



Research papers

Atlantic Ocean Sea Surface Temperatures and Southeast United States streamflow variability: Associations with the recent multi-decadal decline

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ABSTRACT

Unprecedented population growth combined with environmental and energy demands have led to water conflict in the Southeastern United States (SEUS). The states of Alabama, Florida, and Georgia have been engaged in litigation since 1990 on minimum in-stream flows to maintain ecosystems, fisheries and energy demands while satisfying a growing thirst in metropolitan Atlanta. A study of twenty-six unimpaired SEUS (Alabama, Florida, Georgia, Louisiana, Mississippi, North Carolina, and Tennessee) streamflow stations identified a decreased pattern of flow over the past ~25 years with more frequent dry periods being observed in the last several decades. When evaluating calendar year streamflow, a period of high streamflow in the 1970's was followed by a consistent decrease in streamflow from the late 1980's to present. The identification of Atlantic Ocean (AO) Sea Surface Temperature (SST) teleconnections with SEUS streamflow may prove valuable in explaining decadal patterns of streamflow variability. Previous studies have identified the Atlantic Multidecadal Oscillation (AMO) as being teleconnected with SEUS precipitation and streamflow. The current research applied the Singular Value Decomposition (SVD) statistical method to AO Sea Surface Temperatures (SSTs) and SEUS streamflow. Annual streamflow volumes from the twenty-six unimpaired SEUS streamflow stations (1952–2016) were selected as the hydrologic response while average AO SSTs were calculated for three different six month averages (January to June or JFMAMJ, April to September or AMJJAS, and July to December or JASOND) for the year (1951–2015) preceding streamflow. The results confirmed an SST region in the North Atlantic as being teleconnected with SEUS streamflow and that an observed multi-decadal increase in temperatures in this SST region may be associated with the observed recent multi-decadal decline in SEUS streamflow.

1. Introduction

The Southeastern United States (SEUS) has been plagued by droughts in the past several decades. Water conflict, once thought reserved only for the Western U.S. has now resulted in “water wars” among several southern states (Bearden and Andreen, 2017). Population growth throughout the SEUS including major cities such as Atlanta and states such as Florida has stressed a once abundant resource –

streamflow. Decreased streamflow and the resulting water shortages also catapulted three states, Alabama, Florida, and Georgia, into two major legal conflicts, one among Alabama, Florida, and Georgia over the water in the Apalachicola-Chattahoochee-Flint (ACF) system and a second between Alabama and Georgia over the water in the Alabama-Coosa-Tallapoosa (ACT) system. These disputes, which began in 1990, are now more than two decades old, and are playing out in the Supreme Court of the United States in *Florida v. Georgia*. No. 142 Orig. (U.S. filed

Abbreviations: SEUS, Southeastern United States; ACF, Apalachicola-Chattahoochee-Flint; ACT, Alabama-Coosa-Tallapoosa; ENSO, El Nino-Southern Oscillation; PDO, Pacific Decadal Oscillation; AMO, Atlantic Multi-Decadal Oscillation; NAO, North Atlantic Oscillation; PNA, Pacific/North American; AO, Atlantic Ocean; NASH, North Atlantic Subtropical High; SVD, Singular Value Decomposition; PCA, Principle Components Analysis; JFMAMJ, January to June; AMJJAS, April to September; JASOND, July to December; Std, Standard Deviation; NOAA, National Oceanic and Atmospheric Administration; ERSST v3b, Extended Reconstructed SST version 3b; USGS, US Geological Survey; NWIS, National Water Information System; SCF, Square Covariance Fractions; EPA, Environmental Protection Agency; NSF, National Science Foundation; P2C2, Paleo Perspectives for Climate Change Program

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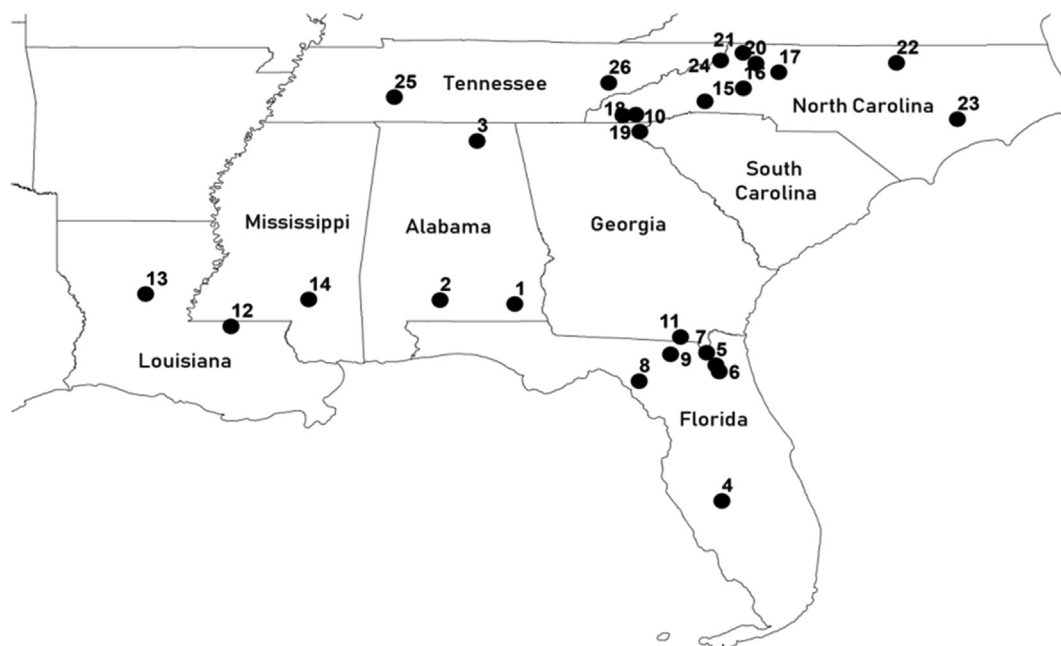


