A synthesis of 20 years of fCO_2 data in the US South Atlantic Bight: Can we see a clear trend through noisy data?

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ABSTRACT

We analyze spatio-temporal fCO_2 observations that span over 26 years in the South Atlantic Bight (SAB) off the southeast United States. Various cruises and one moored time series are used to determine multi-decadal fCO_2 trends. We compare two statistical methods for resolving trends: 1) deseasonalization (removal of the mean seasonal harmonic) using an ensemble mean reference year with a linear least squares best-fit slope; and 2) a Generalized Additive Mixed Model (GAMM) to identify and remove the seasonal signal, with a non-linear best-fit slope. The results from the two methods are not statistically different; however, the GAMM method calculates narrower 95% confidence intervals. Both methods agree that fCO_2 across the SAB is increasing at a rate greater than that of the atmosphere (~2 µatm y^{-1}). Thermal increases could influence outer portions of the SAB, while there is no evidence for thermal influences on the shallower inner portions of the shelf. Even though the moored fCO_2 time series has just less than 10 years of observations, the linear least squares best-fit slope agrees well with the slopes for only the cruise observations over 26 years. Therefore, we assume that even though the moored fCO_2 time series is less than a decade old, the high observational frequency (three hours averaged to one day) provides an accurate assessment of long-term fCO_2 trends.

OBJECTIVES

1. Estimate fCO_2 change in the SAB using cruise observations spanning over 25 years. Since cruises are often sporadic, we compare observations from across the SAB shelf to almost a decade of nearly-continuous moored autonomous observations.
2. Using simple linear methods, an examination of deseasonalization, and comparison to a generalized additive mixed model (GAMM), we show that simple linear techniques in the SAB agree well across regions of the slope as well as to the more complex GAMM.

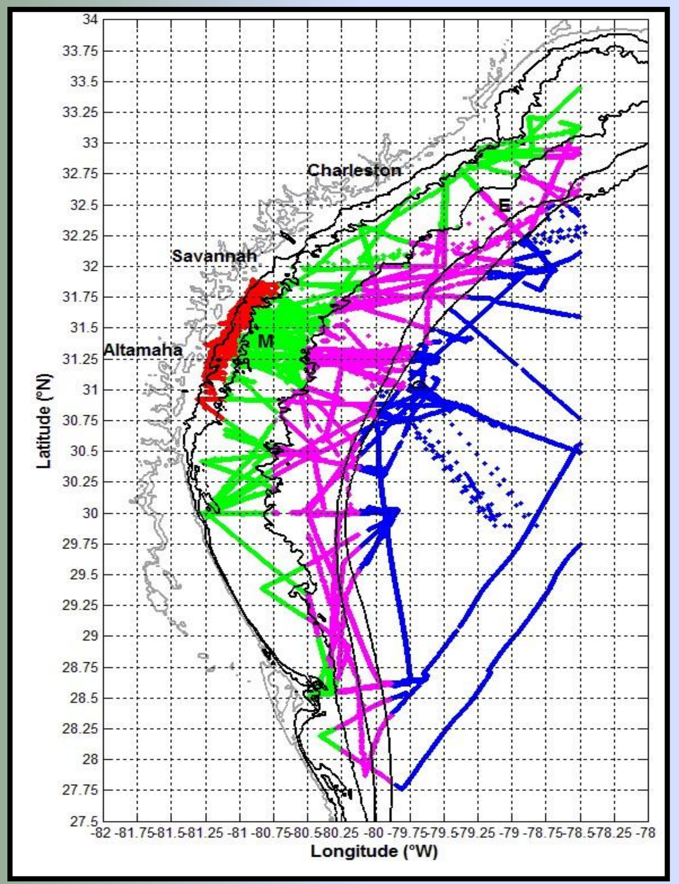

Figure 1. The four regions of the SAB shelf analyzed in this study: coastal, inner, middle, outer. The locations of the Gray's Reef mooring (NDBC-41008; M on the map) on the inner shelf, and the Edisto mooring (NDBC-41004; E on the map) on the middle shelf.

Table 1. Description of CO_2 used in this work. Data from **42** cruises were compiled to form the underway dataset as well as CO_2 from one moored time series and SST from two moored time series.

