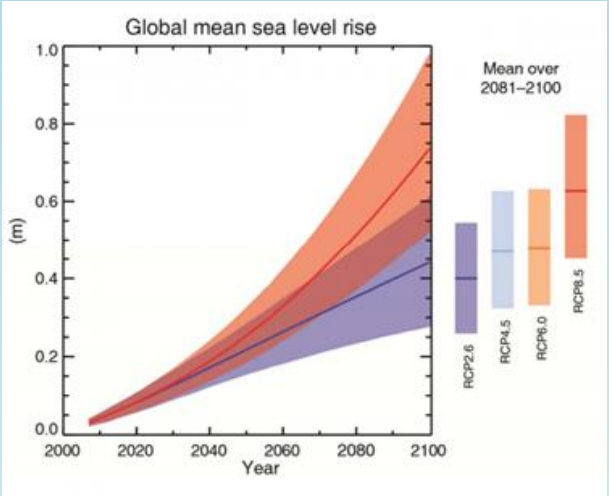
Modeling Sea Level Rise Using Simulations and Observations

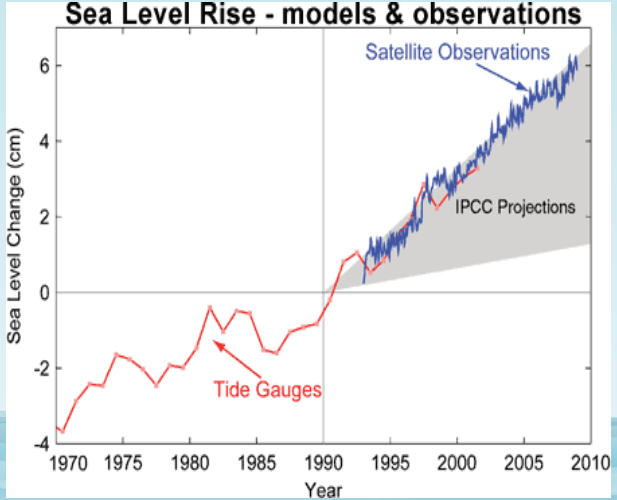
Marisela Madrid & Hanna Vaidya

Why sea level rise in Florida?

Sea level rise = increase in level of the world's oceans

- Global mean sea level (GMSL) is rising 3 mm/yr (no GIA)
- Florida is sinking while the ocean is rising at a faster rate and poses a great threat of flooding
- By 2050-2060, sea level rise may increase up to 0.5 m in Florida

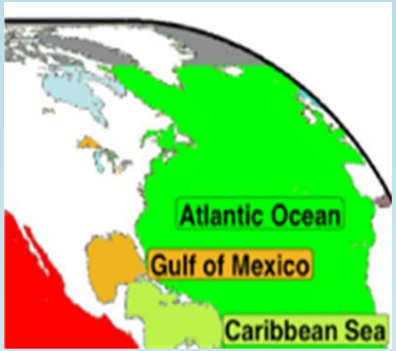




http://www.copenhagendiagnosis.com/

Why do we care?

- Reveals the extent to which local sea level relates to the regional ("adjacent") basins (Atlantic Ocean and Gulf of Mexico) and global sea level
- Indicates to what degree (if any) local or regional factors influence sea level (water temperature, salinity, wind, hydrology, currents, etc.)
- GMSL projections from climate models may underestimate mean sea level rise in coastal regions
- Local infrastructure and planning (8,436 mi of coastline)
- Florida sea level climate studies are a decade old e.g., *(Mitchum, 2011)*



Regional ("adjacent") basins with respect to Florida

Research Objectives

What is driving sea level in coastal Florida?

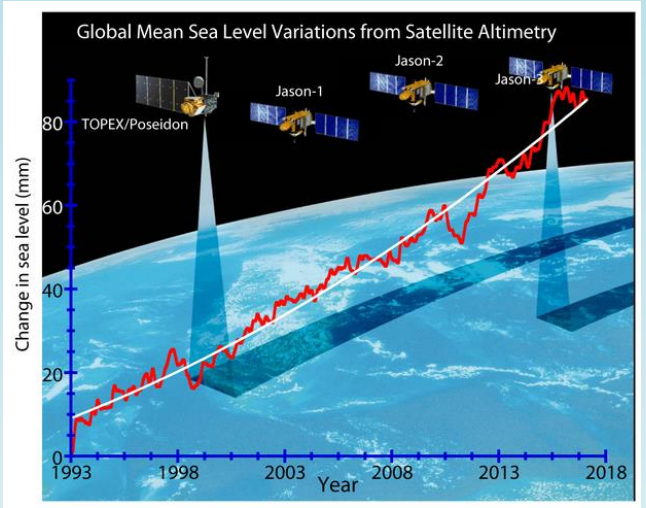
Do large scale sea level estimates (regional and global levels) impact sea level in coastal Florida?

Do various climate factors (water temperature, salinity, and El Niño Southern Oscillation) impact sea level in coastal Florida?

Data

Overall, the time period investigated was 1992-2019

- Global altimetry
- Regional altimetry (North Atlantic, Gulf of Mexico)
- Local (FL) altimetry
- Temperature and Salinity (at 5 m depth) ENSO 3.4 index

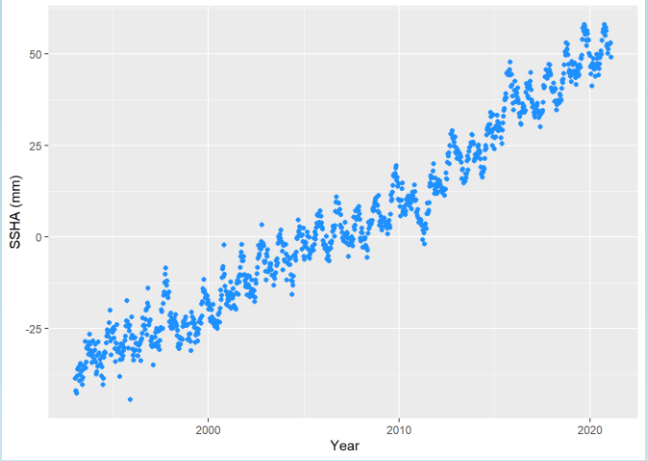


Averaged all datasets to a **yearly resolution** to remove seasonal signals

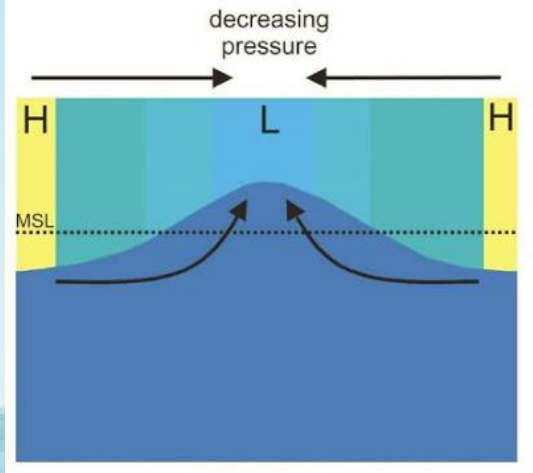
Scientists have detected an acceleration in sea level rise (skepticalscience.com)

Altimetry Data

- Collected from satellites (different satellites for different time periods)
- Global /regional = ~every 10 days
- Local = ~every 5 days
- Corrected for inverse barometer effects
- ****Not corrected for isostasy****