Fig. 1. Location Map of (26) Unimpaired Southeast United States Streamflow Stations.

Sept. 25, 2013) (Bearden and Andreen, 2017). Thus, there are concerns amongst water managers, planners, governments and stakeholders regarding the potential cause(s) of these recent decreases.

Twenty-six unimpaired (Lins, 2012) streamflow stations were identified in the SEUS (Fig. 1, Table 1) and calendar year streamflow was standardized (i.e., mean of zero and standard deviation of one) for the period of 1952 to 2016. A twenty-year filter (i.e., moving average) was then applied to each station. The yearly twenty-year end-year filter values (1971–2016) for each station were then displayed with uncertainty (Fig. 2). Fig. 2 clearly displays a multi-decadal decline in SEUS streamflow beginning around ~1990 with the most recent year in the period of study (2016) being the lowest (20-year filtered) value in the

observed record. Given anthropogenic influences are negligible due to the selection of unimpaired streamflow stations, understanding the drivers of the climatic variability in the SEUS is the key to determining the cause of this multi-decadal decline in streamflow.

Recognition of the influence of ENSO on climate in the SEUS has long been established with El Nino (La Nina) generally associated with increased (decreased) moisture (Kahya and Dracup, 1993) with strong seasonal influence well documented within the literature (Wang and Asefa, 2017; Engström and Waylen, 2018; Maleski and Martinez, 2018). McCabe et al. (2004) evaluated the coupling of the Pacific Decadal Oscillation (PDO) and Atlantic Multi-Decadal Oscillation (AMO) and attributed more than 50% of the United States spatial and temporal

Table 1

Station Number, Station ID, Station Name, State, Cumulative Deficit Flow (measured in Standard Deviations) from 2000 to 2016 for (26) Unimpaired SEUS Streamflow Stations. NS represents Not Significant.

#	Station ID	Station Name	State	Cumulative Deficit in Std. (2000–2016)
1	02361000	CHOCTAWHATCHEE RIVER NEAR NEWTON	AL	−6.8
2	02374500	MURDER CREEK NEAR EVERGREEN	AL	−5.3
3	03574500	PAINT ROCK RIVER NEAR WOODVILLE	AL	−6.6
4	02296500	CHARLIE CREEK NEAR GARDNER	FL	−0.4
5	02246000	NORTH FORK BLACK CREEK NR MIDDLEBURG	FL	−7.6
6	02245500	SOUTH FORK BLACK CREEK NR PENNEY FARMS	FL	−6.0
7	02231000	ST. MARYS RIVER NR MACCLENNEY	FL	−5.7
8	02324000	STEINHATCHEE RIVER NEAR CROSS CITY	FL	−5.3
9	02315500	SUWANNEE RIVER AT WHITE SPRINGS	FL	−6.5
10	02177000	CHATTOOGA RIVER NEAR CLAYTON	GA	−6.0
11	02314500	SUWANNEE RIVER AT US 441, AT FARGO	GA	−7.5
12	07377000	AMITE RIVER NR DARLINGTON	LA	−7.4
13	07373000	BIG CREEK AT POLLOCK	LA	−4.8
14	02472500	BOUIE CREEK NR HATTIESBURG	MS	−5.3
15	02149000	COVE CREEK NEAR LAKE LURE	NC	−6.9
16	02143000	HENRY FORK NEAR HENRY RIVER	NC	−9.7
17	02118500	HUNTING CREEK NEAR HARMONY	NC	−7.0
18	03500000	LITTLE TENNESSEE RIVER NEAR PRENTISS	NC	−6.7
19	03504000	NANTAHALA RIVER NEAR RAINBOW SPRINGS	NC	−3.5
20	02111500	REDDIES RIVER AT NORTH WILKESBORO	NC	−5.4
21	03161000	SOUTH FORK NEW RIVER NEAR JEFFERSON	NC	−3.6
22	02081500	TAR RIVER NEAR TAR RIVER	NC	−6.2
23	02092500	TRENT RIVER NEAR TRENTON	NC	−0.4
24	03479000	WATAUGA RIVER NEAR SUGAR GROVE	NC	−2.8
25	03604000	BUFFALO RIVER NEAR FLAT WOODS	TN	−3.5
26	03498500	LITTLE RIVER NEAR MARYVILLE	TN	−2.2

