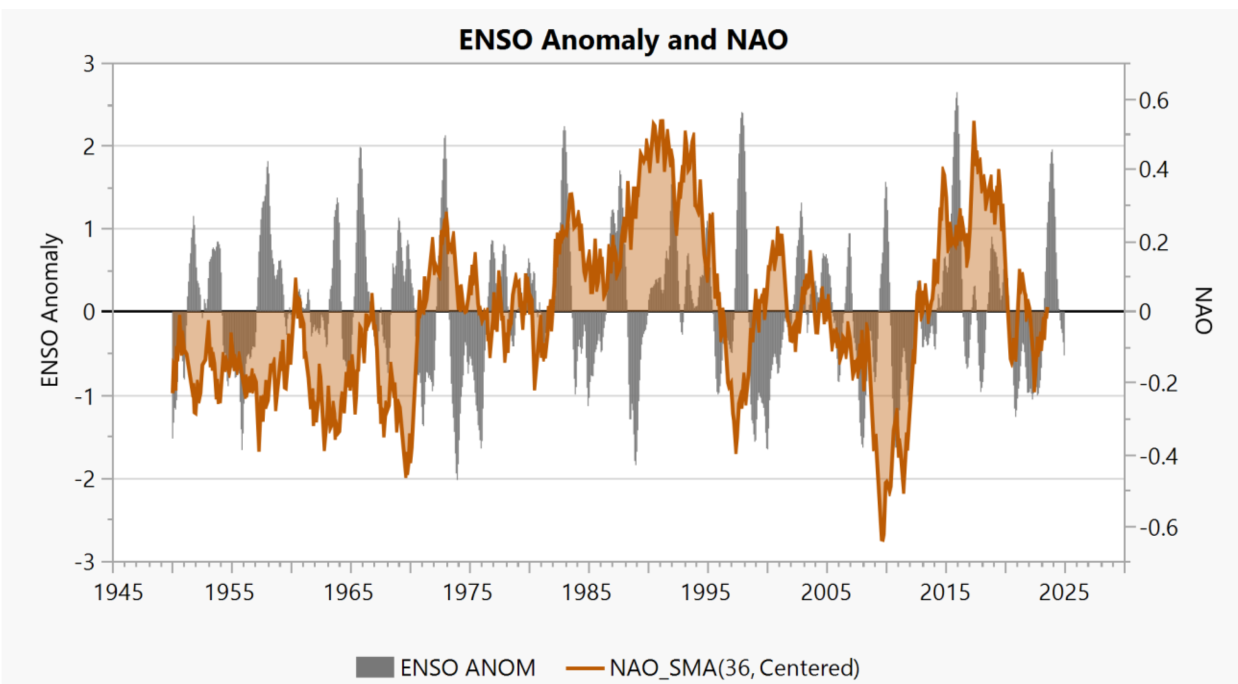


Figure 9. ENSO anomaly and the NAO. ENSO values as reported by NOAA. NAO represented by a 36 month simple moving average.

LOOP CURRENT INTERACTIONS WITH THE ESTUARINE BOUNDARY

The loop current enters the Gulf through the Yucatan Channel and exits through the Florida Straits. It can extend well into the Gulf where the tip of the current breaks off from the main current and forms anti-cyclonic warm core eddies that linger in the Western Gulf (Figure 10). At times, Loop Current eddies interact with Louisiana's coastal boundary which causes a rapid increase in water level and amplifies coastal challenges (Figure 11).

Loop current interactions with the Louisiana coast occurred repeatedly during the last high water timeframe which meant that drainage potential was reduced at the same time as high rainfall and high Mississippi River flooding was occurring. Loop current eddies spilling into the nearshore environment was unexpected and the effects were long lasting. Nearshore sea level remained relatively high until conditions shifted to La Nina, drought dominated weather in 2021. Persistent western circulation during the drought (2022 and 2023) pulled water away from the coast (Figure 11). Through 2025, water remained relatively low as no new Loop Current eddy/nearshore interactions have occurred since the drought.

