Effects of Climate Signals on Freshwater Delivery to Four Georgia Riverine Estuaries

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Abstract. Freshwater delivery helps to determine estuarine characteristics and may be influenced by large-scale climate oscillations. Variability in precipitation and river discharge to the Ogeechee, Satilla, and St. Marys River estuaries (GA) was examined in relation to several climate signal indices and compared to earlier results for the Altamaha River estuary. Empirical orthogonal function (EOF) analysis showed that monthly precipitation can be largely described by a temporal signal that is spatially uniform across each watershed (EOF 1), modulated by spatial patterns along (EOF 2) and across (EOF 3) the long axes of the watersheds, although analysis of three EOFs was not supported in all watersheds. The time series (principal components, PCs) associated with each precipitation EOF was best correlated with a different climate signal, and the dominance of climate signals changed seasonally: PC 1 with the Bermuda High Index in summer-fall, and PC 1 and PC 2 with El Niño/Southern Oscillation in fall-winter. Atlantic Multidecadal Oscillation (AMO) correlation patterns differed across watersheds, in part due to data avail-ability for discerning spatial patterns. In the Altamaha, the AMO was correlated with PC 3, altering the seasonality of freshwater delivery. In the other watersheds, PC 3 could not be evaluated but AMO was correlated with PC 1 in winter. No correlations were found with the North Atlantic Oscillation. Correlations between climate signals and river discharge mirrored those with precipitation, with additional lags. Seasonal switching of climate signal dominance could lead to differential propagation of climate signals through ecosystems, depending on critical seasons for keystone species.

INTRODUCTION

The typical levels and characteristic variability of freshwater input help to define key physical features of an estuary, such as the salinity gradient, currents, residence times of water and dissolved and particulate constituents, and sediment characteristics. These in turn define habitat availability for estuarine organisms, including intertidal and subtidal vegetation, animals, and microbes. The sources of freshwater to estuaries may be direct precipitation, overland runoff, groundwater, and river discharge, all of which may be influenced by large-scale climate patterns with varied effects on precipitation and temperature at regional scales. Thus, it is important to understand how climate influences freshwater delivery to estuaries and how changes in climate could alter estuarine ecosystem structures and processes.

We examined several climate patterns or drivers for linkages to watershed precipitation and river discharge to four estuaries in Georgia. Our previous analysis for the Altamaha River watershed found linkages to the Bermuda High, El Niño / Southern Oscillation (ENSO), and the Atlantic Multidecadal Oscillation (Sheldon and Burd 2014). Some climate signals showed no linkages with freshwater delivery (North Atlantic Oscillation (NAO), El Niño Modoki) and for others, the patterns found echoed the ENSO signal (Pacific Decadal Oscillation, Pacific / North American Pattern). Here we have repeated these analyses using the methods of Sheldon and Burd (2014) for the Ogeechee, Satilla, and St. Marys river watersheds and compared the results to the Altamaha analysis. To the extent that long-term climate changes may manifest themselves through changes in these known climate drivers, this understanding will aid in predicting potential ecosystem responses to climate change.

METHODS

Watershed precipitation patterns were examined using empirical orthogonal function (EOF) analysis, a type of principal components analysis that finds both spatial (EOF loadings) and temporal (principal components

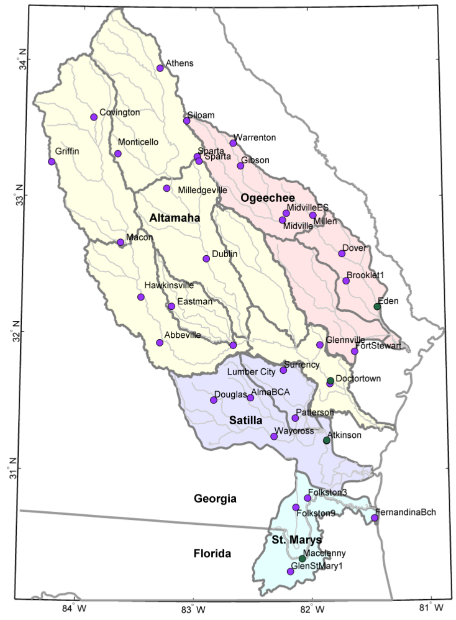

Figure 1: Watersheds and data stations. Purple dots are precipitation stations used in the EOF analyses; green dots are river discharge gauges.