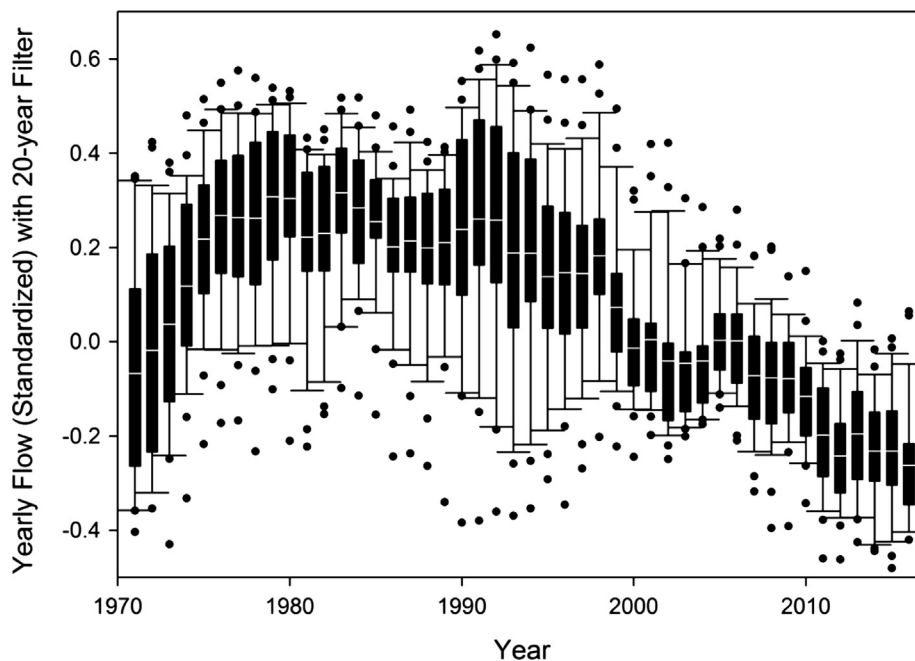


Fig. 2. Yearly standardized flow volumes for twenty-six unimpaired SEUS streamflow stations with 20-year (end-year) filter for 1971 to 2016. The mean is represented by the white line while the lower boundary of the black box represents the 25th percentile while the upper boundary of the black box represents the 75th percentile. The lower whisker represents the 10th percentile while the upper whisker represents the 90th percentile. Outliers are displayed as black dots.

variance in multi-decadal drought frequency to the PDO and AMO. They found that the AMO warm phase was associated with SEUS drought and was enhanced when coupled with a PDO warm phase. In evaluating the AMO impact on rainfall, [Enfield et al. \(2001\)](#) determined that most of the United States has less than normal rainfall during the AMO warm phase. When correlating the North Atlantic Oscillation (NAO) with spring precipitation in Southeastern coastal states, [Stahle and Cleaveland \(1992\)](#) did not identify a signal. This lack of an NAO signal in the SEUS was later confirmed by [Tootle et al. \(2005\)](#) when evaluating continental U.S. streamflow. [Leathers et al. \(1991\)](#) associated the Pacific/North American (PNA) pattern with SEUS temperature, but a significant correlation was not identified with precipitation. Furthermore, recent work by [Engstrom and Waylen \(2018\)](#) showed patterns of NAO and PNA, in addition to Arctic Oscillation varied over the short term, with significant, yet temporally variable influence, while also confirming the disassociation between the Arctic Oscillation and NAO.

While the El Niño-Southern Oscillation (ENSO) and its projected phase (El Niño – Warm, La Niña – Cold) makes headlines in SEUS water management, the warming and cooling of AO SSTs and the potential influence on SEUS streamflow should be considered. While studies have evaluated AO climatic variability and have included SEUS hydrologic response ([Enfield et al., 2000](#)), these studies typically focus on established AO climate signals (e.g., AMO and NAO). The use of AO SSTs eliminates any biases that are inherent in these pre-defined indices. An identification and understanding of any underlying AO climatic driver will benefit the water availability prediction and management for this region.

Various statistical techniques exist to determine the relationship between two, spatial-temporal fields such as SSTs and streamflow, including canonical correlation analysis, combined principal component analysis and singular value decomposition (SVD; [Tootle and Piechota, 2006](#)). [Bretherton et al. \(1992\)](#) concluded that SVD was simple to use and preferable for general use, while [Wallace et al. \(1992\)](#) found that SVD was a powerful technique that isolates the most important modes of variability. Multiple studies have used SVD to evaluate SST and hydrologic variability ([Table 2](#); [Bhandari et al., 2018](#); [Sagarika et al., 2016](#); [Chitsaz et al., 2016](#); [Risko and Martinez, 2014](#); [Oubeidillah et al., 2011, 2012](#); [Lamb et al., 2010](#); [Aziz et al., 2010](#); [Soukup et al., 2009](#); [Tootle et al., 2008](#); [Tootle and Piechota, 2006](#); [Shabbar and Skinner,](#)