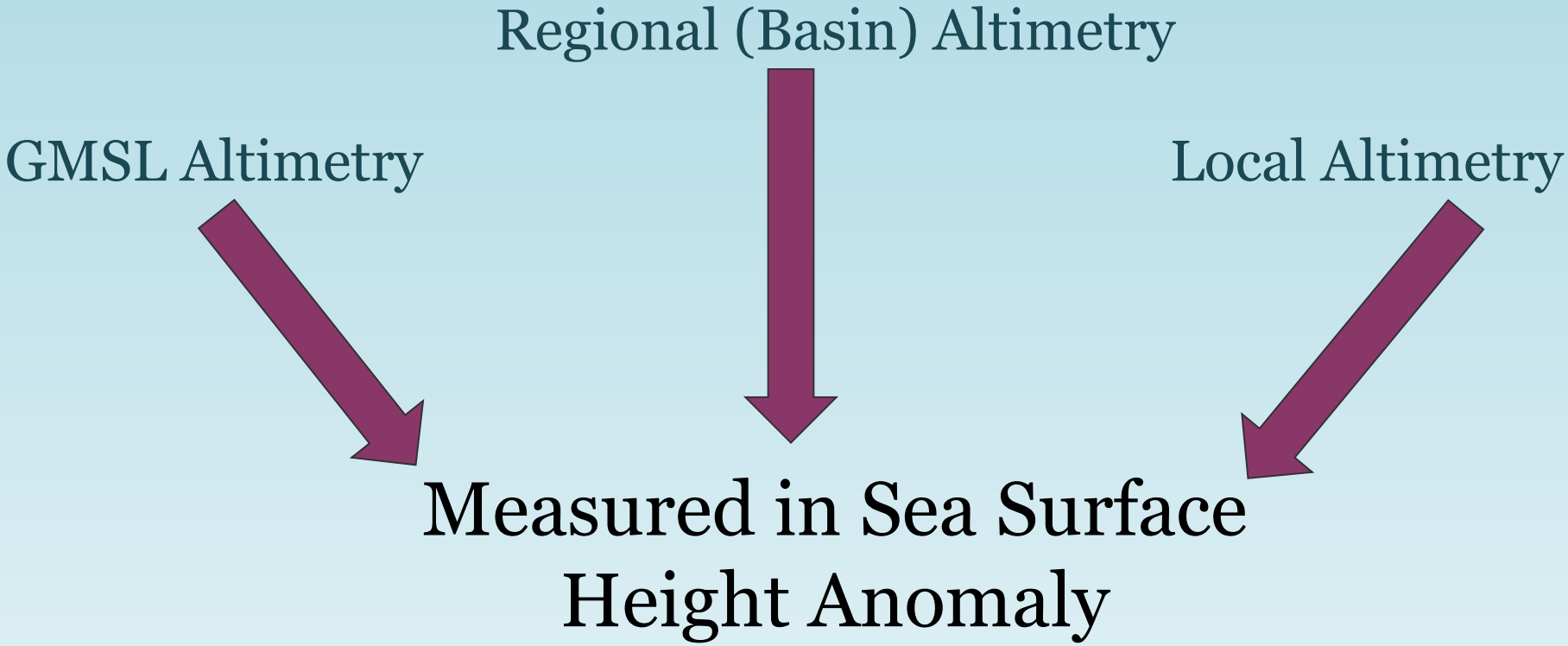


GMSL altimetry time series (1992-2021)



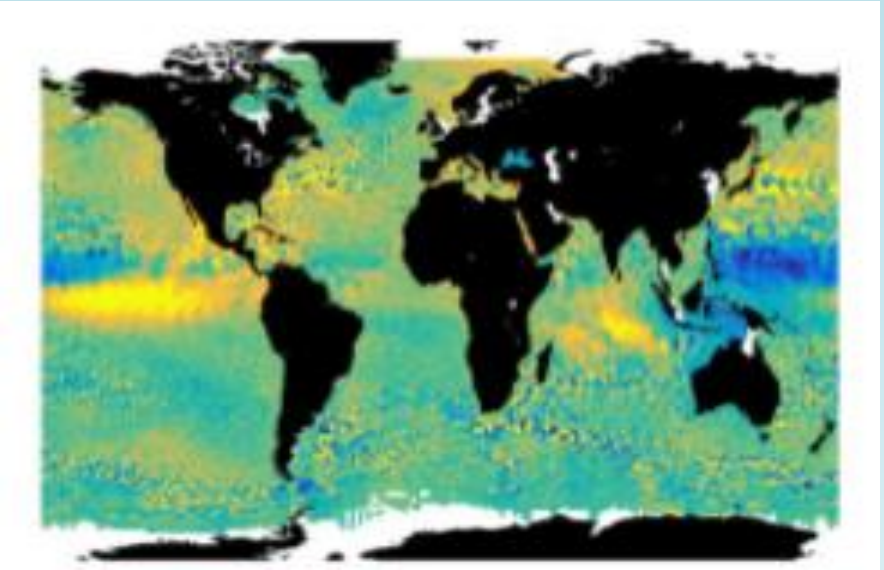
Inverse barometer effect

Cliff Mass Weather Blog: High Pressure Produces Low Sea Level


Regional (Basin) Altimetry
GMSL Altimetry
Local Altimetry
Measured in Sea Surface Height Anomaly

Sea Surface Height Anomaly (SSHA)

- How altimetry data is processed
    - A spatiotemporal mean map is computed using grids from all available years (1992-2019) and then is subtracted from individual grid values to estimate anomalies



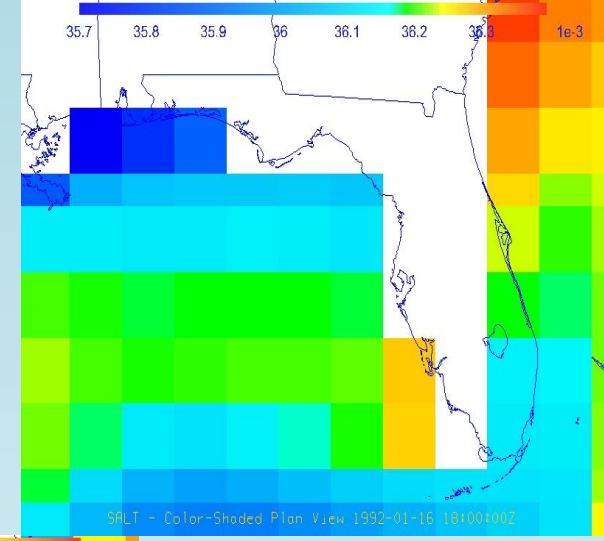
alti-gridding-jpl-PODAAC-UserGuide_20200227 (nasa.gov)

ECCO Consortium, Fukumori, I., Wang, O., Fenty, I., Forget, G., Heimbach, P., & Ponte, R. M.. 2021

Temperature & Salinity Data (1992-2019)

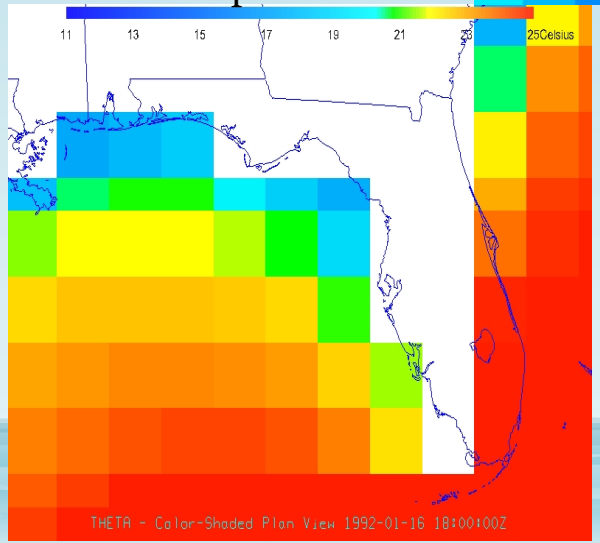
- Monthly-averaged ocean temperature (°C) and salinity (PSU) at 5 meters depth from Estimating the Circulation and Climate of the Ocean (ECCO)

- Based on the MIT general circulation model that has been fit to various satellite and sensor observations



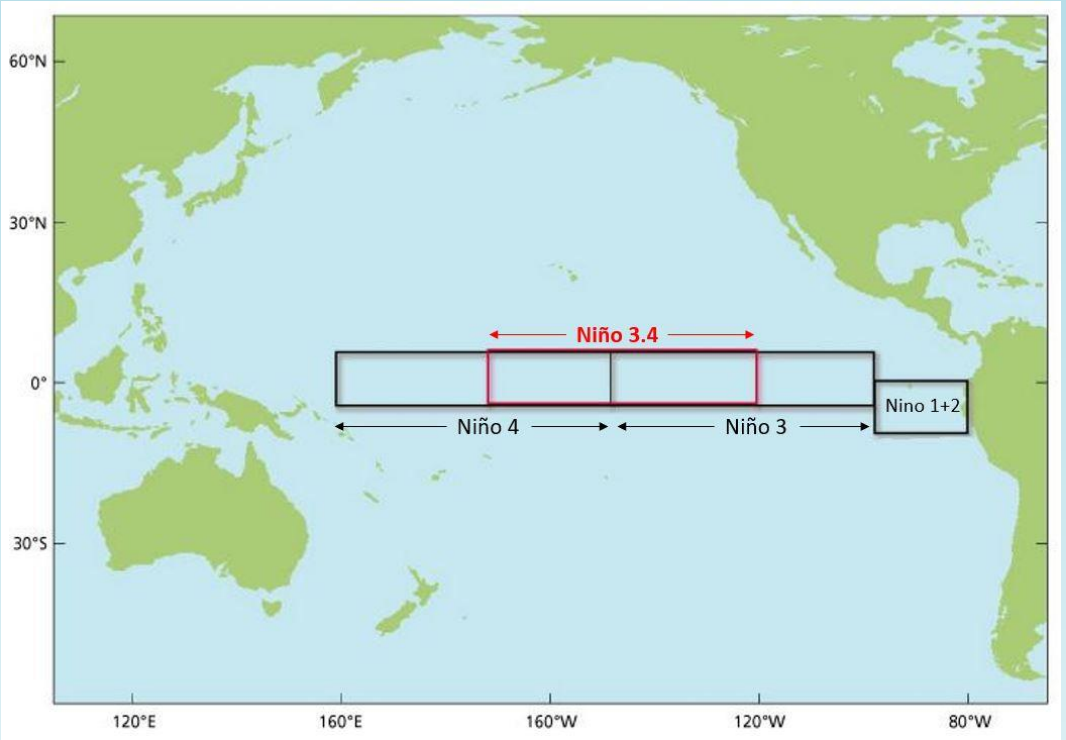
Salinity

Temperature



ENSO 3.4 Data

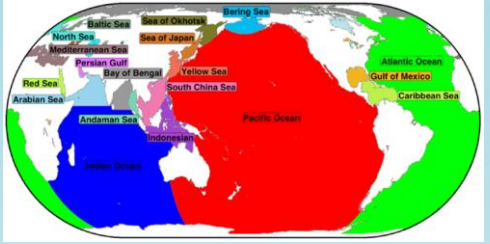
- El Niño Southern Oscillation
- Index based on sea surface temperature anomalies over region shown
- Affects the atmospheric circulation
- Data from PMEL