Data	Platform	Dates and frequency
fCO_2	Vessel of opportunity (*M/V Rabelais*)	1991-1996, seasonal
fCO_2	Dedicated Ocean Acidification cruises (NOAA; *R/V Ronald H. Brown, R/V Gordon Gunter*)	July 2007, August 2012, July 2015
pCO_2	Dedicated SAB carbonate chemistry (*R/V Savannah, R/V Cape Hatteras, R/V Joe Ferguson*)	Seasonal 2000 through 2016
pCO_2	Moored (NDBC-41008)	July 2006 to the present; daily means
SST	Moored (NDBC-41004 & 41008)	1994 and 1990 to the present; daily means

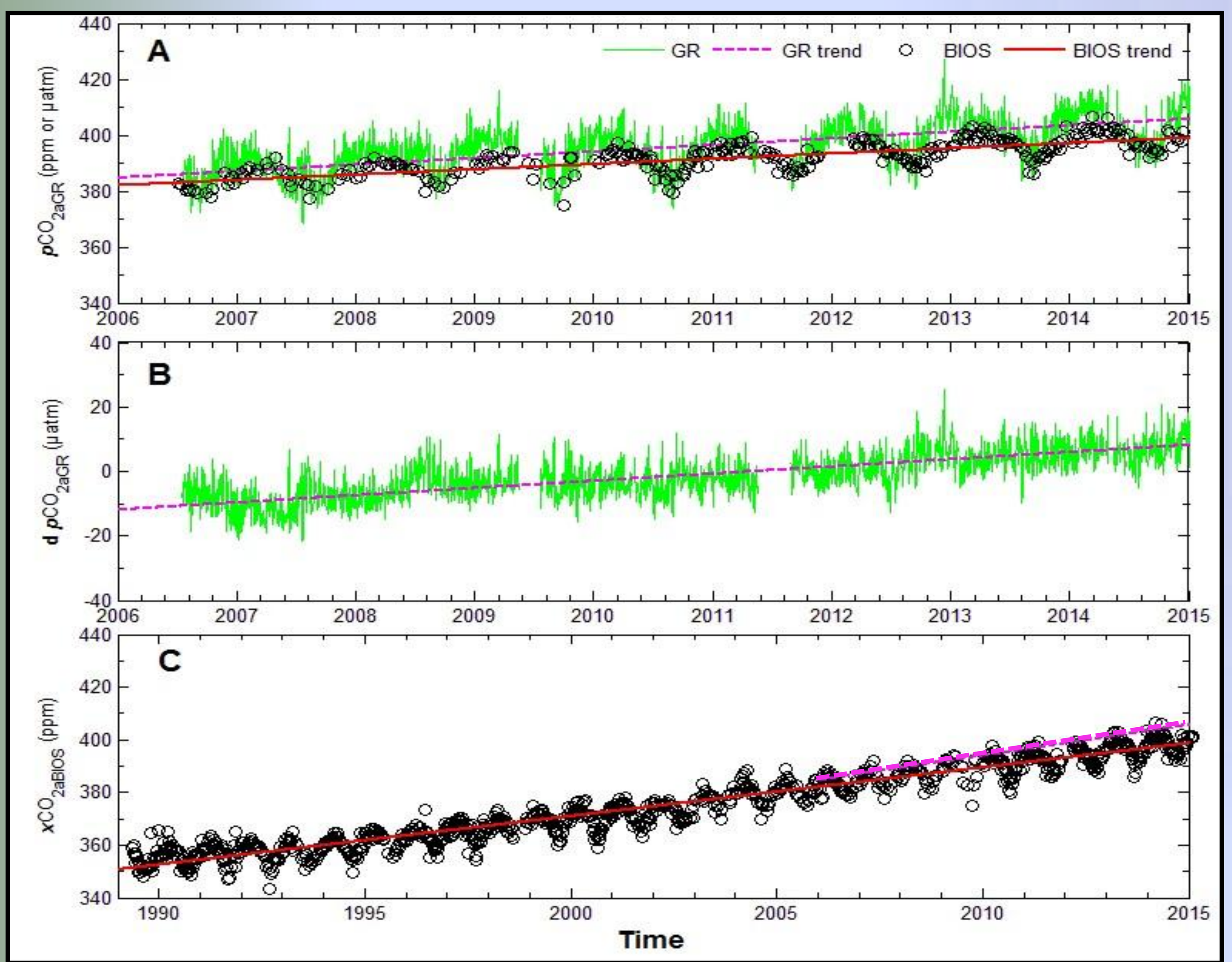

Figure 2. Testing a deasonalization method using a climatological ensemble mean for shorter time series (Gray's Reef almost 10 yrs): comparison of over **25 years of CO_2 in the air** from the GlobalView Bermuda site (**BIOS**). **A:** Time series of daily mean Gray's Reef (green), the Gray's Reef (GR) trend (dashed pink line) and BIOS bi-weekly observations; **B:** deseasonalized GR using an ensemble mean removes more of the seasonal signal than using a mean of the time series; **C:** the trend calculated from deseasonalized GR (2.0 ± 0.7 µatm; pink line) is not statistically different from the trend calculated from non-deseasonalized BIOS observations (1.8 ± 0.7 µatm; red line).

GAMM METHOD DESCRIPTION

Penalized splines fit the seasonal cycle and second-degree polynomials are used to model SSS, SST, and their interaction. Sampling date is included as a linear effect. The trend is the fCO_2 slope. An explicit assumption of lag 1 autocorrelation is included to account for lack of independence of consecutive observations taken close together in time.