(PC)) patterns. For this study of the Ogeechee, Satilla, and St. Marys watersheds, multi-decadal time series of monthly total precipitation were available from the NOAA National Climatic Data Center[1] at 4-10 sites per watershed (Fig. 1), and the most consistent timeframe for all three watersheds was Dec. 1956 to May 2010. Data preparation and EOF analyses were performed for each watershed following Sheldon and Burd (2014).

These analyses used fewer data than the Altamaha watershed analyses, which had examined several cases using data from 7-13 precipitation stations (Fig. 1) over much longer timeframes. Those analyses found similar EOF patterns regardless of the number of sites and timeframe (Sheldon and Burd 2014), suggesting that patterns are robust. Results from the study watersheds are compared with a 1904-2004 Altamaha dataset using eight stations.

The PCs from the EOF analyses were compared with monthly standardized anomalies of river discharge (U.S. Geological Survey) at the most downstream gauging stations (Fig. 1) and climate indices. In order to eliminate analytical problems due to autocorrelation, we first removed seasonal cycles by normalizing each time series month-by-month (e.g., January observations were normalized using the long-term mean and standard deviation for January). If any series still contained autocorrelation, we fit an autoregressive moving average (ARMA) model and used the residuals for subsequent analyses. Variables were cross-correlated month by month with 0-2 year lags in order to detect partial-year correlations and changing lag times.

The climate signals that we used in this study were those that had shown significant and unique correlations with precipitation and river discharge in the Altamaha watershed analysis (Sheldon and Burd 2014). In spite of the lack of correlation with the NAO in that study, we also included it again here because it has sometimes been shown to be important elsewhere in the southeastern US (Coleman and Budikova 2013). Climate signals and data sources are described briefly below.

North Atlantic Oscillation (NAO)

The NAO describes north-south fluctuations in air pressure differences between the higher and central latitudes of the North Atlantic Ocean. We used monthly station-based (Azores-Iceland) index data from the National Center for Atmospheric Research[2].

Bermuda High Index (BHI)

The BHI, which describes the east-west position of the southern pole of the NAO, was constructed as the monthly normalized sea level pressure difference between Bermuda and New Orleans, using the same NCAR station data as Katz et al. (2003). It varies on short (monthly, seasonal) time scales.

El Niño / Southern Oscillation (ENSO/SOI)

El Niño (La Niña) events are warm (cold) episodes in the eastern tropical Pacific Ocean that affect global climate on seasonal to annual time scales through atmospheric teleconnections. The Southern Oscillation Index (SOI), one measure of the atmospheric component of this pattern, is usually calculated based on the air pressure anomaly between Tahiti and Darwin, Australia and corresponds well with changes in eastern tropical Pacific Ocean temperatures. We used raw pressure data from the Australian Bureau of Meteorology[3] and normalized the pressure difference by month.

Atlantic Multidecadal Oscillation (AMO)

The AMO is an index of the monthly mean North Atlantic sea surface temperature anomaly, which varies on decadal time scales. We used index values from the NOAA Earth System Research Laboratory.