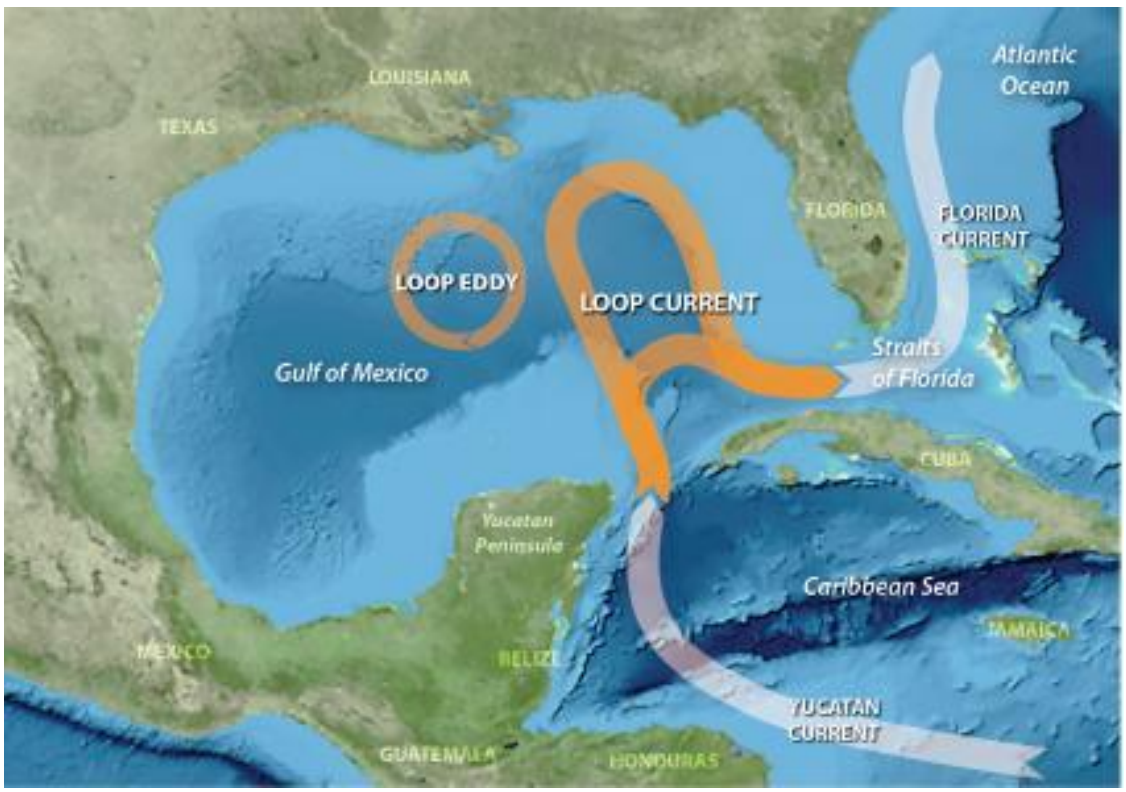


Figure 10. Diagram depicting the Loop Current tracks and shed eddy formation (credit NOAA).