Strong El Niño and Winter in the Twin Cities | Minnesota DNR (state.mn.us)

What we've done

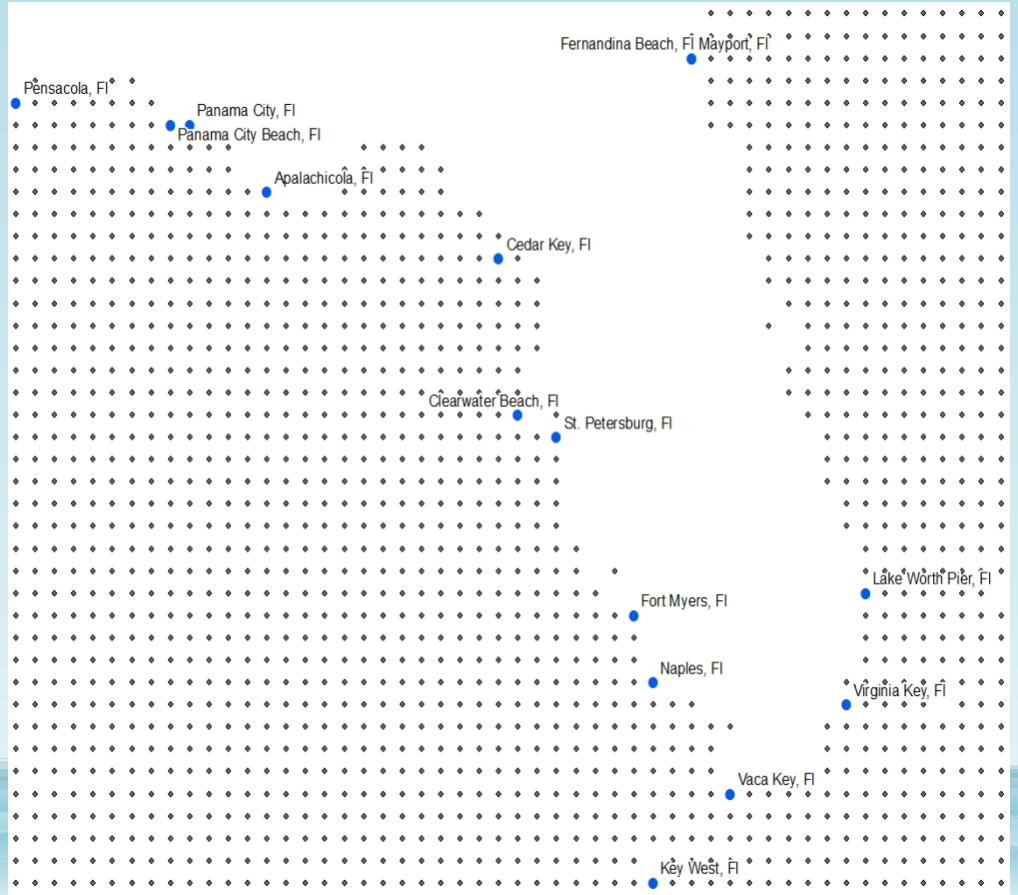
- Three scales: global, regional (basin), and local sea level
- Looked at trends and variability across these scales
- Compared local sea level with both basin and global rates
- Modeled SSHA data against climate indices



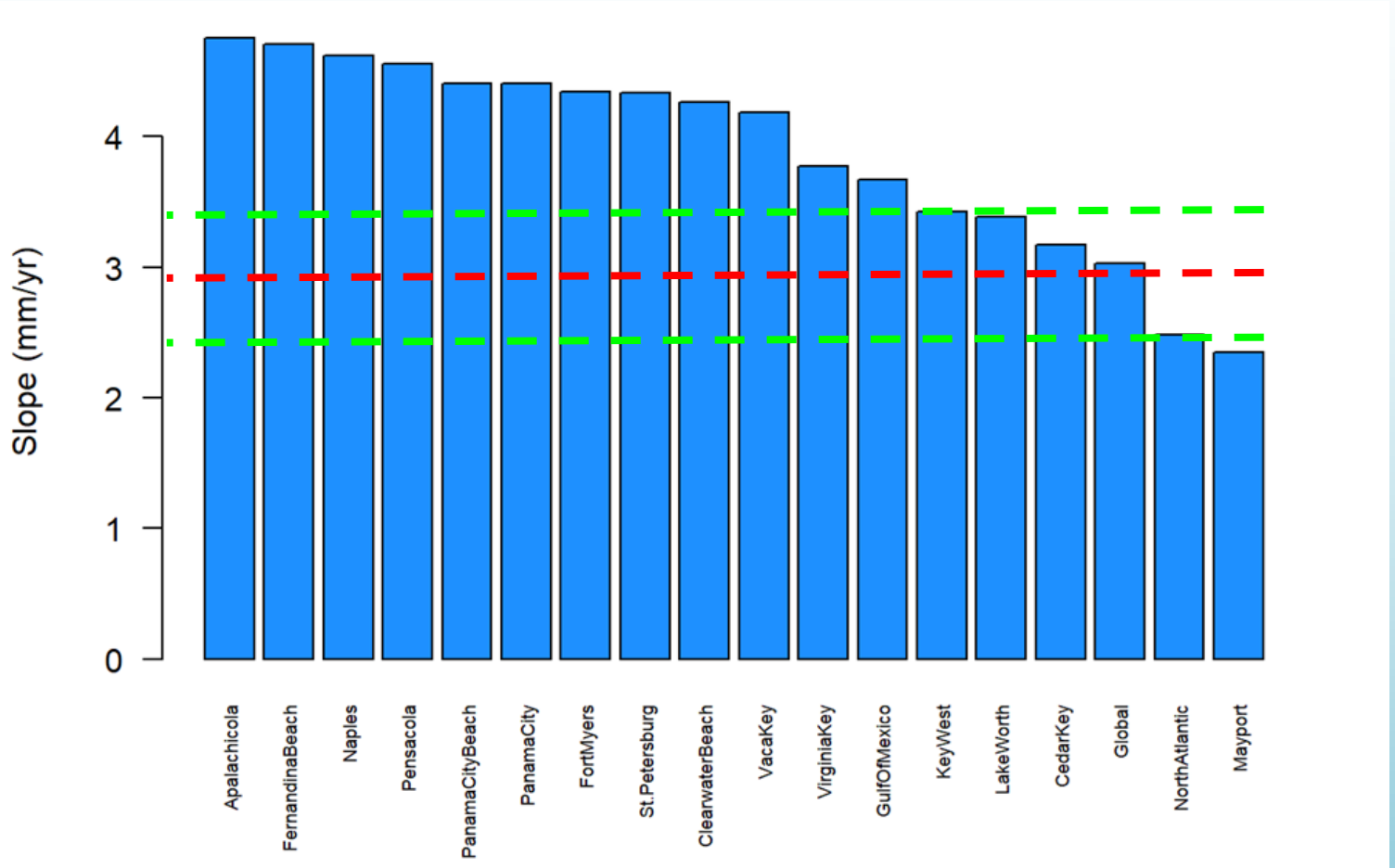
Our Goal: **Modeling Sea Level in Florida**