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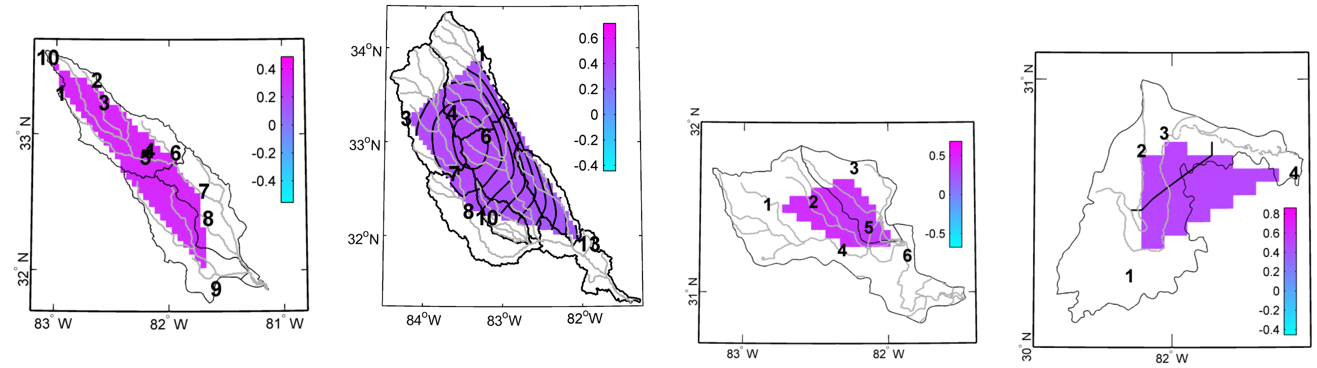
[1] *http://www.esrl.noaa.gov/psd/data/climateindices/list/*

[2] *http://www.cgd.ucar.edu/cas/catalog/*

[3] *http://www.bom.gov.au/climate/*



Ogeechee Altamaha Satilla St. Marys

Figure 2: Precipitation EOF 1 in the watersheds of the Ogeechee (68% variance explained), Altamaha (67%), Satilla (69%), and St. Marys (76%) rivers. Numbers are precipitation stations (see Fig. 1). Scale is relative EOF loading.

RESULTS

Precipitation Patterns

The Altamaha watershed analysis identified three EOFs as showing significant patterns rather than noise. The Ogeechee analysis with 10 stations identified two significant EOFs, and the Satilla and St. Marys with 6 and 4 stations, respectively, just one EOF. This most likely reflects the smaller amount of data for these watersheds, because the EOFs that were not statistically significant still resembled their counterparts in the Altamaha analysis. EOF 1 accounted for two-thirds to three-fourths of the variance in normalized precipitation in each watershed and was nearly spatially uniform (Fig. 2). This indicates that precipitation varied generally in unison across each watershed at the monthly scale, according to the value of PC 1. EOF 2 explained about 10% of the variance and had a spatial pattern that alternated NW-SE (Fig. 3). It represents a seesaw modulation of precipitation patterns up- and down-watershed, switching with the sign of PC 2. EOF 3 in the Altamaha watershed (6% of the variance) had a spatial pattern that radiated from the southwest (Fig. 4), representing a cross-watershed modulation in precipitation patterns.

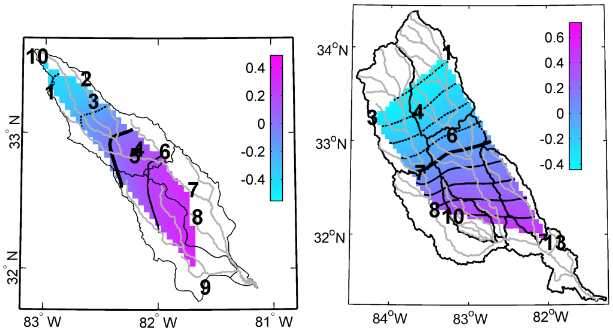


Figure 3: Precipitation EOF 2 in the watersheds of the Ogeechee (left, 10% variance explained) and Altamaha (right, 11%) rivers. Numbers are precipitation stations (see Fig. 1). Scale is relative EOF loading.

Correlations with Climate Signals

Linear correlations (Pearson r) between climate indices and other variables (all standard anomalies) were mostly weak to moderate. Non-uniform lags generally provided the highest correlations, and in all cases correlations persisted only during certain seasons. Correlations of climate signals with river discharge at the downstream gauge often lagged those with precipitation by an additional month. As with the Altamaha, we found no correlations between the NAO and precipitation or river discharge in any of the watersheds.

The BHI was moderate/strongly correlated with the precipitation PC 1 time series in each watershed from late spring through fall (with no lag) and with river discharge lagged approximately one month (Fig. 5). This indicates that the Bermuda High directly affects routing of storms to or around this entire region during summer and fall.