[2004](#); [Rajagopalan et al., 2000](#); [Wang and Ting, 2000](#)). These studies investigated SST and hydrologic (e.g., snowpack, drought, precipitation, streamflow) response. While the use of Principal Components Analysis (PCA) is very common in this type of analysis, SVD has the advantage of being able to evaluate the cross-covariance matrix of two spatial-temporal fields to identify similarities between them. PCA, on the other hand, evaluates only one spatial-temporal field. As previously stated, the use of SVD with SSTs and streamflow eliminates the limitations associated with using pre-defined SST regions (e.g., AMO) of climate variability and the resulting streamflow response to phases (e.g., warm or cold) of these climate signals.

Therefore, the hypothesis of the current research is that an AO SST region (or regions) exists that is (are) teleconnected with SEUS streamflow. The identification of a specific AO SST climatic driver of SEUS streamflow would represent an important contribution. The motivation of the current research is that the AO SST region (or regions) identified and the teleconnection to SEUS streamflow may explain the recent multi-decadal decline in SEUS streamflow. Although extensive work has been conducted exploring climatic associations to precipitation and streamflow patterns in the SEUS, full characterization of the recent multi-decadal streamflow decreases in the SEUS and the validation of the climatic drivers of these decreases have yet to be conducted. This study provides clarification of the extent, duration and magnitude of SEUS streamflow variability and the associated large scale climate forcing mechanisms, a crucial first step toward providing the context needed by water managers and policy makers to make more informed decisions regarding available water resources within the SEUS.

2. Data and methods

2.1. Atlantic Ocean (AO) Sea Surface Temperatures (SSTs)

The NOAA Extended Reconstructed SST version 3b (ERSST v3b; [Smith and Reynolds, 2008](#)) were downloaded from the NOAA Earth System Research Laboratory (<http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.ersst.html>). The monthly ERSST SST averages are at the 200-km spatial resolution and cover from 1854 through 2017. In this study, the regional SST averages spanning from 20° South to 70° North and 80° West to 2° West were computed. The defined region

Table 2

Previous studies referenced in this work that utilize the SVD statistical technique for climate analysis, including the author, date of publication and the context in which SVD analysis was utilized in the study/region of interest.

Author	Year	SVD Context/Regional Evaluation
Aziz et al.	2010	Pacific SST on Upper Colorado River Basin Snowpack
Bhandari et al.	2018	Multi-region study climate teleconnections & streamflow
Bretherton et al.	1992	Method comparison for coupled climate pattern analysis
Chitsaz et al.	2016	Method comparison for pre-processing climate data
Lamb et al.	2010	SST index w/ SVD for prediction of Colorado River flow
Newman and Sardeshmukh	1995	Limitations of SVD techniques w/meteorological data
Oubeidillah et al.	2012	Atlantic SST for Adour-Garonne Basin (France) streamflow
Oubeidillah et al.	2011	Pacific SST on snowpack/streamflow Upper CO/Great River Basin
Rajagopalan et al.	2000	ENSO/SSTs teleconnection to U.S. 20th century summer droughts
Risko and Martinez	2014	Multi-climate predictor analysis of West-Central FL streamflow
Sagarika et al.	2016	Pacific SST and Z ₅₀₀ on western U.S. seasonal streamflow
Soukup et al.	2009	SST and Z ₅₀₀ on long-lead-time North Platte River streamflow
Shabbar and Skinner	2004	Global SST on summer drought patterns in Canada
Tootle et al.	2008	Pacific & Atlantic SST on Colombian streamflow variability
Tootle and Piechota	2006	Pacific & Atlantic SST on continental U.S. streamflow variability
Uvo et al.	1998	Pacific/Atlantic SST on monthly precipitation, Northeastern Brazil
Wallace et al.	1992	Multi-method analysis of Pacific SST & 500-mb height anomalies
Wang and Ting	2000	Co-variability of Pacific SST and winter precipitation in the U.S.

includes 1239 grid cells over the AO. The averages of AO SSTs were calculated for three different six-month periods including: January to June (JFMAMJ), April to September (AMJJAS), and July to December (JASOND). In this study, the AO SST data were used from 1951 to 2015.

2.2. Unimpaired streamflow

Data from unimpaired streamflow stations (Fig. 1, Table 1) were obtained from the US Geological Survey (USGS) National Water Information System (NWIS). The average monthly streamflow rates were retrieved from the NWIS website (<http://waterdata.usgs.gov/nwis>). The average monthly streamflow rate in cubic-feet per second (cfs) for each month in the calendar year were summed and converted into streamflow volumes using appropriate conversions. The calendar year period of cumulative streamflow volume was used and the period of record was 1952–2016 (65 years). For this study, unimpaired streamflow stations (stations identified with minimal anthropogenic influences) were selected (Lins, 2012). While there were many streamflow stations with records extending further back in time, many had large gaps of missing data or were discontinued in recent times. Only streamflow stations with complete records were evaluated. The selected period of record for streamflow (1952–2016) balanced the number of stations that had complete records with an acceptable length of record. This resulted in twenty-six (26) streamflow stations being used in the current research.