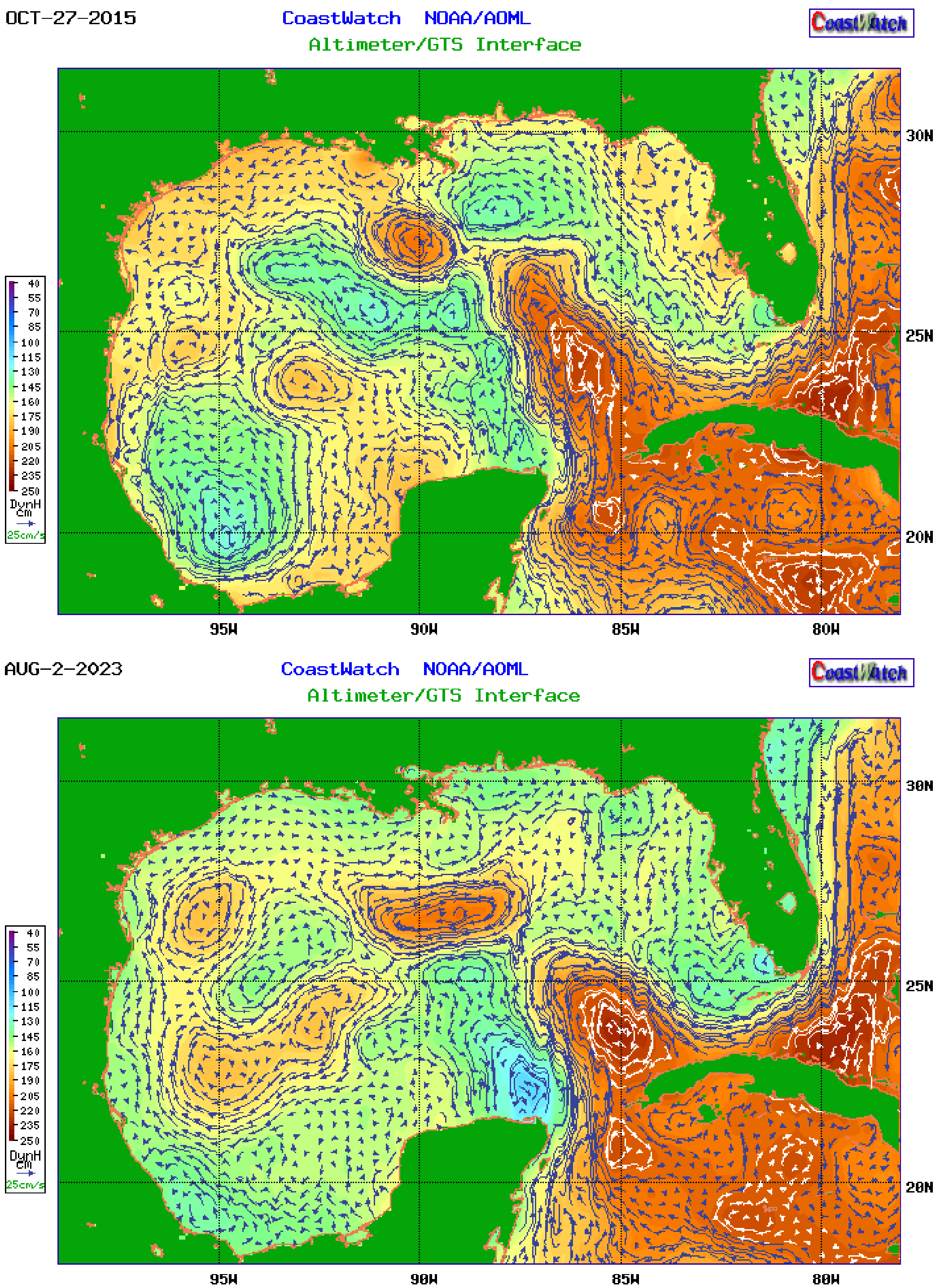


Figure 11. Sea surface height from NOAA's CoastWatch dataset. Top image captures conditions at the onset of the last flood cycle (October 2015). Note a shed eddy is interacting with nearshore currents. Bottom image captures conditions during the 2023 drought. Note the envelope of low water that forms along the coastal margin when circulation patterns are from the west.

BOUNDARY CONDITIONS SUMMARY

It is clear that Gulf sea level responds to global scale processes and that cycles of flood and drought can be extreme with impacts to nearshore hydrology that persist for years. In coastal Louisiana, we have no choice but to adapt to nearshore conditions in the Gulf. Having collected CRMS data through an entire 18.6 year lunar nodal cycle (2006.5 to 2025.1), we do now have insight into when we should expect high water and when we should expect low water. NAO negative and La Nina should be accompanied by drier conditions, lower Mississippi River levels, lower precipitation and lower sea levels. NAO positive and El Nino should come with higher tides, higher precipitation, higher sea level, and more coastal inundation. When these conditions align with peaks in the lunar nodal cycle, effects will be amplified. We are currently at the phase of the lunar cycle where the moon's effect on water level is the least and we have NAO- weather and low water. The next peak is in 2034.4. It is reasonable to expect hydrologic conditions to be at least as bad as if not worse than they were between 2015 to 2020. Louisiana's coastal citizens should anticipate the next flood cycle and consider what actions may be taken now to help alleviate future inundation problems.