SOI in summer-winter was correlated weakly to moderately with the precipitation PC 1 time series in each watershed in the following fall-winter. In the Ogeechee and Altamaha watersheds, the fall-winter SOI was also moderately correlated with precipitation PC 2 in winter (Fig. 6). In the Satilla and St. Marys watersheds, where PC 2 was noisy and not used, PC 1 correlations were stronger but combined aspects of PC 1 and PC 2 correlations in the other watersheds. This may be an artifact of having fewer data. SOI correlations with river discharge resembled those with precipitation with additional lags of

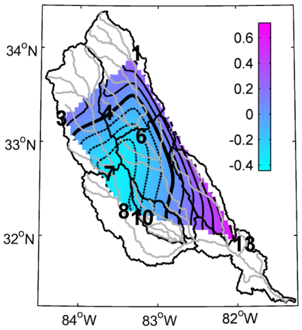
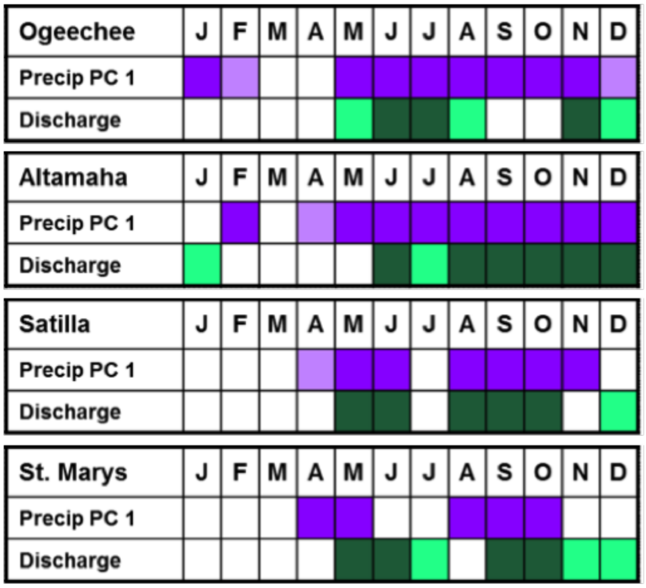


Figure 4: Precipitation EOF 3 explained 6% of the variance in the Altamaha River watershed. Numbers are precipitation stations (see Fig. 1). Scale is relative EOF loading.

about a month. ENSO effects take a few months to reach this region, are primarily a fall-winter phenomenon, and appear to be acting on two modes of precipitation variability (EOF 1, the overall pattern, and EOF 2, differences in upper and lower watersheds).

In the Altamaha watershed, where three EOFs could be considered, the AMO was most strongly correlated with precipitation PC 3 in December and June with lags up to a year. In the Ogeechee watershed, there were weak correlations with precipitation PC 1 in winter and none with PC 2, and PC 3 could not be evaluated. In the Satilla and St. Marys watersheds, where only precipitation PC 1 could be evaluated, the AMO was correlated weakly to moderately with PC 1 in early summer and early winter, with lags up to 1 year (Fig. 7). This stronger correlation with PC 1 (explaining more precipitation variability) in the two more southern watersheds could indicate stronger AMO effects in south Georgia, or it may be an artifact of having fewer precipitation stations and smaller watersheds and not being able to distinguish three EOF patterns, so the leading EOF may incorporate some elements of patterns that would be distinct if more data were available.

AMO correlations with river discharge were generally stronger than those with precipitation except in the St. Marys watershed. One might argue that river discharge may be integrating precipitation and other effects in ways that are not reflected in the precipitation analysis, especially in the watersheds with poor precipitation data coverage, resulting in a more robust analysis with river discharge. By this argument, the St. Marys River discharge may be problematic for this analysis because the most downstream gauge (at Macclenny, FL) is relatively far upstream of the mouth, so it may not reflect the same area as the precipitation data. However, the results from the BHI and SOI analyses suggest that the leading precipitation PCs are well coupled with downstream river discharge in all four estuaries, and climate signals that affect precipitation are reflected in river discharge. The problem may, instead, be that this 54-year analysis is less robust than the 100-year Altamaha analysis, considering that the AMO is a multidecadal signal and we may have too few cycles of it during this analysis period to be able to detect correlations reliably. The apparent overall effect of AMO in the Altamaha watershed and in Florida is to alter the peak seasonality of freshwater delivery (Kelly and Gore 2008; Sheldon and Burd 2014). The apparent effects of AMO in the three estuaries studied here, although less certain, are consistent with the earlier studies.