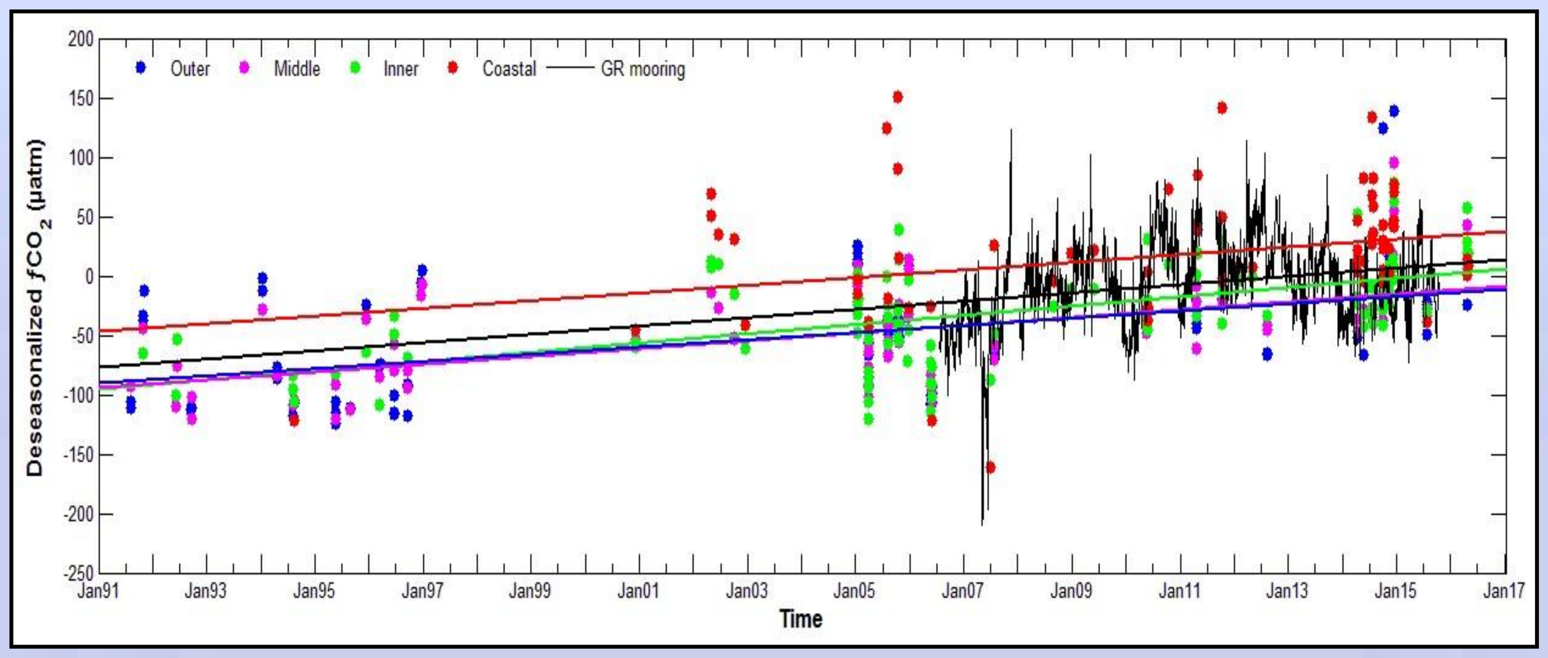

Figure 3. Deseasonalized GR mooring and shelf observations using an ensemble mean calculated from mooring data. Values below 0 represent anomalously low fCO_2. Trends are calculated using linear least squares of Deseasonalized values. The trend line colors match the colors of the symbols for the respective shelves. The trends agree well, however, the 95% confidence