2 - HYDROLOGY GROUP FORMATION NOTES

The approach to defining CRMS hydrology groups to be used in data summaries for this report began with a full suite of classes that were defined by region (Chenier/Deltaic), tidal connectivity, and marsh type with active deltas separated from other tidal fresh marshes (termed GeoTide classes; N=11). Groups were reduced to exclude region as tidal connectivity and region were synonymous. Deltaic plain marshes are mostly tidal due to their location on the landscape. Wetlands transition from tidal saline marsh to tidal fresh marsh to non-tidal fresh marshes and swamps going inland. Chenier Plain marshes are mostly impounded (non-tidal) with a few tidal stations outside of levees or connected to shipping channels. Classes were reduced from eleven to seven using discriminant analysis.

Upon further review, meaningful differences in elevations in the two active deltas were recognized as the Atchafalaya delta marsh sites were much higher than the Mississippi delta marsh sites so the active delta group was sub-divided. Atchafalaya swamp sites were higher than other swamps across the coast and the Pearl River swamp sites were much more tidal than other swamps so those two regions were separated from other swamps.

DISCRIMINANT ANALYSIS

The original hydrology GeoTide classes had eleven groups separated hydrologically and geographically by Chenier and Deltaic plain. These groups overreached the hydrologic data in some classes where little difference was present in the data set (Figure 12). An example of this is the Deltaic plain impounded saline group which through the discriminant testing was misclassified with five other groups increasing from the seven original CRMS sites correctly classified to 25 total CRMS sites (Table 1). Also the Delta plain impounded fresh group only had one of a possible 9 CRMS sites correctly classified based on the pre-selected site groupings. Many of the other groups were classified either completely correct or very nearly so. Therefore, the decision was made to remove the Chenier/Deltaic separation and proceed with a more solely hydrologically driven classification method.