Ogeechee	J	F	M	A	M	J	J	A	S	O	N	D
Precip PC 1	■	▨			■	■	■	■	■	■	■	▨
Discharge					▨	■	■	▨			■	▨

Altamaha	J	F	M	A	M	J	J	A	S	O	N	D
Precip PC 1		■		▨	■	■	■	■	■	■	■	■
Discharge	▨					■	▨	■	■	■	■	■

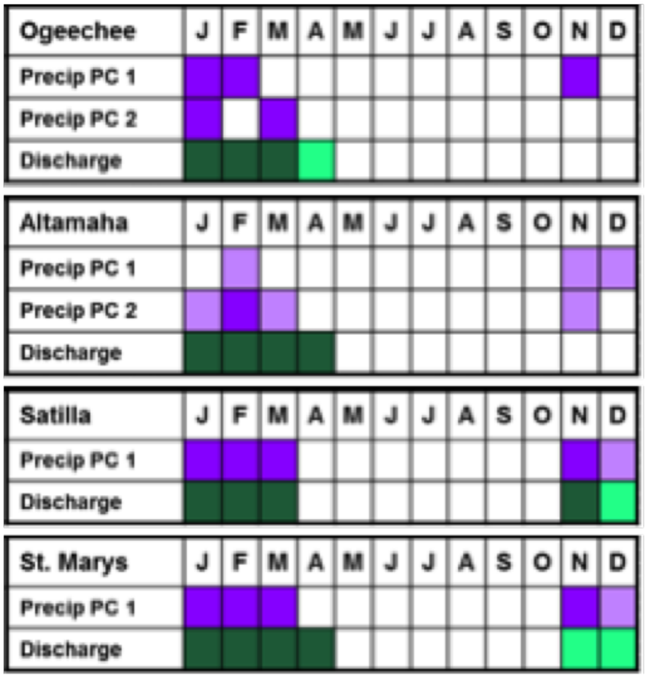
Satilla	J	F	M	A	M	J	J	A	S	O	N	D
Precip PC 1				▨	■	■		■	■	■	■	
Discharge					■	■		■	■	■		▨

St. Marys	J	F	M	A	M	J	J	A	S	O	N	D
Precip PC 1				■	■			■	■	■		
Discharge					■	■	▨		■	■	▨	▨

Figure 5: Correlations between Bermuda High Index and indicated months of precipitation principal com-ponent (PC) and river discharge in each watershed. Lighter colors: $r^2 < 0.09$, darker colors $r^2 > 0.09$; $p < 0.05$.

DISCUSSION

The analyses presented here and in Sheldon and Burd (2014) have found statistical linkages between three climate signals and freshwater delivery to four Georgia estuaries. The complex, seasonally alternating pattern of climate signals that affects precipitation and river discharge in the Altamaha River watershed (Sheldon and Burd 2014) extends to the neighboring Ogeechee, Satilla, and St. Marys watersheds. The Bermuda High and El Niño/Southern Oscillation connections appear to be consistent across the Georgia coast, with Bermuda High position affecting rainfall during summer-fall and ENSO affecting it during late fall-winter. The Atlantic



Ogeechee	J	F	M	A	M	J	J	A	S	O	N	D
Precip PC 1	🟪	🟪									🟪	
Precip PC 2	🟪		🟪									
Discharge	🟩	🟩	🟩	🟢								

Altamaha	J	F	M	A	M	J	J	A	S	O	N	D
Precip PC 1		🟣									🟣	🟣
Precip PC 2	🟣	🟪	🟣								🟣	
Discharge	🟩	🟩	🟩	🟩								