Coatal FL Locations

15 altimetry locations that correspond to tide gauge stations along coastal FL



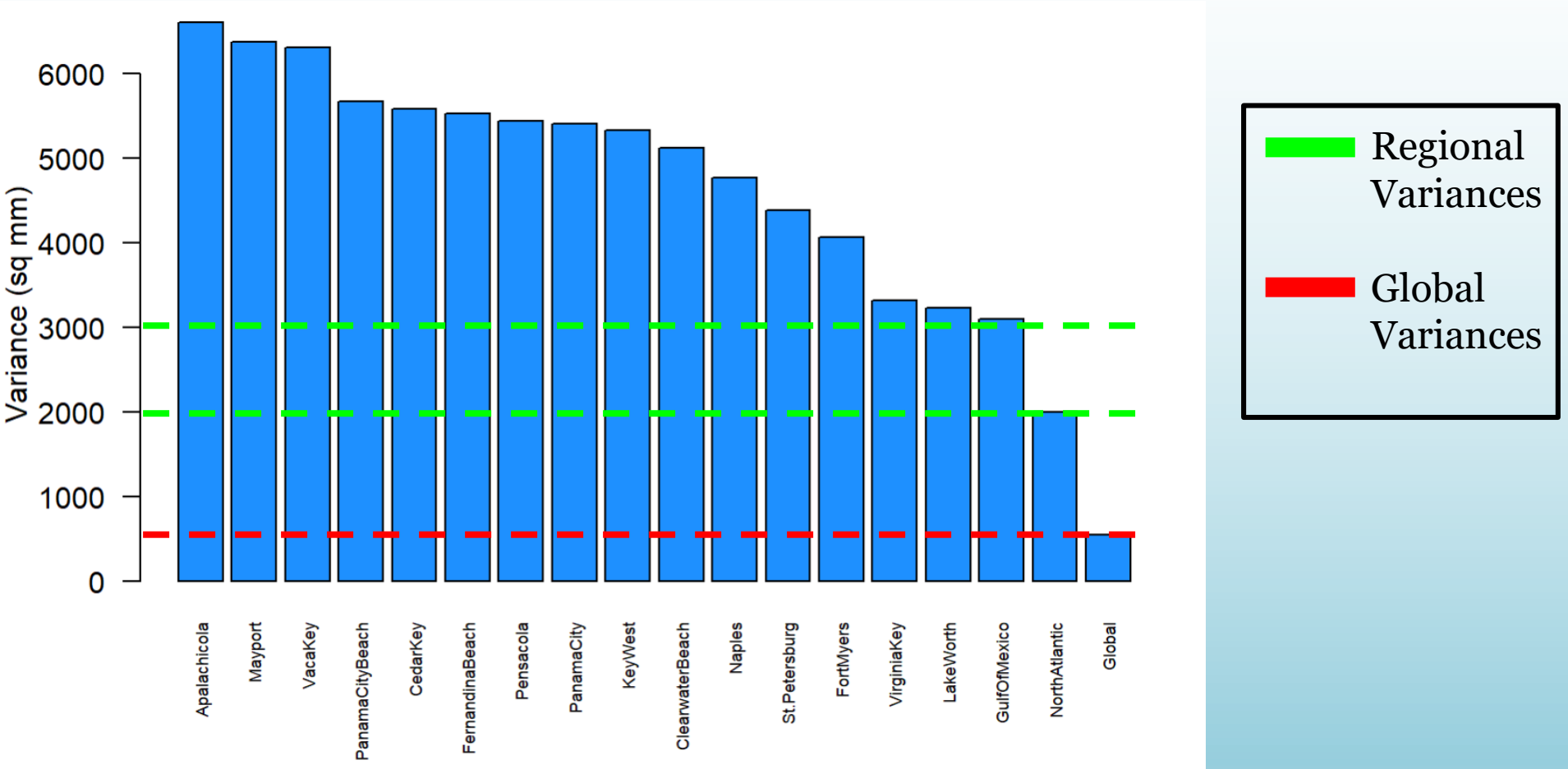
Trend



Regional Slopes

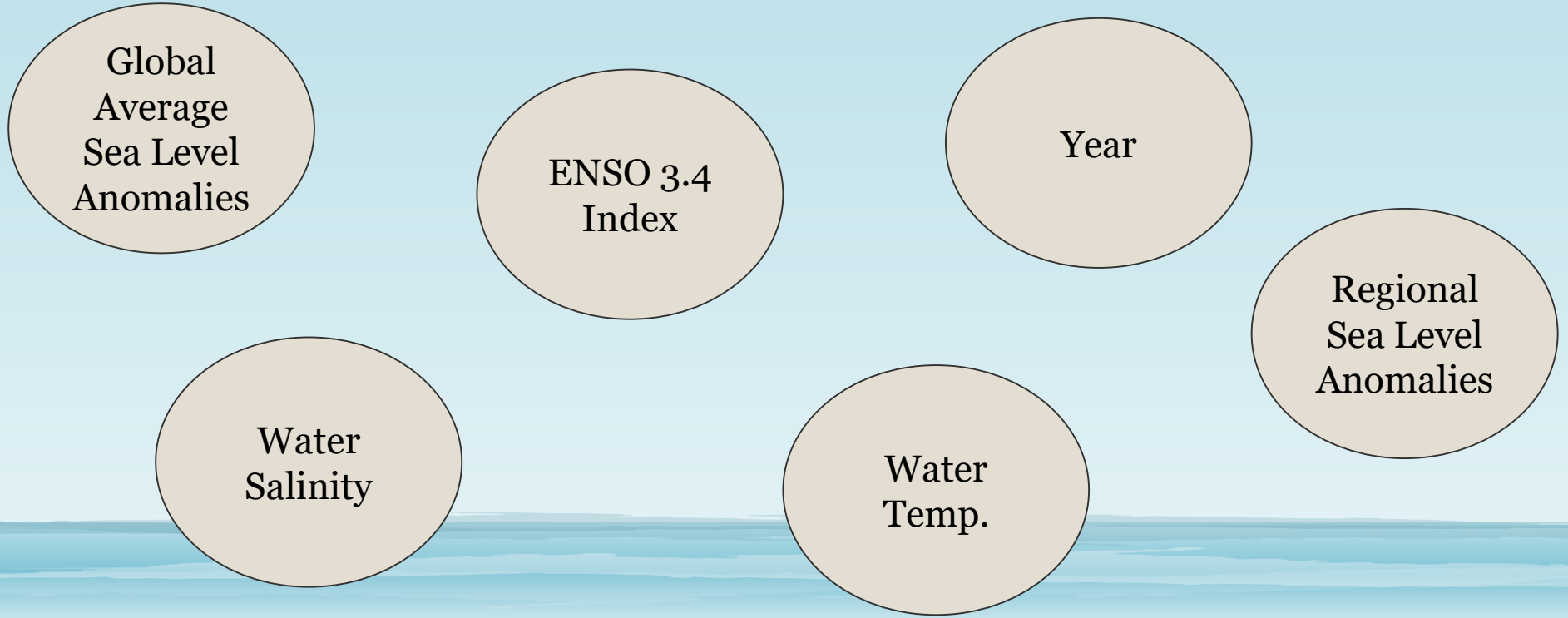
Global Slope

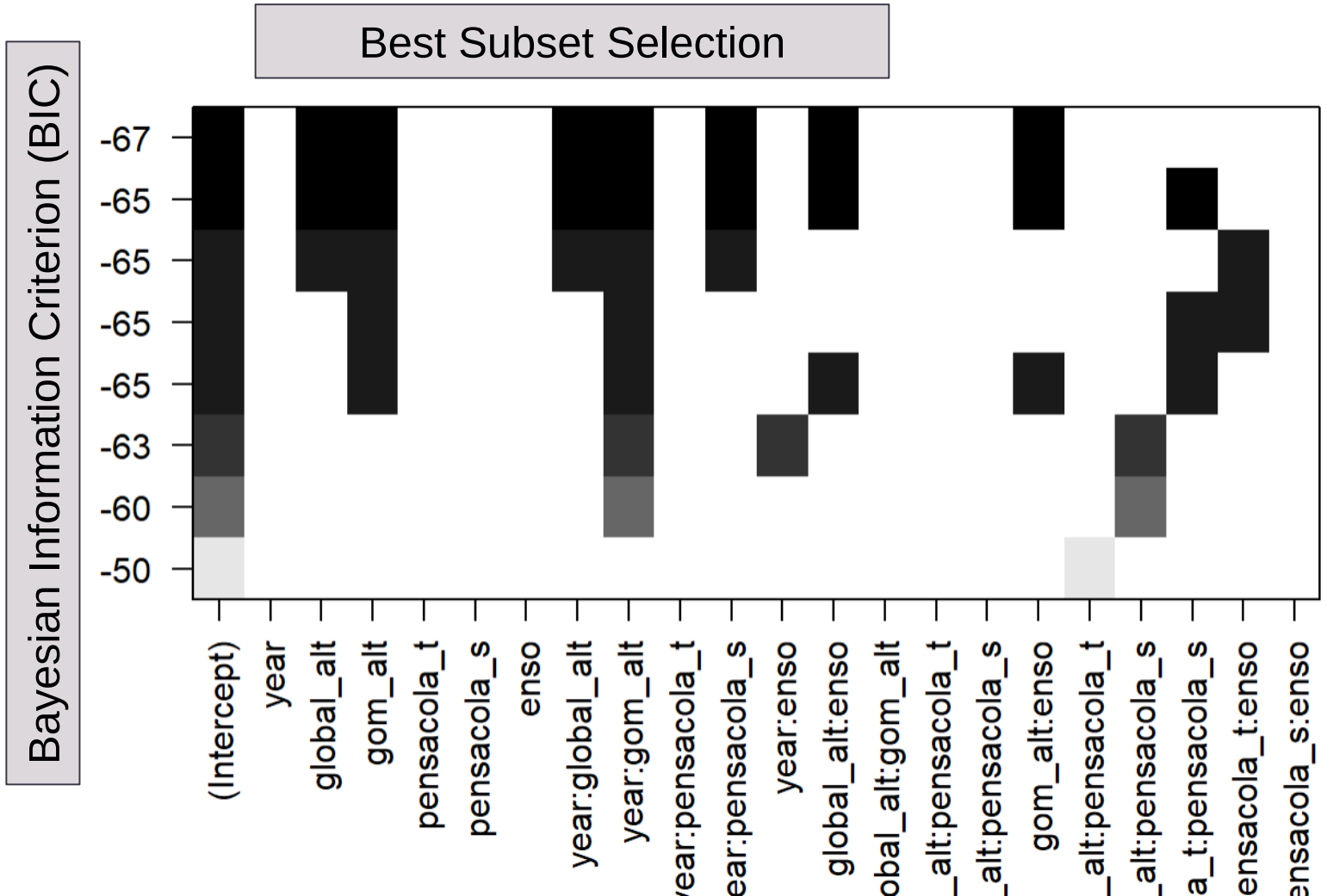
Variability



How Can We Model Sea Level?