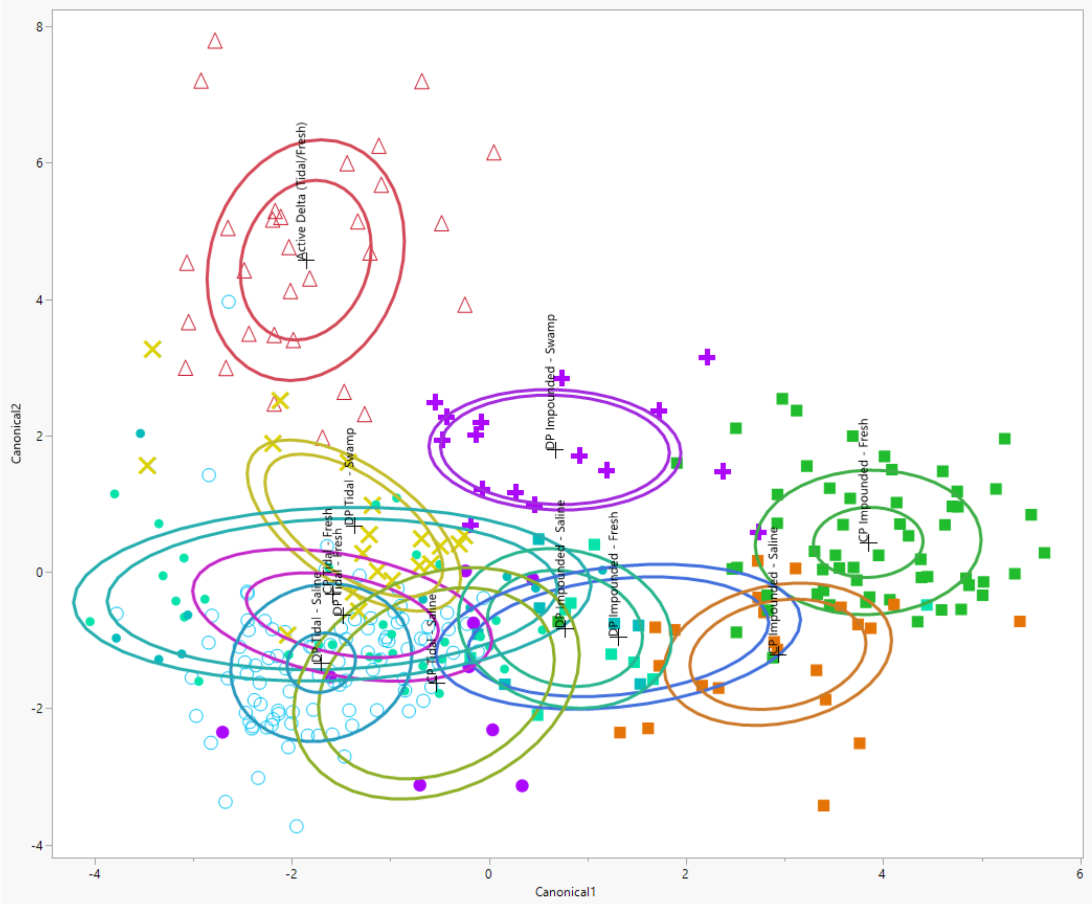


Figure 12. Discriminant analysis using a quadratic method on CRMS sites arranged by geographic and hydrologic group assignments. The Deltaic plain impounded fresh and the Deltaic plain impounded saline did not group as planned in testing and the removal of the geographic component of the classification led to cleaner more interpretable groups which could consistently be classified in a subsequent discriminant analysis.

Table 1. Misclassification metrics and number of CRMS sites by geographic and hydrologic group assignment based on all hydro variables. This was an effective classification approach for most of the classes but not all. Specifically the Deltaic plain impounded fresh and the Deltaic plain impounded saline performed poorly, with the latter only having one CRMS site classified into the group.

Source	Count	Number Misclassified	Percent Misclassified	Entropy RSquare	-2LogLikelihood
Training	303	28	9.24092	0.66794	416.316

Actual	Predicted Count										
GeoTide Class	**Active Delta**	**CP Imp - Fresh**	**DP Imp - Fresh**	**CP Imp - Saline**	**DP Imp - Saline**	**DP Imp - Swamp**	**DP Tidal - Swamp**	**CP Tidal - Fresh**	**DP Tidal - Fresh**	**CP Tidal - Saline**	**DP Tidal - Saline**
Active Delta	30	0	0	0	0	0	0	0	0	0	0
CP Imp - Fresh	0	52	0	0	4	0	0	0	0	0	0
DP Imp - Fresh	0	0	1	0	8	0	0	0	0	0	0
CP Imp - Saline	0	4	0	14	4	0	0	0	0	0	0
DP Imp - Saline	0	0	0	0	7	0	0	0	0	0	0
DP Imp - Swamp	0	0	0	0	0	16	0	0	0	0	0
DP Tidal - Swamp	0	0	0	0	0	0	19	0	0	0	0
CP Tidal - Fresh	0	0	0	0	1	0	0	7	0	0	2
DP Tidal - Fresh	0	0	0	0	0	0	0	0	32	0	0
CP Tidal - Saline	0	0	0	0	1	0	0	0	0	6	2
DP Tidal - Saline	0	0	0	0	0	0	0	2	0	0	91

Post original group assignment, CRMS sites with the appropriate data types and completeness where grouped into the following categories for data synthesis and discussion: Active Delta, Tidal Swamp, Tidal Fresh, Tidal Saline, Impounded Swamp, Impounded Fresh, and Impounded Saline. The groupings were tested with a linear discriminant analysis featuring the quadratic method applied to the raw data and selected groups to assess the predicted membership of categories based on the observed continuous variables (Figure 13). This yielded a misclassification percentage of 1.65, with the most misclassification between the fresh and saline tidal and impounded groups (Table 2). These hydrologic conditions operate on an ever changing range of quantitative measures. For the objective of data synthesis and interpretation, categorical groups where used that share some overlap at the borders but as seen in the analysis are excellent predictors of appropriate group fit.