Satilla	J	F	M	A	M	J	J	A	S	O	N	D
Precip PC 1	🟪	🟪	🟪								🟪	🟣
Discharge	🟩	🟩	🟩								🟩	🟢

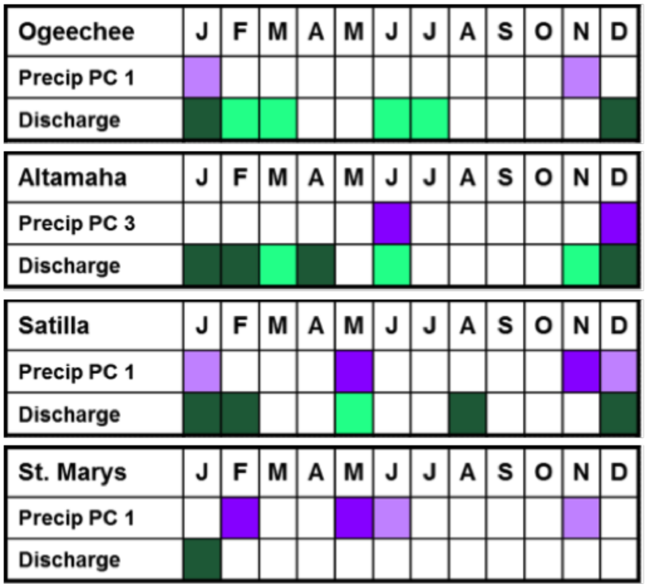
St. Marys	J	F	M	A	M	J	J	A	S	O	N	D
Precip PC 1	🟪	🟪	🟪								🟪	🟣
Discharge	🟩	🟩	🟩	🟩							🟢	🟢

Figure 6: Correlations between Southern Oscillation Index and indicated months of precipitation principal components (PC) and river discharge in each water-shed. Lighter colors: $r^2 < 0.09$, darker colors $r^2 > 0.09$; $p < 0.05$.

Multidecadal Oscillation imposes a long-term seasonality modulation, although a longer timeframe would be required to examine that pattern with greater certainty. We also evaluated the North Atlantic Oscillation but found no consistent correlations with freshwater delivery in any of the watersheds. Climate-precipitation signals all propagated, to some extent, to lower watershed river discharge 0-1 month later. Thus, changes in large-scale climate signals as well as the interplay among them have the potential to affect the amount and seasonality of freshwater entering these estuaries, which in turn will affect fundamental estuarine characteristics such as longitudinal salinity profiles and mixing time scales.

Analysis of monthly data was crucial to finding these connections because seasonal patterns of variables were different, correlations did not persist year-round, and the optimum lags were different for each correlation. Imposing seasonal groupings or lagging all the data uniformly year-round would have led to erroneous conclusions.

The seasonal change in dominance of different climate signals suggests that interactions with critical seasons for organisms' growth or reproduction could lead to differential climate signal propagation throughout an ecosystem. For example, Wieski and Pennings (2014) found that annual net primary production of the dominant salt marsh plant Spartina alterniflora at sites around the Altamaha River estuary was best related to Altamaha River discharge during its growing season (March-September), a period that we found is moderately to strongly influenced by the Bermuda High.



Ogeechee	J	F	M	A	M	J	J	A	S	O	N	D
Precip PC 1	🟣										🟣	
Discharge	🟩	🟢	🟢			🟢	🟢					🟩

Altamaha	J	F	M	A	M	J	J	A	S	O	N	D
Precip PC 3						🟪						🟪
Discharge	🟩	🟩	🟢	🟩		🟢					🟢	🟩

Satilla	J	F	M	A	M	J	J	A	S	O	N	D
Precip PC 1	🟣				🟪						🟪	🟣
Discharge	🟩	🟩			🟢			🟩				🟩

St. Marys	J	F	M	A	M	J	J	A	S	O	N	D
Precip PC 1		🟪			🟪	🟣					🟣	
Discharge	🟩											

Figure 7: Correlations between Atlantic Multidecadal Oscillation and indicated months of precipitation principal components (PC) and river discharge in each watershed. Lighter colors: $r^2 < 0.09$, darker colors $r^2 > 0.09$; $p < 0.05$.

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