Linear/Multiple Regression

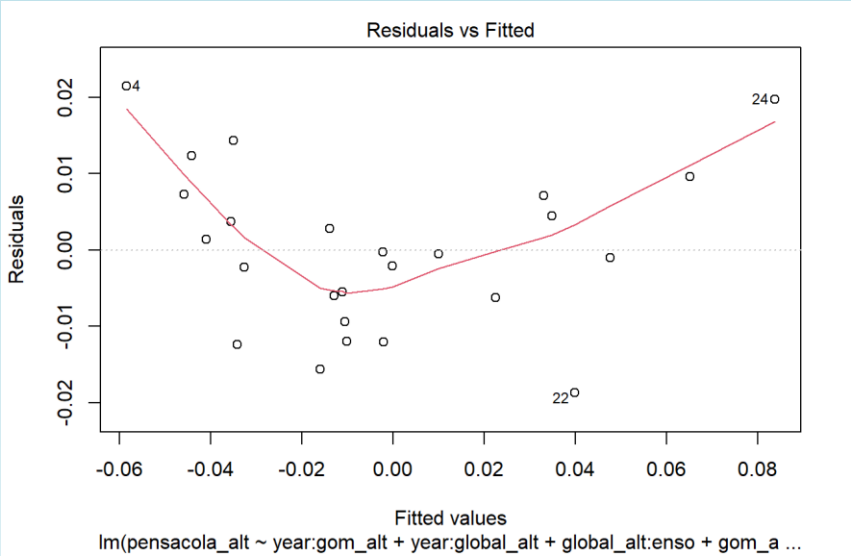




*Darker boxes = more relevant predictors/ models

Best Multiple Regression Model:

$$\text{Local SSHA} = year \cdot regional\ SSHA\ x_1 + year \cdot GMSL\ x_2 + GMSL \cdot ENSO\ x_3 + regional\ SSHA \cdot \text{ENSO}\ x_4 + temperature \cdot salinity\ x_5 + intercept$$



Lack of Homoscedasticity
(red line does not follow y = 0 line)

All interaction terms

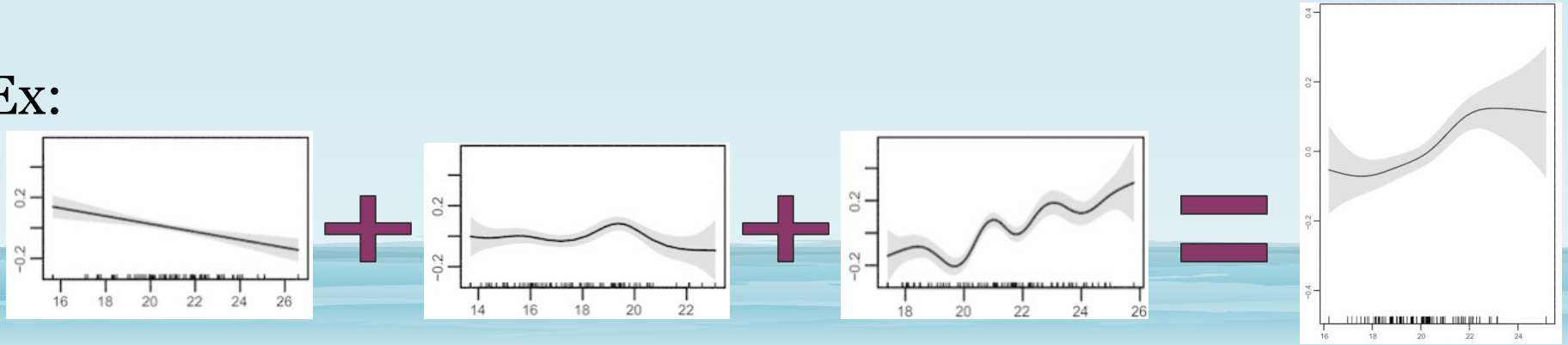
Probably not linear

How Can We Model Sea Level?

Using a **Generalized Additive Model** (GAM)

- Nonparametric model fitted using cubic splines
- Response is modeled as the sum of the smoothed functions of the predictors which adds substantial flexibility to model sea level changes

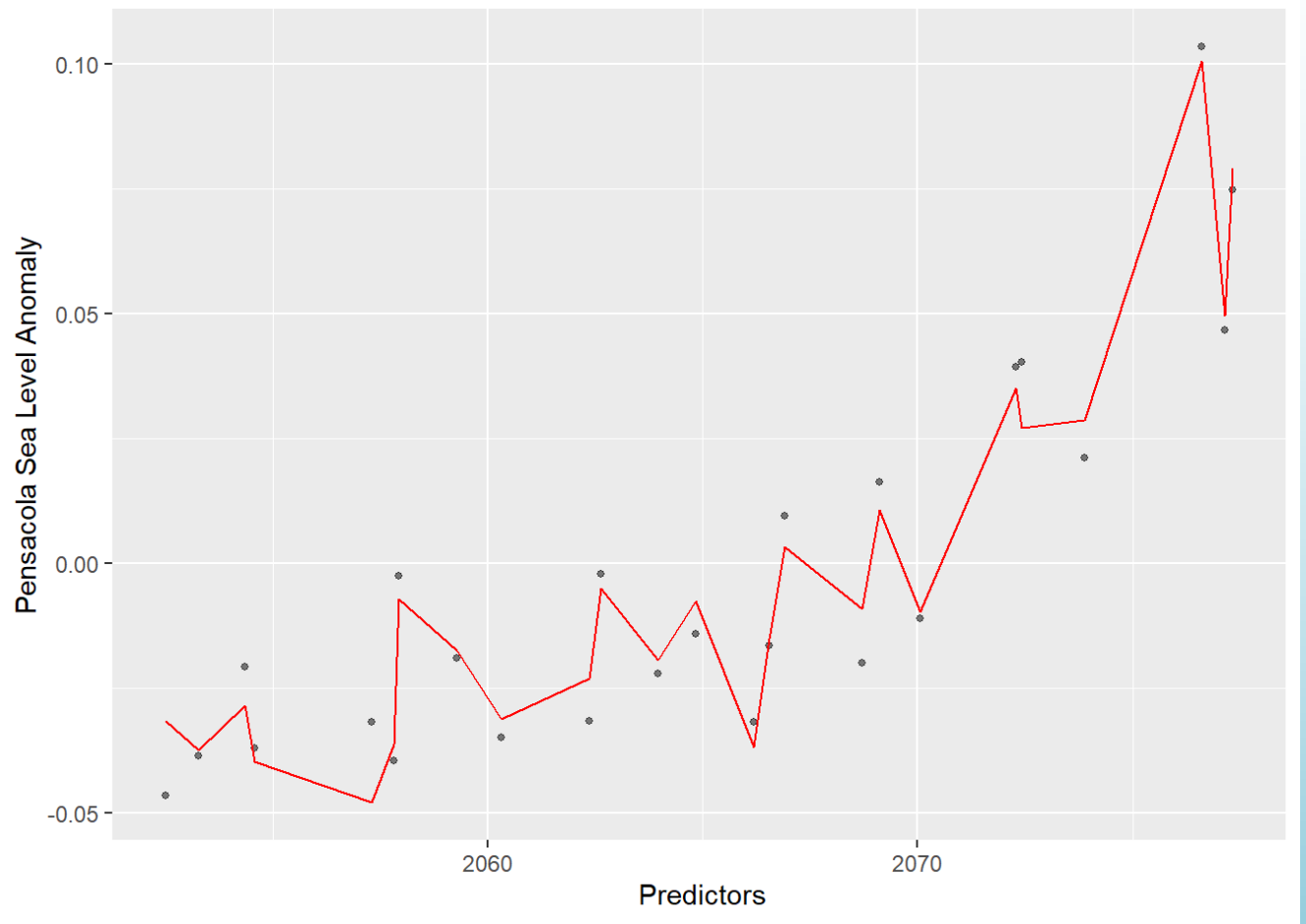
Ex:



Best GAM:

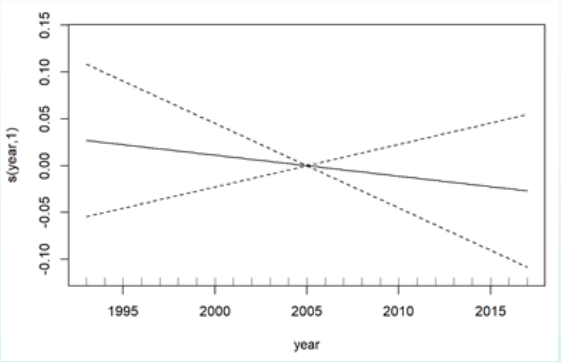
Y	A	G	E	S	T
EAR	DJ BASIN	LOBAL AVG	NSO	ALINITY	EMPERATURE

Best GAM:

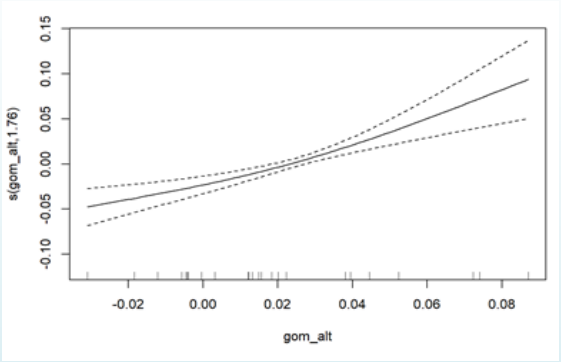


- R^2 values across all 15 locations range from 0.7 to 0.95 (very good)
- Lowest average Akaike information criterion (AIC) values

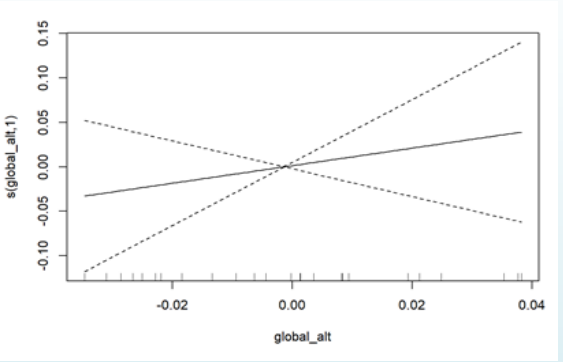
Smoothed Predictor Functions



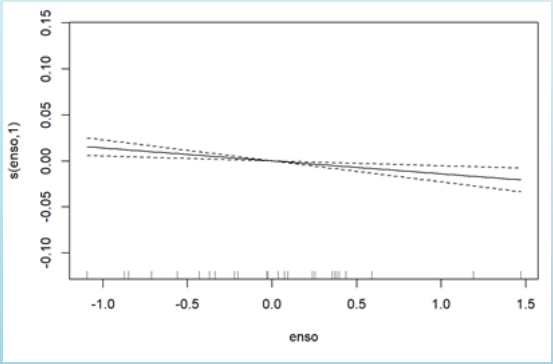
Year



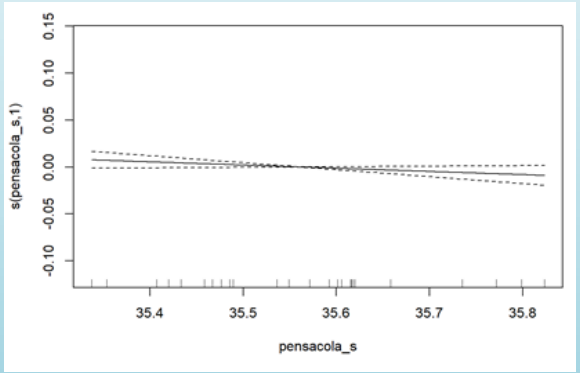
Regional (Basin) SSHA (m)



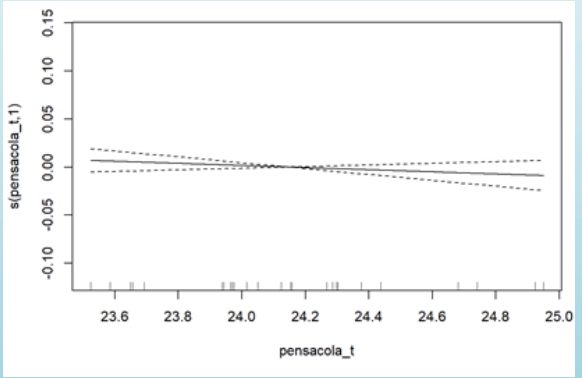
GMSL (m)



ENSO

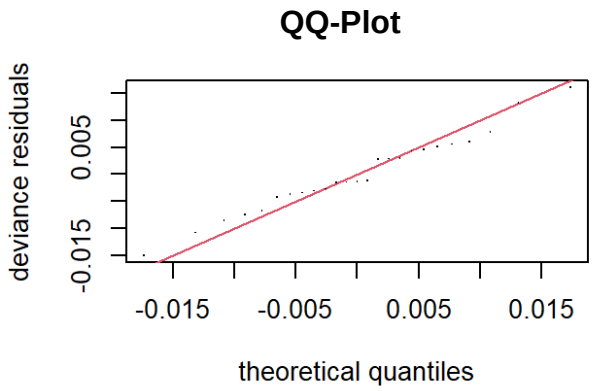


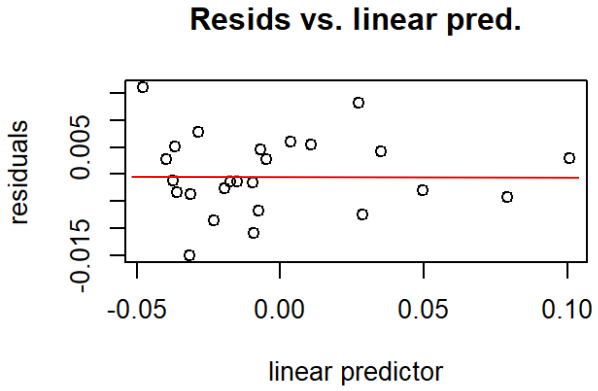
Salinity (PSU)

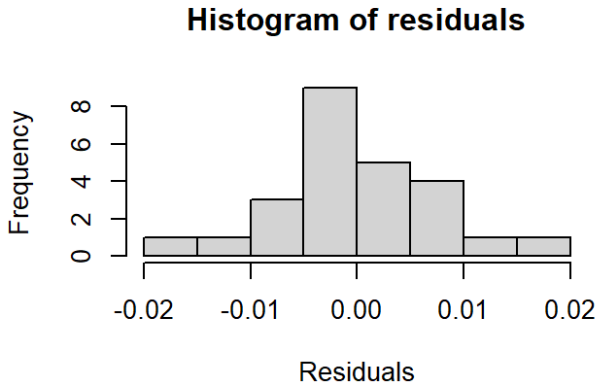


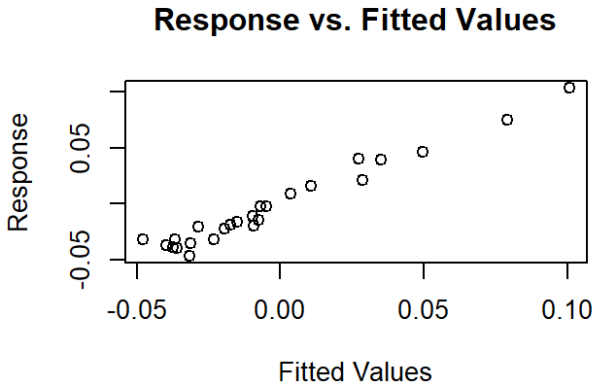
Temperature (°C)