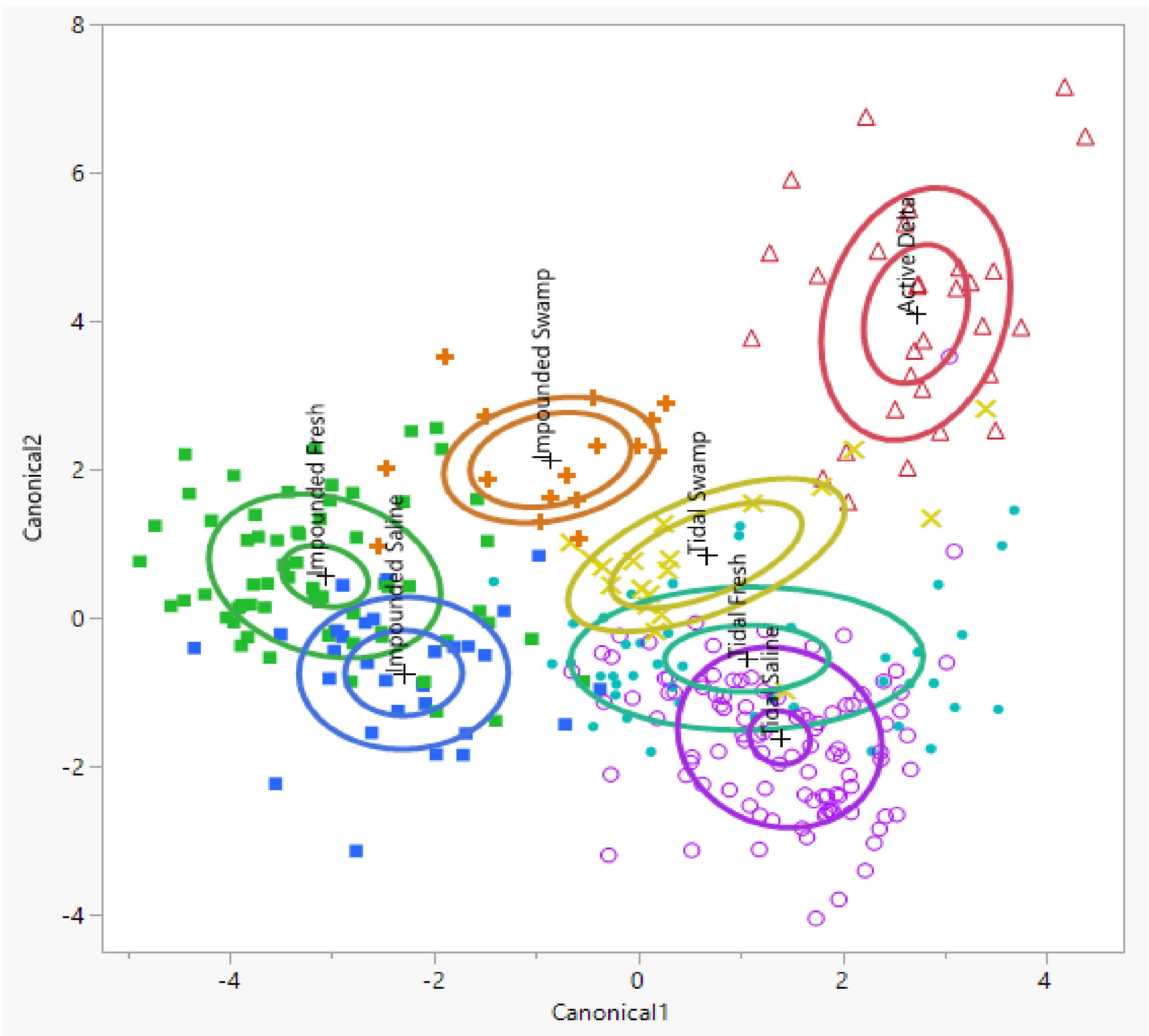


Figure 13. Discriminant analysis using a quadratic method on CRMS sites hydrologic group assignments. The fresh and saline tidal and impounded groups overlap as this categorical arrangement for simplicity represents a continuum of hydrologic conditions.

Table 2. Misclassification metrics and number of CRMS sites by hydrologic group assignment based on all hydro variables.