2.3. Singular value decomposition (SVD)

SVD is a powerful statistical tool for identifying coupled relationships between two, spatial-temporal fields. Bretherton et al. (1992) provides a detailed discussion of the theory of SVD, while Tootle et al. (2008) and Tootle and Piechota (2006) provide a brief description of SVD, as applied in the current research (Table 2).

Initially, a matrix of standardized AO SST anomalies and a matrix of standardized streamflow anomalies were developed. The time dimension of each matrix (i.e., 65 years) must be equal while the spatial component (i.e., AO SST cells and streamflow stations) can vary in dimension. The cross-covariance matrix was then computed for the two spatial, temporal matrices and SVD was applied to the cross-covariance matrix and physical information regarding the relationship between the two was obtained. The resulting SVD of the cross-covariance matrix created two matrices of singular vectors and one matrix of singular values. The singular values were ordered such that the first singular value (1st mode) was greater than the second singular value and so on.

Bretherton et al. (1992) defines the squared covariance fraction (SCF) as a useful measurement for comparing the relative importance of modes in the decomposition. Each singular value was squared and divided by the sum of all the squared singular values to produce a fraction (or percentage) of squared covariance for each mode.

Finally, the two matrices of singular vectors were examined, generally referred to as the left (i.e., AO SSTs) matrix and the right (i.e., streamflow) matrix. The first column of the left matrix (1st mode) was projected onto the standardized AO SSTs anomalies matrix and the first column of the right matrix (1st mode) was projected onto the standardized streamflow anomalies matrix. This resulted in the 1st temporal expansion series of the left and right fields, respectively. The left heterogeneous correlation values (for the 1st mode) were determined by correlating the AO SST values of the left matrix with 1st temporal expansion series of the right field and the right heterogeneous correlation values (for the 1st mode) were determined by correlating the streamflow values of the right matrix with the 1st temporal expansion series of the left field. Utilizing a approach similar to Rajagopalan et al. (2000) and Uvo et al. (1998), heterogeneous correlation figures displaying significant correlation values for AO SSTs were developed for each predictor season (JFMAMJ, AMJJAS and JASOND). Similarly, significant streamflow stations for each predictor season were also identified. While SVD is a powerful tool for the statistical analysis of two spatial, temporal fields, there exist several limitations to its use that should be investigated (Newman and Sardeshmukh, 1995). Generally, if the leading (1st, 2nd, 3rd) modes explain a significant amount of the variance of the two fields, then SVD can be applied to determine the strength of the coupled variability present (Newman and Sardeshmukh, 1995). However, when using SVD to examine two fields, the examiner must exhibit caution when attempting to explain the physical cause of the results (Newman and Sardeshmukh, 1995).

3. Results

3.1. SVD analysis

The cumulative SCF for the first three modes was above 90% in all cases (JFMAMJ, AMJJAS, JASOND). Generally, if the leading three modes explain a significant (greater than 80%) amount of the variance between the two fields, then SVD can be applied to determine the strength of the coupled variability present (Newman and Sardeshmukh, 1995). Therefore, SVD can and has been applied successfully in the current research efforts.