GAM Output



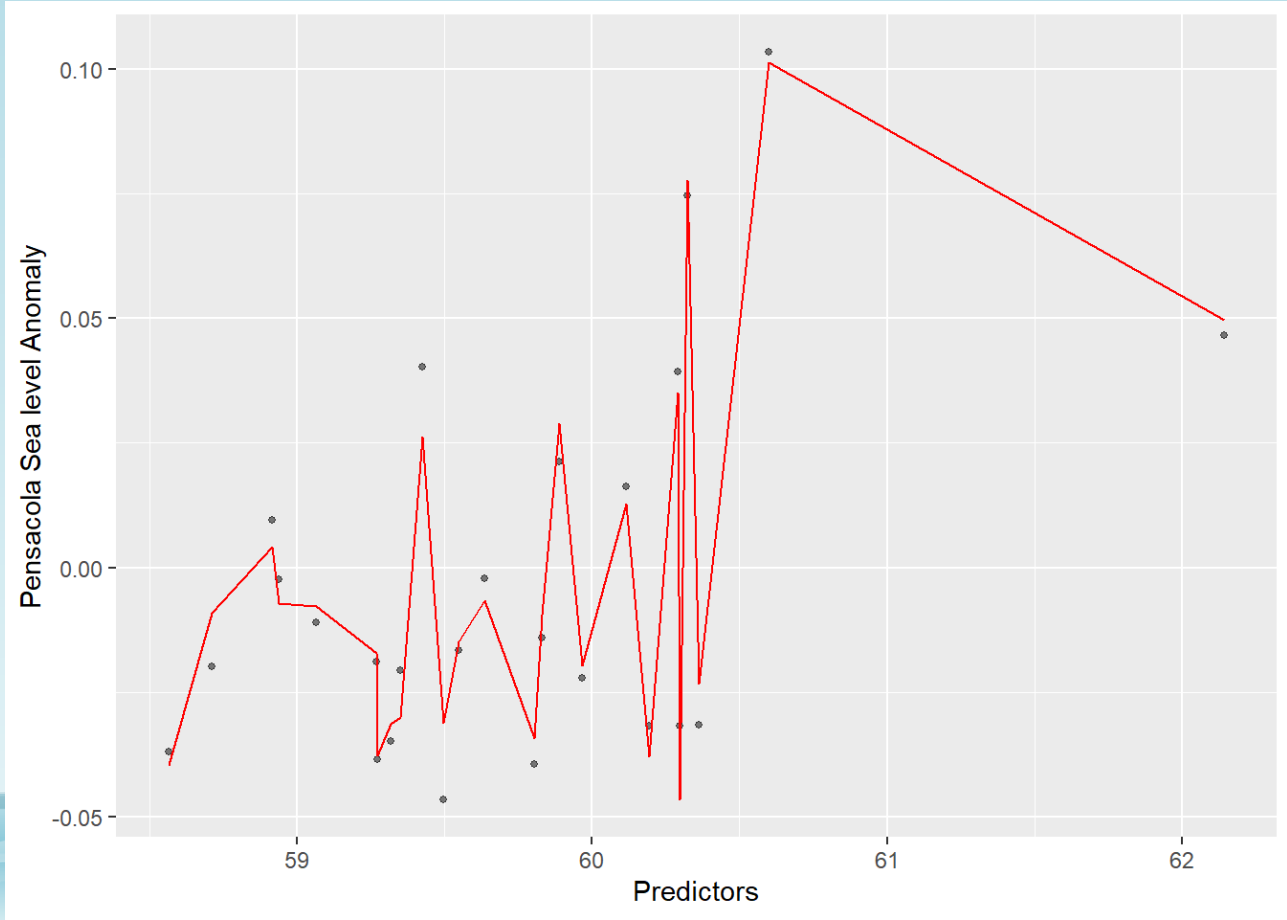




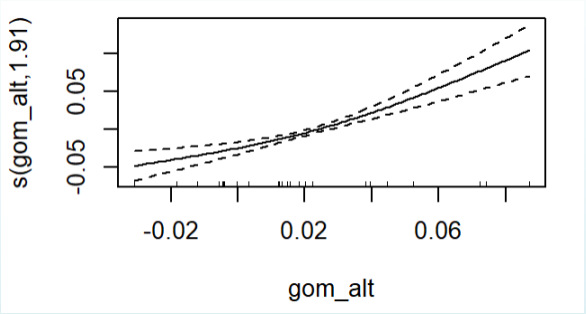


These four panels depict criteria that assess whether the model assumptions are met

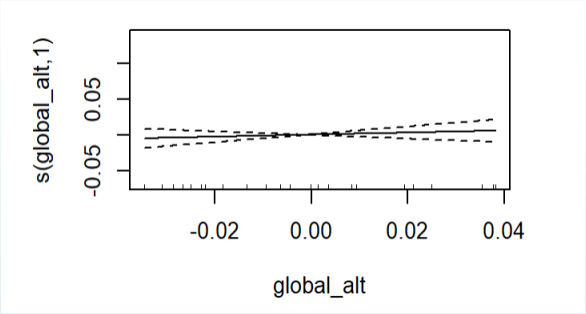
Year as a Predictor?



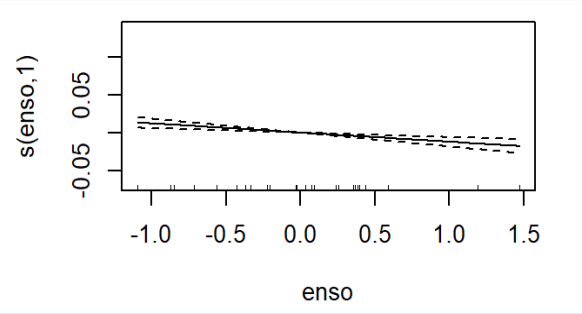
Smoothed Predictor Functions (model without year)



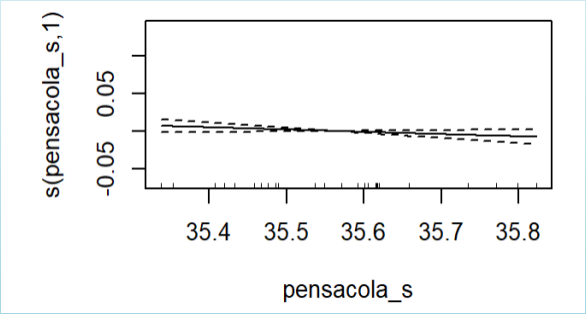
Regional (Basin) SSHA (m)



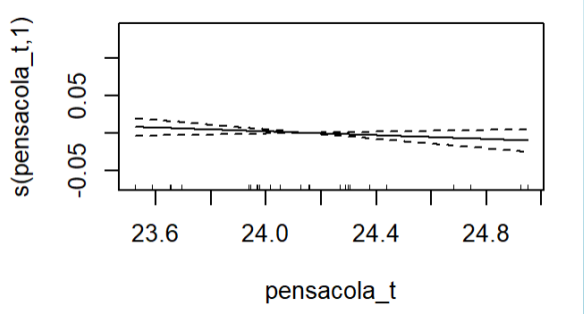
GMSL (m)



ENSO

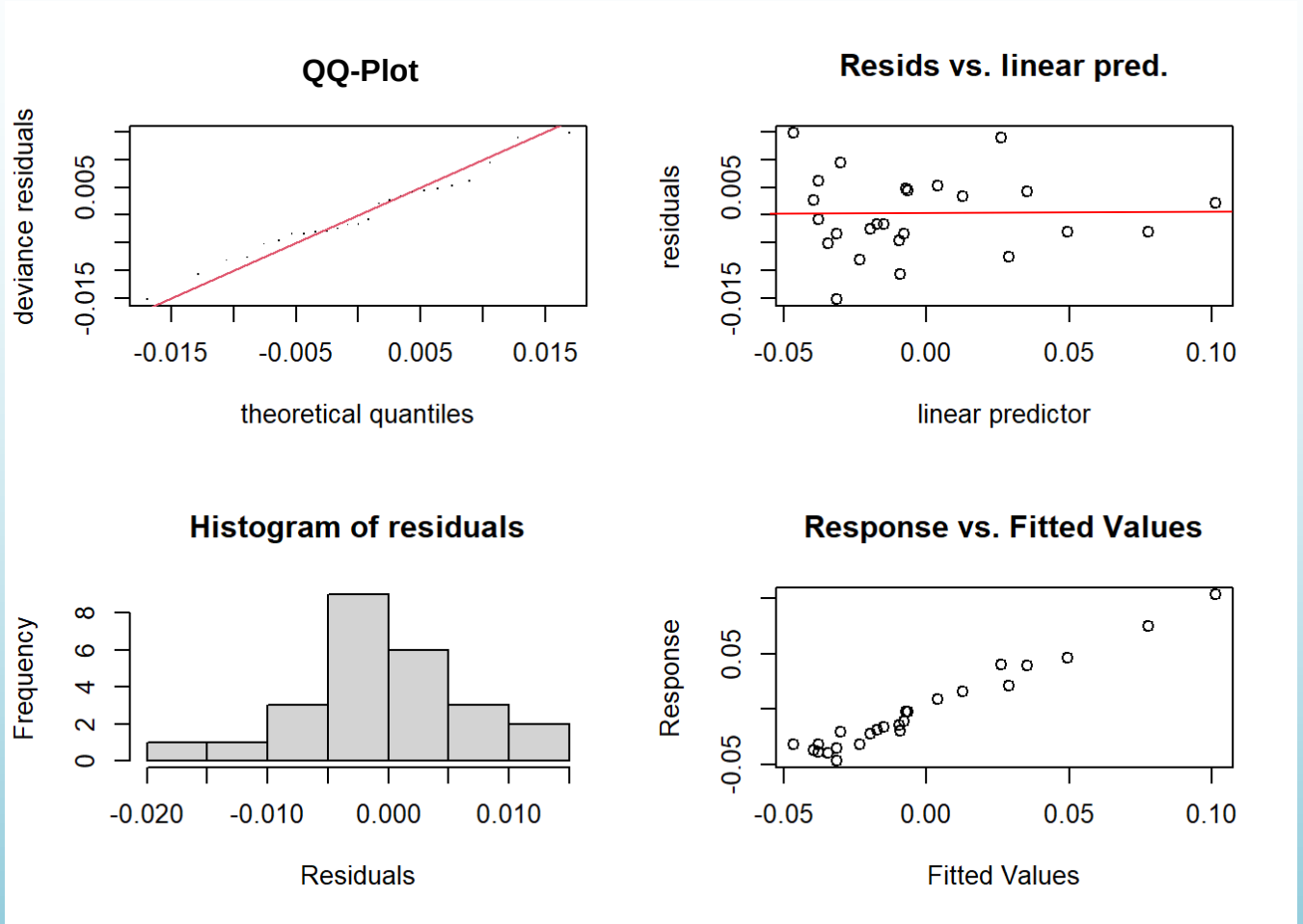


Salinity (PSU)