Source	Count	Number Misclassified	Percent Misclassified	Entropy RSquare	-2LogLikelihood
Training	303	5	1.65017	0.96399	38.2567

Actual	Predicted Count						
Hydro Groups	**Active Delta**	**Impounded Fresh**	**Impounded Saline**	**Impounded Swamp**	**Tidal Fresh**	**Tidal Saline**	**Tidal Swamp**
Active Delta	30	0	0	0	0	0	0
Impounded Fresh	0	63	2	0	0	0	0
Impounded Saline	0	1	28	0	0	0	0
Impound Swamp	0	0	0	16	0	0	0
Tidal Fresh	0	0	0	0	42	0	0
Tidal Saline	0	0	0	0	0	102	0
Tidal Swamp	0	0	0	0	2	0	17

3 – ACCRETION RATE REVIEW

For this analysis, VA rates were calculated across PS as a regression through accretion (mm) and time (years) in measurement (Table 3). The rates derived from this approach are very similar to rates derived from the oldest plot sets and diverge from rates derived from newer plot sets (Figure 14). In fact, newer plot sets overestimate full term accretion by >50% (Figure 15).

If data users are looking for one number to represent sites over time, accretion from the oldest plot sets would be best. It is also appropriate to calculate a rate across plot sets as described if it is important to use every data point. It would not be appropriate to average rates from different plot sets as they would be over inflated by rates from recently established plots.

Accretion rates from different aged plots begin to approximate long term rates after about 15 years (Figure 15).

Table 3. CRMS Accretion Plot Set Summary

CRMS Accretion Plot Set	PS Establishment Season	Median Establishment Date	Max Sample Season	PS Age as of 4/1/2024 (yrs)
PS1	Spring 2008	1/22/2008	Spring 2022	16.2
PS2	Spring 2010	3/17/2010	Spring 2023	14.1
PS3	Spring 2012	3/20/2012	Spring 2024	12.0
PS4	Spring 2014	4/1/2014	Spring 2022	10.0
PS5	Fall 2016	10/6/2016	Spring 2023	7.5
PS6	Spring 2018	4/3/2018	Spring 2024	6.0
PS7	Spring 2020	4/1/2020	Spring 2023	4.0
PS8	Spring 2023	2/28/2023	Spring 2024	1.1