intervals (CI's) are broad using this method for removing seasonal signals.

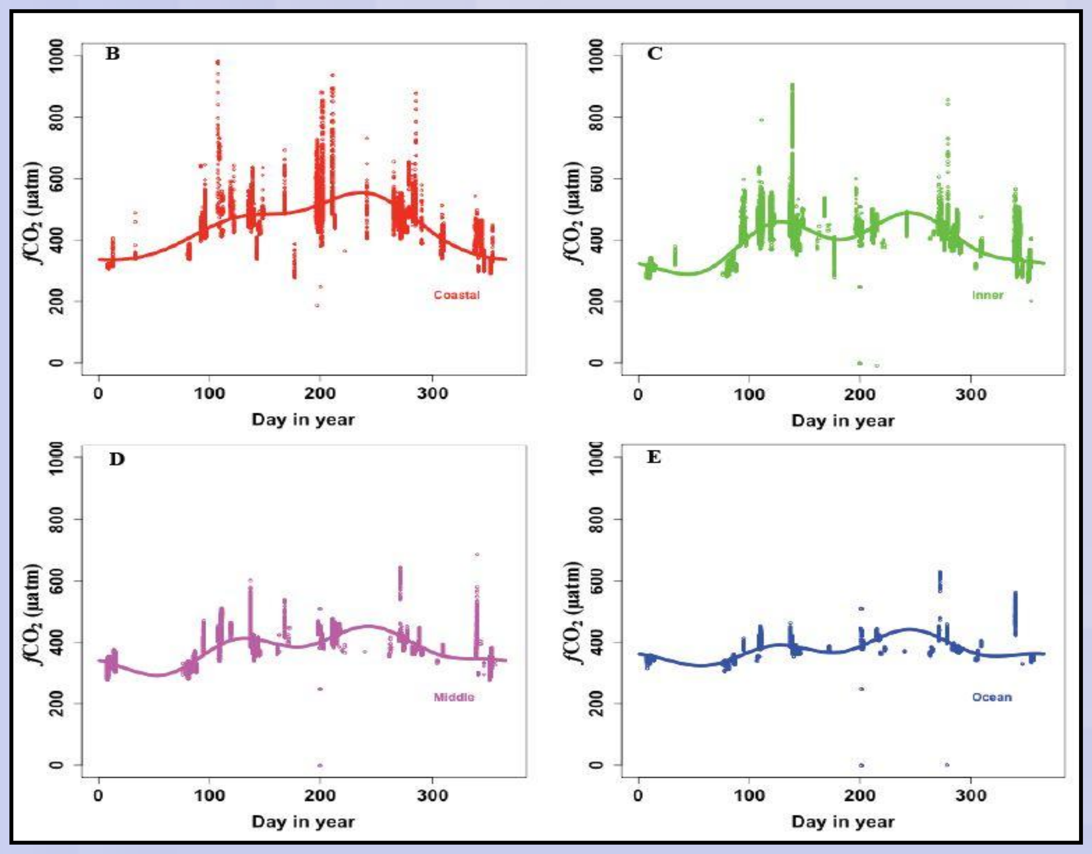

Figure 4. A generalized mixed additive model[1] (GAMM) identifies more of the seasonal changes than deseasonalizing with an ensemble mean, resulting is calculated trends that are not statistically different from the deseasonalization method (**Table 2**), but with more narrow 95% CI's.