Temperature (°C)

GAM Output


QQ-Plot
deviance residuals
-0.015
0.005
-0.015
-0.005
0.005
0.015
theoretical quantiles
Resids vs. linear pred.
residuals
-0.015
0.005
-0.05
0.00
0.05
0.10
linear predictor
Histogram of residuals
Frequency
0
2
4
6
8
-0.020
-0.010
0.000
0.010
Residuals
Response vs. Fitted Values
Response
-0.05
0.05
-0.05
0.00
0.05
0.10
Fitted Values

Year as a Predictor?

Examining a model without year…

A G E S T model

Less ambiguity, but worse fit (lower R^2 values, higher AIC values)

Conclusions

- Regional (basin) and GMSL contribute to local sea level (similar behavior)
- Water temperature (5 m depth), water salinity (5 m depth), and ENSO 3.4 index are all relevant factors for local sea level in Florida
- Florida coastal sea levels are rising faster than GMSL

3 mm/yr
(global, no GIA)

vs.

> 4 mm/yr
(FL, no GIA)

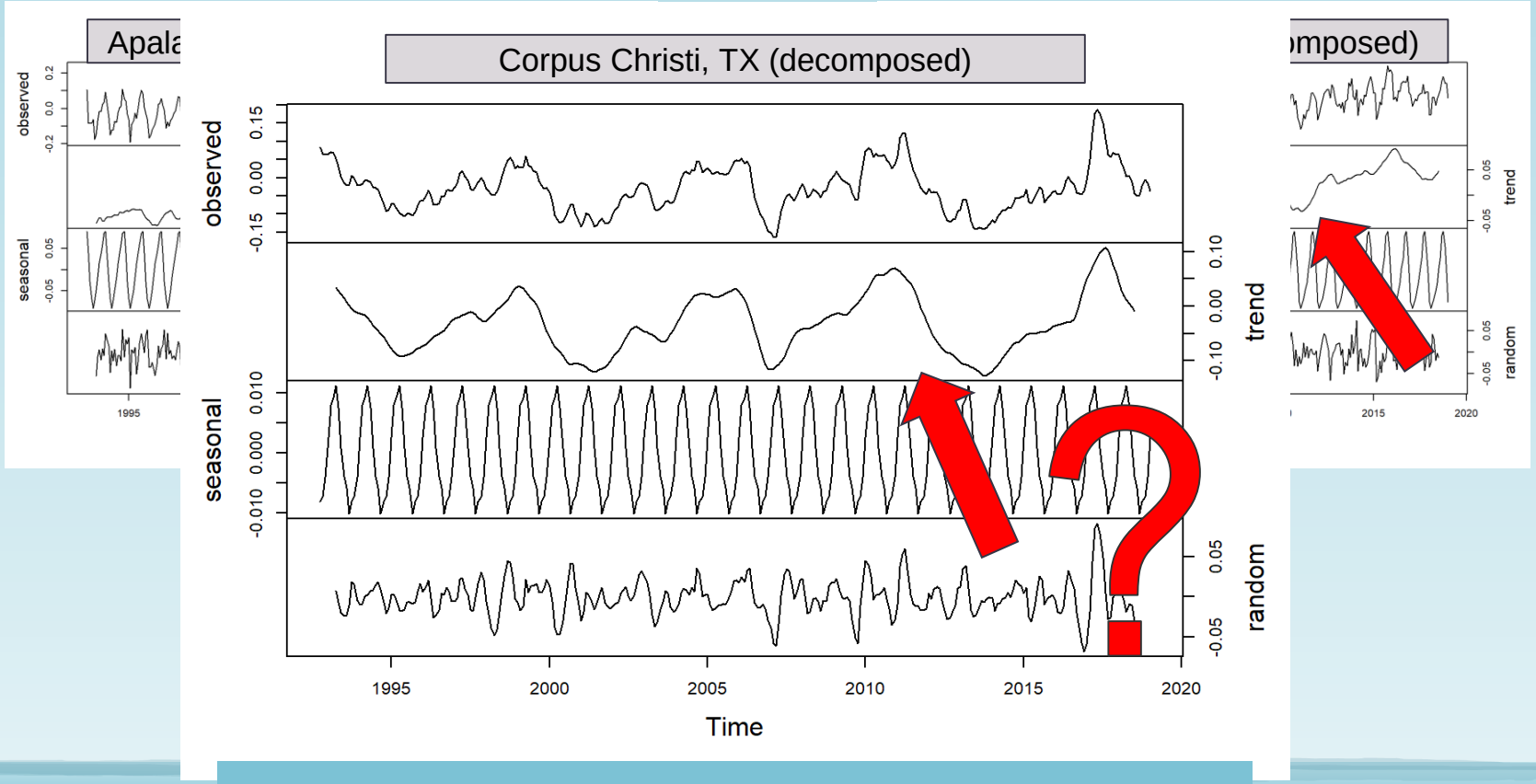
Future Work

Altimetry → Tide Gauge (Ground Truth)

Year as predictor (proxy variable) → More Factors?

(Prandi et. al)

Future Work



What happened in 2011 in Florida?

Research Team

Marisela Madrid, Turtle Mountain Tribal College

Dr. Steven Lazarus, Dept. of Ocean Engineering and Marine Sciences

Dr. Nezamoddin N. Kachouie, Dept. of Mathematical Sciences

Hanna Vaidya, Wake Forest University

Robbie Breininger, Graduate Student Assistant

References

ALLISON, I., 2009. The Copenhagen Diagnosis: Climate Science Report, 2009. Updating the World on the Latest Climate Science. Sydney: The University of New South Wales Climate Change Research Centre (CCRC).

Center for Operational Oceanographic Products and Services. NOAA. Sea Level Trends. 2021.

Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merrifield, G.A. Milne, R.S. Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer and A.S. Unnikrishnan, 2013.
Cliff Mass Weather Blog. High Pressure Produces Low Sea Level. 2011.

Cook, A.R. and Schaefer, J.T., 2008. The relation of El Niño–Southern Oscillation (ENSO) to winter tornado outbreaks. Monthly Weather Review, 136(8), pp.3121-3137.

ECCO Consortium, Fukumori, I., Wang, O., Fenty, I., Forget, G., Heimbach, P., & Ponte, R. M.. 2021. ECCO Ocean Temperature and Salinity - Monthly Mean 0.5 Degree (Version 4 Release 4). Ver. V4r4. PO.DAAC, CA, USA. 2021.

Fukumori, I., Wang, O., Fenty, I. 2020. *ECCO version 4 release 4 User Guide*.

Hastie, T.J. and Tibshirani, R.J., 1990. *Generalized additive models* (Vol. 43). CRC press.

Mitchum, G.T., 2011. Sea level changes in the Southeastern United States. *Florida Climate Institute*.Pierre Prandi, Anny Cazenave, and Melanie Becker.

Prandi, P., Cazenave, A. and Becker, M., 2009. Is coastal mean sea level rising faster than the global mean? A comparison between tide gauges and satellite altimetry over 1993–2007. *Geophysical Research Letters*, 36(5).

Strauss, B., Tebaldi, C., Kulp, S., Cutter, S., Emrich, C., Rizza, D. and Yawitz, D., 2014. Florida and the surging sea: a vulnerability assessment with projections for sea level rise and coastal flood risk.

Tamisiea, M.E. and Mitrovica, J.X., 2011. The moving boundaries of sea level change: Understanding the origins of geographic variability. Oceanography, 24(2), pp.24-39.

Wakelin, S.L., Woodworth, P.L., Flather, R.A. and Williams, J.A., 2003. Sea-level dependence on the NAO over the NW European Continental Shelf. *Geophysical Research Letters*, 30(7).

Website, 2020. NOAA NESDIS (STAR). Laboratory for Satellite Altimetry/Sea Level Rise. *Regional sea level time series*. Regional sea level time series data and plots.

Questions?