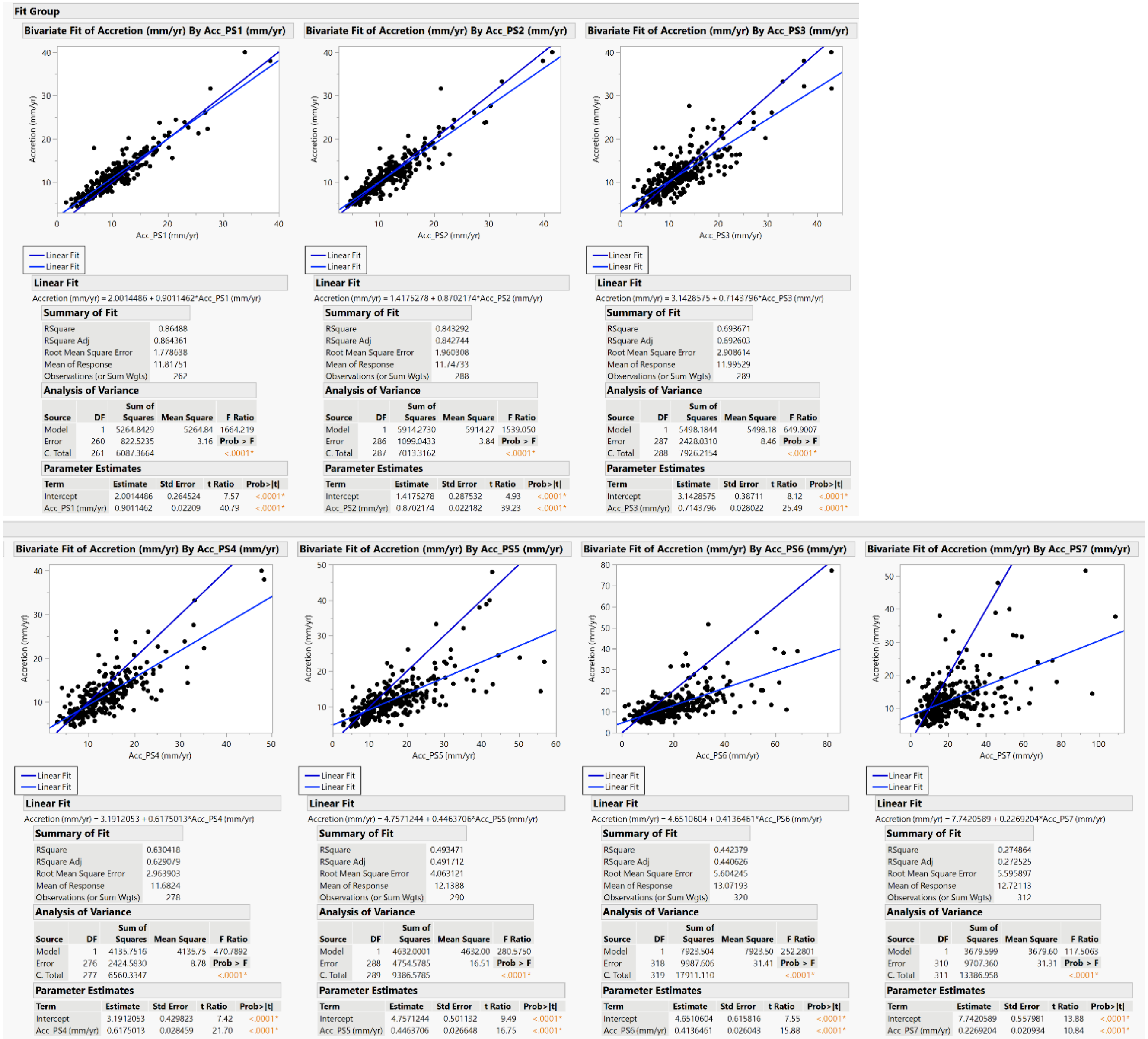
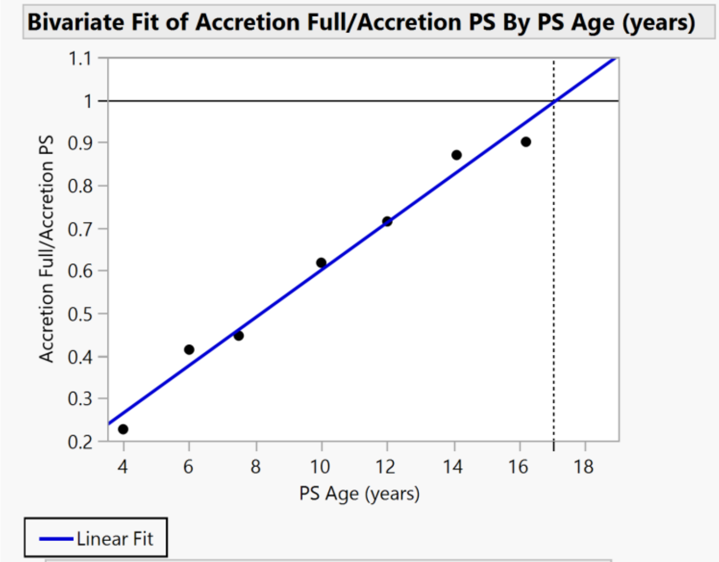


Figure 14. Bivariate fit of accretion rate used for this analysis (Accretion mm/yr) against rates derived by Plot Set for PS 1 – PS 7. Black line has slope of 1:1 and is constrained through 0. Blue line is unconstrained linear regression. Note the older plot sets approximate the time integrated rate while the newer plot sets capture much higher rates of accretion due to the fluffiness of relatively new, unconsolidated soils.



Linear Fit

Accretion Full/Accretion PS = 0.0408964 + 0.0559299*PS Age (years)

Summary of Fit

RSquare	0.981154
RSquare Adj	0.977385
Root Mean Square Error	0.037576
Mean of Response	0.598597
Observations (or Sum Wgts)	7

Figure 15. Plot of slopes from Figure 5-2 against plot set age.
Estimate Full Accretion = Plot Set Accretion at year 17 though linear trend appears to level off after year 14