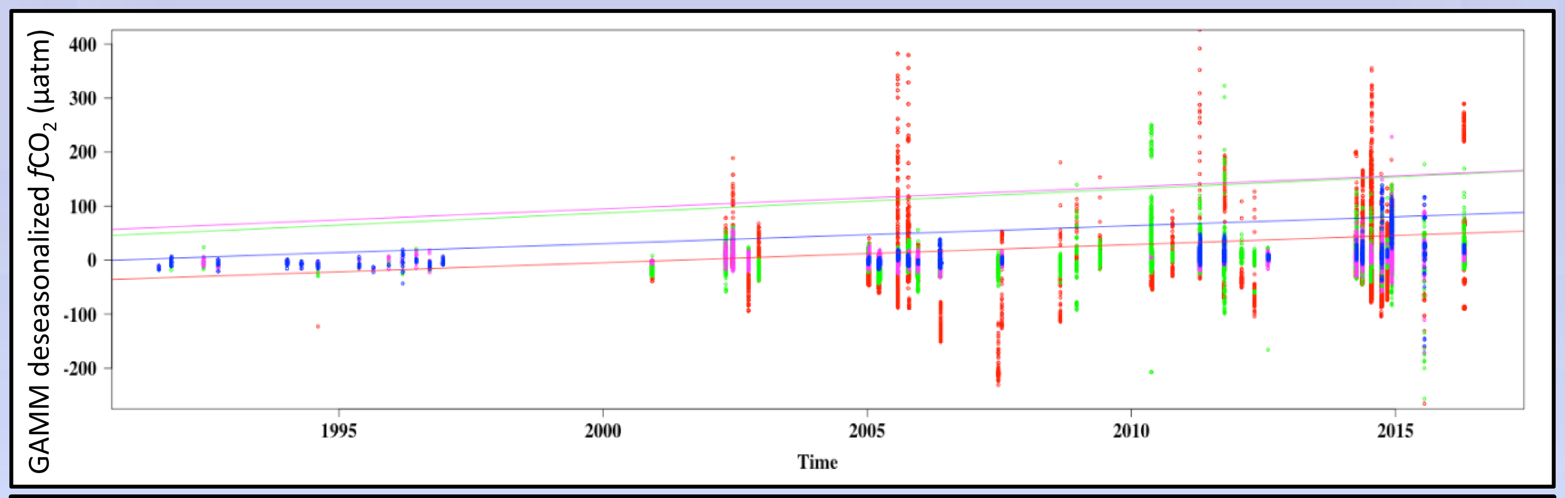

Figure 5. GAMM deseasonalized spatio-temporal cruise fCO_2 time series. The colors are the same as those indicated in Figure 3.

Table 2. fCO_{2w} trends and 95% CI's of the four SAB shelf regions using the deseasonalization method and the GAMM. NDBC measured SST trends are also included from the 41004 (on the middle shelf) and 41008 (on the inner shelf). GR and NDBC trends are calculated from daily means. GAMM is only used on the sporadic cruise data.

	Deseasonalized (µatm y^{-1} or °C y^{-1})	95% CI	GAMM (µatm y^{-1})	95% CI
Outer	3.0	3.2	3.3	0.3
Middle	3.2	2.3	4.1	0.4
41004 (SST)	0.07	0.03	--	--
Inner	3.7	2.2	4.5	0.6
Coastal	3.2	5.2	3.4	1.3
GR	3.5	0.9	--	--
41008	-0.05	0.04	--	--