The results of this study show that the majority of the variability in

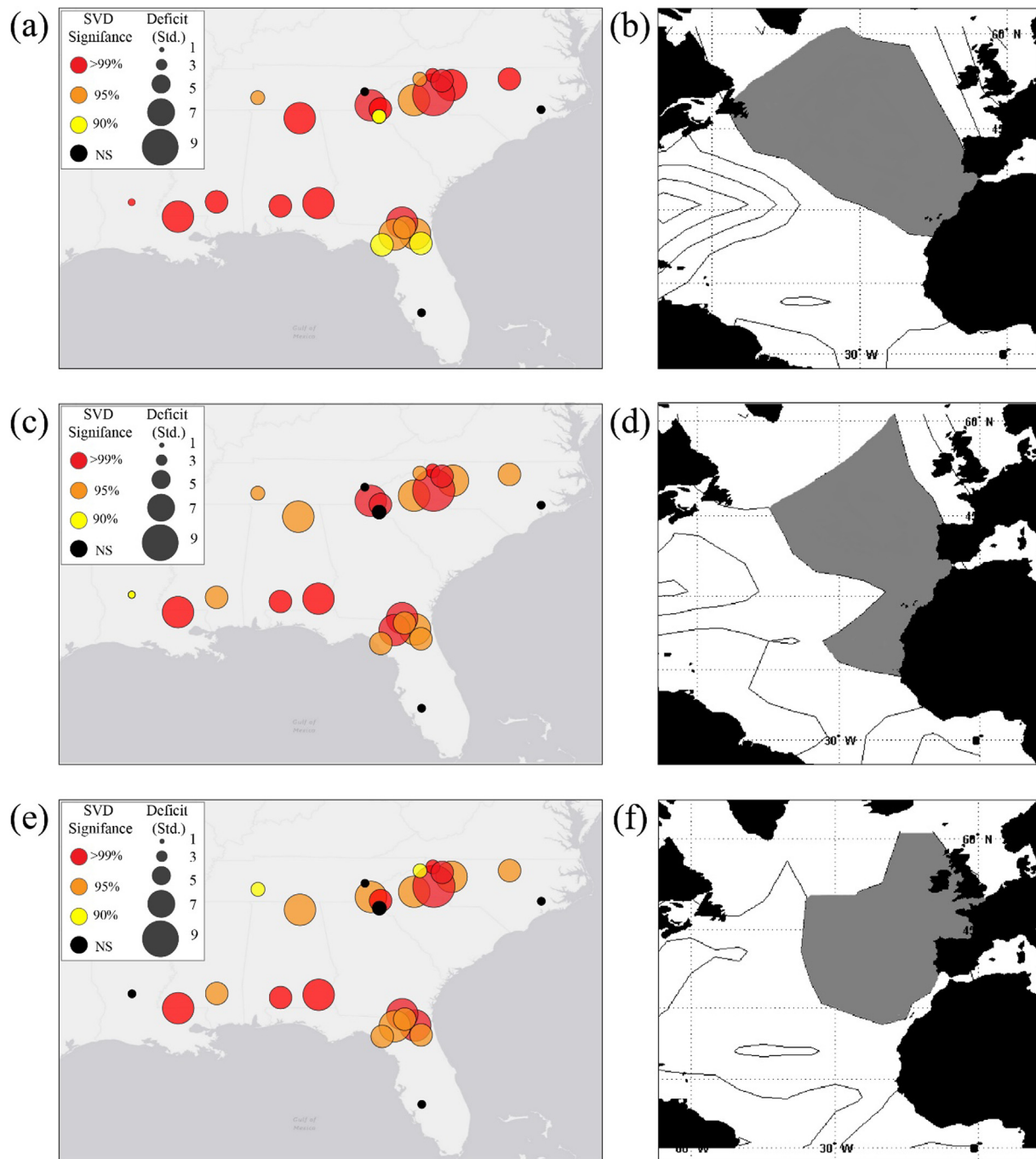


Fig. 3. Heterogeneous correlation maps of the streamflow stations indicating SVD Significance (90%, yellow; 95%, orange; > 99%, red; not significant – NS, black) and binned cumulative deficit flows (measured in standard deviations – Std.) from 2000 to 2016 for (26) unimpaired SEUS streamflow stations (Table 1) indicated by diameter (magnitude) of the circles for predictor periods (a) JFMAMJ, (c) AMJJAS, and (e) JASOND; Corresponding AO SSTs > 99% significance are identified in grey shaded contour for SVD predictor periods (b) JFMAMJ, (d) AMJJAS, and (f) JASOND. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the data is explained in the 1st mode. The 1st mode Square Covariance Fractions (SCF) ranged from 81% to 85% for the JFMAMJ, AMJJAS and JASOND predictor periods. Given that the overwhelming majority of the variability was explained in the first mode, only results for the first mode were provided.

3.1.1. AO SSTs and SEUS streamflow

Three maps (JFMAMJ, AMJJAS and JASOND) were developed for the 1st mode and the AO SST region (> 99% significance) was highlighted in grey (Fig. 3). A consistent pattern, in all three maps, displays

AO SSTs in the North Atlantic Ocean that were teleconnected with SEUS streamflow. Referring to Table 1 (SVD Significance: JFMAMJ, AMJJAS and JASOND), the vast majority of unimpaired streamflow stations, for each season, were also significant.

3.2. SEUS AO SST index

For each of the three predictor periods (JFMAMJ, AMJJAS and JASOND), cells were identified with in the “grey zone” which exceeded 99.9% significance. A time series (1951–2015) was developed in which

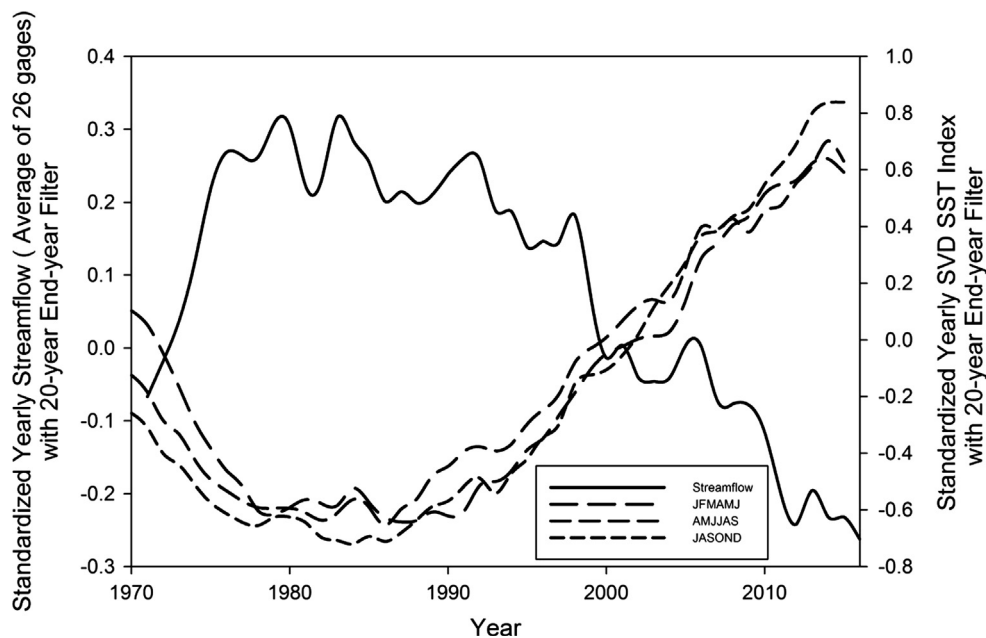


Fig. 4. SVD SST Index (JFMAMJ, AMJJAS and JASOND) with 20-year filter and Average (Twenty-six stations) Annual Streamflow with 20-year filter.

the standardized SST for each cell selected was averaged for each year. Thus, a yearly (1951–2015) SVD SST index for SEUS streamflow was developed for each predictor period (JFMAMJ, AMJJAS and JASOND). This SVD SST index (1951–2015) was then compared to standardized, unfiltered yearly streamflow (average for twenty-six stations from 1952 to 2016). To assess the decadal to multi-decadal signals in the SVD SST Index and the average annual streamflow data, a 20-year filter was applied to all data (Fig. 4). When correlating the 20-year filtered SVD SST index for each predictor period (JFMAMJ, AMJJAS and JASOND) with 20-year filtered SEUS streamflow (average for 26 stations), the variance (R^2) explained was 93%, 91% and 90%, respectively. The R^2 value reflects the relationship between the 20-year filtered data (seasonal SVD SST indices and average annual streamflow for 26 gages). The results clearly show the warming trend in AO SSTs that began in the 1980's coincides with a rapid decline in SEUS streamflow. Thus, SVD validated a multi-decadal teleconnection between North Atlantic Ocean SSTs and SEUS streamflow. A further investigation of the seasonal SVD SST indices and each streamflow station at a yearly resolution revealed highly significant relationships. For the JFMAMJ SVD SST predictor period, 81% of the gages achieved a significance of 95% ($p < 0.05$) while 69% of the gages achieved a significance of 99% ($p < 0.01$). For the AMJJAS SVD SST predictor period, 85% of the gages achieved a significance of 95% ($p < 0.05$) while 65% of the gages achieved a significance of 99% ($p < 0.01$). For the JASOND SVD SST predictor period, 81% of the gages achieved a significance of 95% ($p < 0.05$) while 62% of the gages achieved a significance of 99% ($p < 0.01$). Thus, the SVD SST Indices developed for each predictor period (season) were highly correlated with individual streamflow gages for the various (6, 3 and 0-month) lead-times. While the relationship between Atlantic Ocean SSTs and SE streamflow response clearly exhibits a multi-decadal pattern, the yearly relationship was very encouraging and may provide predictive skill in long lead-time forecasting of streamflow in this region.

4. Discussion

4.1. Climatic drivers of SEUS streamflow decline

Was the recent decline in SEUS streamflow predicted? AMO, PDO and United States water resources, including streamflow, have been

investigated for the Southeastern United States (Tootle et al., 2004; Wang and Asefa, 2017; Engström and Waylen, 2018; Maleski and Martinez, 2018). When evaluating water-year unimpacted streamflow from 1952 to 2002, an AMO signal was identified in the Southeast United States such that the AMO cold (warm) phase was associated with increased (decreased) streamflow (Tootle et al., 2004). Engström and Waylen (2018) further identified that both AMO and ENSO conditions had the strongest influence in the fall, corresponding to the dry season in southern states, amplifying water shortage. The AMO began shifting from a cold to warm phase during the early 1990's and was considered to be in a warm phase beginning around ~1996 (Trenberth and Fasullo, 2017). It should be noted the AMO warm phase appeared to peak around 2008 and the peak was the highest in the observed record (1870 to present; Trenberth and Fasullo, 2017). Thus, the AMO warm phase, which is associated with decreased moisture in the Southeast United States, appears to coincide with the recent Southeast United States streamflow record lows within the observed record and the magnitude of the AMO warm phase appears to mirror that of the Southeast United States decrease.