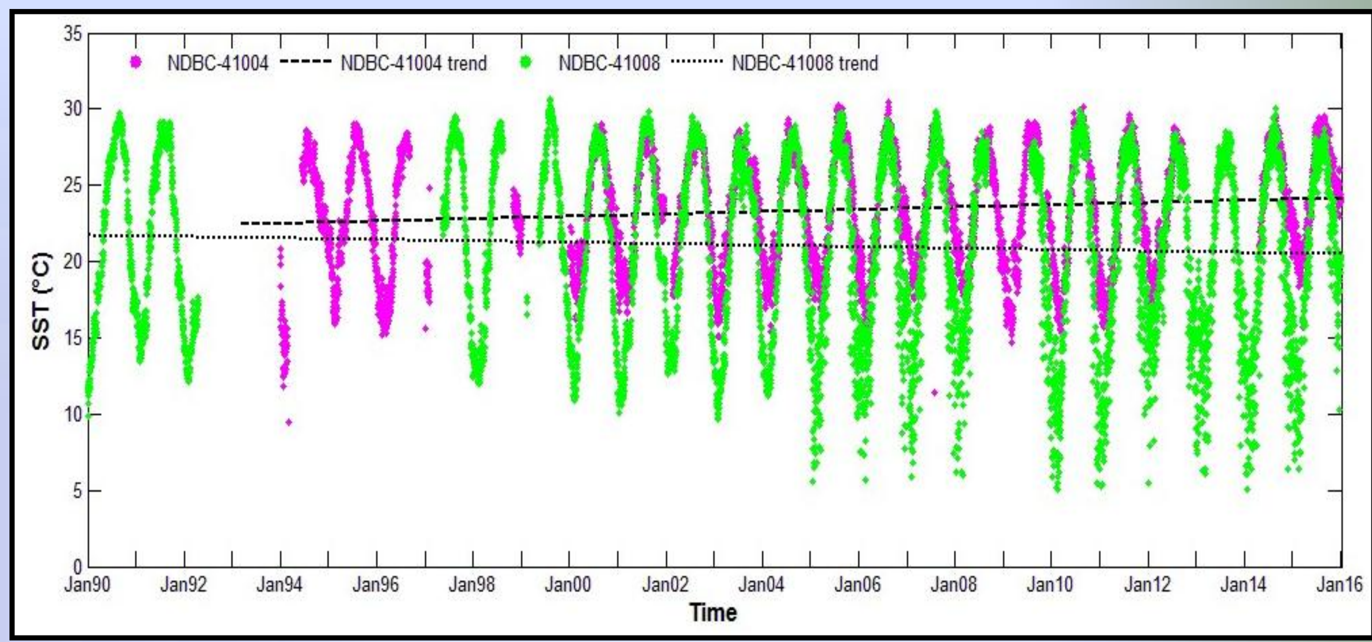

Figure 5. SST trends calculated from the NDBC moorings using linear least squares on the inner and middle shelves. SST on the inner shelf is decreasing, and is not likely a source of the fCO_2 increase, whereas SST on the middle shelf is increasing slightly and could be a source to the fCO_2 increase in that region.

CONCLUSIONS

- fCO_2 is increasing across the SAB, and the change in each region is greater than that of the anthropogenic-driven increase in the atmosphere. Therefore, other factors also contribute to the increase.
- The inner shelf SST trend is -0.05 °C y^{-1} (**Table 2**), thus the resulting SST effect, assuming 350 was the partial pressure at the beginning of the time series, is: -0.05*350*4.3% = -0.8 µatm y^{-1}. The middle shelf SST trend is 0.07 °C y^{-1}, thus the SST effect is 1.1 µatm y^{-1}. ***Thus, there must also be a substantial non-SST contribution to the fCO_2 increase on the inner and middle shelves.***
- The calculated trends using both the deseasonalization and GAMM methods are not statistically different, due to the large 95% CI's.
- 95% CI's using the deseasonalization method are likely greater than those using the GAMM because more of the seasonal signal is removed using the GAMM method, thus removing much of the extreme variability in the time series.
- The advantage of the GAMM method is that it may remove more of the variability in the seasonal signal, thus providing a narrower range in the uncertainty. If, however, the use of this method is not appropriate, linear least squares may provide reasonable results if the time series is long enough or if the frequency is high.
- Since there is far more cruise data for warm months, there is also sampling bias. Therefore, we are unable to use traditional[2] thermal versus non-thermal decomposition methods. Future work should focus on determining the other sources of fCO_2 increase.

REFERENCES

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