Tootle et al. (2005) confirmed an AMO signal in SEUS streamflow in which the warm (cold) phase of the AMO results in decreased (increased) streamflow. Furthermore, it also confirmed an ENSO signal in SEUS streamflow in which cold – La Nina (warm – El Nino) results in decreased (increased) streamflow. The coupling of AMO Warm and ENSO Warm (La Nina) also showed significant decreases in SEUS streamflow. Tootle et al. (2005) stated that given the current AMO warm phase, the development of a La Nina could severely impact decreased streamflow (i.e., drought) in the southeastern United States. While the current SVD analysis confirms the teleconnection of a multi-decadal North Atlantic (perhaps “AMO like”) SST pattern with SEUS streamflow and a plausible explanation of the multi-decadal decline in SEUS streamflow, was the extraordinary decline in SEUS streamflow since ~2000 enhanced by multiple La Nina events? Five La Nina events (2000, 2007, 2008, 2010, and 2011) have occurred since 2000. For the twenty-six SEUS streamflow stations, the average annual deficit streamflow (measured in standard deviations of annual flow) for the five La Nina events was -1.02 , with a range of -0.38 to -1.43 . Thus, from 2000 to 2016 (17 years), the five La Nina years resulted in an average cumulative deficit of just over five standard deviations of annual streamflow volume. Spatially, the decline in annual streamflow

was consistent across the twenty-six gage SEUS region. When evaluating the cumulative deficit of streamflow (measured in standard deviations of annual flow) since 2000 (2000–2016), all twenty-six gages displayed deficit flows (Table 1). Johnson et al. (2013) evaluated climate signals in the Apalachicola-Chattahoochee-Flint (ACF) river basin which encompasses a large region of the SEUS. While their study was limited to pre-defined Pacific Ocean and Atlantic Ocean indices (e.g., Nino 3.4, AMO), they confirmed a similar coupling effect of AMO and ENSO in SEUS streamflow as Tootle et al. (2005). Since ENSO, specifically La Nina type conditions, are a known driver for droughts within the Southeastern United States, with a cycle of 2–3 years via modulating moisture flux transport (Kam and Sheffield, 2016), the combination of warm phase of the AMO, a cool phase of the PDO and La Nina conditions would likely result in enhanced drought conditions within the Southeastern United States, as noted in McCabe et al. (2004) and Tootle et al. (2005), and observed within the recent record of historically low flows within the Southeastern United States.

Forecasting the end to the recent decrease in Southeast United States streamflow is very uncertain. If as indicated by the SVD analysis, AMO warm phase is enhancing La Nina conditions, resulting in the recent historically low streamflow in the Southeastern United States, the extent (and magnitude) of the current AMO phase may provide some predictive information. The preceding AMO cold phase (around 1965–1995) was approximately 30 years in length while the AMO warm phase (around 1925–1965) preceding the cold phase was approximately 40 years in length. Given that the current AMO warm phase began around 1995, we would anticipate that the AMO enhancement of weak to moderate La Nina years would end between 2025 and 2035.

4.2. Paleo perspectives on recent SEUS streamflow declines

Paleo reconstructions (using tree-ring proxies) of streamflow in the Southeast United States are relatively limited in this region however, they by and large indicate that the instrumental period is not representative of the full range of natural variability; extremes of both hydrological drought and pluvial periods of greater duration and magnitude than those observed in the 20th century are common and the influence of large-scale circulation features generally do not appear to be consistent through time (e.g., Stahle and Cleaveland 1992; Cook et al., 2007; Seager et al., 2009; Pederson et al., 2012; Harley et al., 2017; Ho et al., 2017; Maxwell et al., 2017). However, both the work by Stahle and Cleaveland (1992) and Maxwell et al. (2017) suggest that the North Atlantic Subtropical High (NASH) has a strong influence on precipitation in the southeast. The NASH is a circulation anomaly embedded within the AMO and warm (cold) AMO conditions lead to weakening (strengthening) of the NASH that in turns leads to drier (wetter) conditions over North America in general, and particularly in the Eastern United States during the warm season (also see Hu et al., 2011). The findings by Stahle and Cleaveland (1992) and Maxwell et al. (2017) suggest that the association between the current warm AMO and streamflow decreases in Southeast United States streamflow over the past two decades identified in our analysis may be consistent over longer periods than can be identified in the observational record. Future work will necessitate an expanded network of paleo reconstructions of streamflow throughout the SEUS to place the impact of SSTs within the observed record into a long-term context, allowing for a more complete understanding of the influence of both high and low frequency large-scale climate teleconnections within the region.

5. Conclusions

Recent streamflow declines, drought conditions and population growth have resulted in water conflicts between several of the Southern states (Bearden and Andreen, 2017), with half of the interstate water conflict cases currently pending before the Supreme Court are in the

SEUS. Low streamflow will remain one of the top water policy issues to watch in the SEUS water resources spectrum, necessitating the need for better understanding of the climatic drivers of low streamflow throughout the region.

The current research, utilizing “raw” AO SST datasets confirmed a strong teleconnection with SEUS streamflow and, thus, a likely explanation of the historic decline of SEUS streamflow in the multi-decadal warming of North Atlantic SSTs enhanced by multiple La Nina events since ~2000. The SEUS AO SST index developed for the JFMAMJ (six month lead time), the AMJJAS (three month lead time) and JASOND (zero month lead time) may prove useful in long lead time forecasting of SEUS streamflow and will likely increase forecast model skill when compared to using pre-defined indices such as the AMO, providing a critical tool in the fight to sustain water resources in the SEUS now, and into the future.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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