

CLIMATE VARIABILITY  
AND SOUTHEAST  
U.S. PRECIPITATION

by

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A THESIS

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## ABSTRACT

A study of the seasonal effects of interannual and interdecadal climactic influences on southeast U.S. precipitation is presented. Precipitation data was gathered from 183 precipitation gauges provided by The National Oceanic and Atmospheric Administration's (NOAA) National Center for Environmental Information (NCEI). The phases (warm/positive or cold/negative) of oceanic-atmospheric influences of the Pacific Ocean [El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO)] and the Atlantic Ocean [Atlantic Multidecadal Oscillation (AMO)] were identified for the preceding year (1969-2013) to the precipitation data (1970-2014). Three statistical significance tests (1) two-sample t-test (90% significance), (2) rank-sum (90% significance) and (3) effect-size (threshold of 0.8 to -0.8) were used to evaluate precipitation response to the positive/negative phases of the oceanic-atmospheric influences of the Pacific and Atlantic Oceans. The warm phases of ENSO and PDO were associated with increased annual precipitation in the southeastern region of the United States, while the cold phase of the AMO was associated with increased annual precipitation. While providing affirmation of these associations, this study considers the variation in seasonal precipitation of the southeastern U.S. The results indicate strong winter [January-March (JFM)] signals by all three oceanic-atmospheric influences and a strong summer [July-September (JAS)] signal by the PDO.

## DEDICATION

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## 1. INTRODUCTION

It is widely evident that oceanic-atmospheric variability influences streamflow (Tootle et al. 2005) and precipitation (Enfield et al. 2001) in the United States. Information gathered from such studies is vital for forecasters of streamflow and precipitation. In the southeast, temporal variability of precipitation can have an extreme effect on water availability for agricultural purposes and water reservoir management. The study presented here investigates both annual and seasonal precipitation response in the southeastern U.S. resulting from three oceanic-atmospheric influences: the El Niño-Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO). Water managers, planners and members of the agricultural industry may gain a greater insight on climatic variability and seasonal precipitation with the current study, allowing them to provide improved forecast and assessments of reservoir and irrigational needs.

ENSO refers to the naturally occurring phenomenon consisting of a periodic large-scale warming or cooling of the central eastern equatorial Pacific Ocean off the coasts of Peru and Ecuador. The warming and cooling of the ocean is caused by the changes in pressures across the equatorial Pacific Ocean. During a warm phase, there is high surface pressure over the western region and low surface pressure over the south-eastern tropical Pacific. When these pressures are reversed, having low surface pressure over the western region and high surface pressure over the southeastern region, a cold phase occurs (Philander 1990). The warm phase is referred to as El Niño while the cold phase is referred to as La Niña. The ENSO signal in the southeast U.S. has

long been established such that El Niño is typically associated with increased moisture and La Niña is associated with decreased moisture. The PDO has been described as an ENSO-like pattern of Pacific climate variability. During a warm phase of the PDO the sea-surface temperatures (SSTs) have a tendency of being cool in the central North Pacific and warm along the west coasts of North and South America. While ENSO typically has a periodicity of approximately 2-7 years, the PDO is an interdecadal phenomenon and oscillates over the span of 50 years, with each particular phase (cold or warm) persisting for approximately 25 years. (Mantau and Hare 2002). The AMO is associated with basin-wide variability of Atlantic Ocean seas surface temperatures (SSTs), ranging from 0°F to 70°F (Gray et al. 2004). Similar to the PDO, the AMO is associated with a much lower frequency than ENSO, having periodicity of 60-100 years (Gray et al. 2004).

Enfield et al. (2001) evaluated seasonal rainfall and streamflow data over the continental U.S. using climate divisions and correlated the data with indices representing AMO and ENSO indices. Enfield et al. (2001) focused on both the multi-decadal and interannual characteristics of these data sets by linearly detrending the time series of the data through the application of ten-year running averages. They found that AMO warm phases are associated with decreased rainfall in the majority of the continental United States. Enfield et al. (2001) states that this geographical pattern of variability is largely due to changes in summer precipitation. They also found that the variability of ENSO influenced winter (JFM) precipitation patterns varied significantly depending on the AMO phase (Enfield et al. 2001).

Tootle et al. (2005) analyzed continental U.S. streamflow response to individual and coupled oceanic-atmospheric influences of both interannual (ENSO) and inter-decadal/decadal [PDO, AMO and the North Atlantic Oscillation (NAO)] influences by using data from 639

unimpaired streamflow gauges. The influence of these oceanic-atmospheric influences was evaluated using the nonparametric rank-sum significant test. Tootle et al. (2005) observed streamflow variability across the U.S. for both the individual and coupled oceanic-atmospheric influences.

The study presented here uses data from 183 gauges across eight southeastern states to analyze the individual effects of the interannual (ENSO) and interdecadal (PDO and AMO) on the annual and seasonal (three-month averages) precipitation in the southeastern United States. Three statistical significance tests (1) two-sample t-test (90% significance), (2) rank-sum (90% significance) and (3) effect-size (threshold of 0.8 to -0.8) were applied to determine if a climate signal (or signals) were present in the southeast U.S. precipitation response. The t-test requires the data to be normally distributed, which was assumed for this study. The nonparametric rank-sum test does not require the assumption of normality and was used to test climate signals and continental U.S. streamflow (Tootle et al. 2005), and climate signals and western U.S. snowpack (Hunter et al. 2006). The effect size is a simple and effective test to quantify the difference between two vectors [e.g., annual or seasonal precipitation in the years of a PDO Cold (Warm) phase]. The start year of 1970 was chosen due to the climate shift that occurred in the Pacific basin during the mid-1970s (Meehl et al. 2009). The goal of this research was to improve the understanding of how interannual (ENSO) and interdecadal (PDO and AMO) oceanic-atmospheric phenomena individually influence the annual and seasonal precipitation variability in the southeast U.S. following this climate shift.

## 2. DATA AND METHODOLOGY

Precipitation gauge data for the southeastern U.S. was obtained from NOAA (<https://www.ncdc.noaa.gov/data-access>) while data for the interannual (ENSO) and interdecadal (PDO and AMO) oceanic-atmospheric influences were obtained from several sources. The raw precipitation gauge data is located here: <https://seusp.weebly.com/>.

### 2.1 PRECIPITATION DATA

The precipitation data set used in the following analysis consists of 183 NOAA National Climatic Data Center (NCDC) precipitation gauges for the years 1970 to 2014 (Figure 1, Table 1, Appendix A). The data sets contain monthly precipitation data for years prior to 1970, but that data was not considered due to the climate shift of the mid-1970s that was highlighted by Meehl et al. (2009). The monthly data sets were provided in total inches of precipitation. Monthly precipitation data for each gauge was summed annually and for the following three month averages: January-February-March (JFM), April-May-June (AMJ), July-August-September (JAS), and October-November-December (OND) (Appendix B, Appendix C). The phase (warm/positive or cold/negative) of the interdecadal or interannual climatic influences were identified one year prior (1969-2013) to the precipitation data.

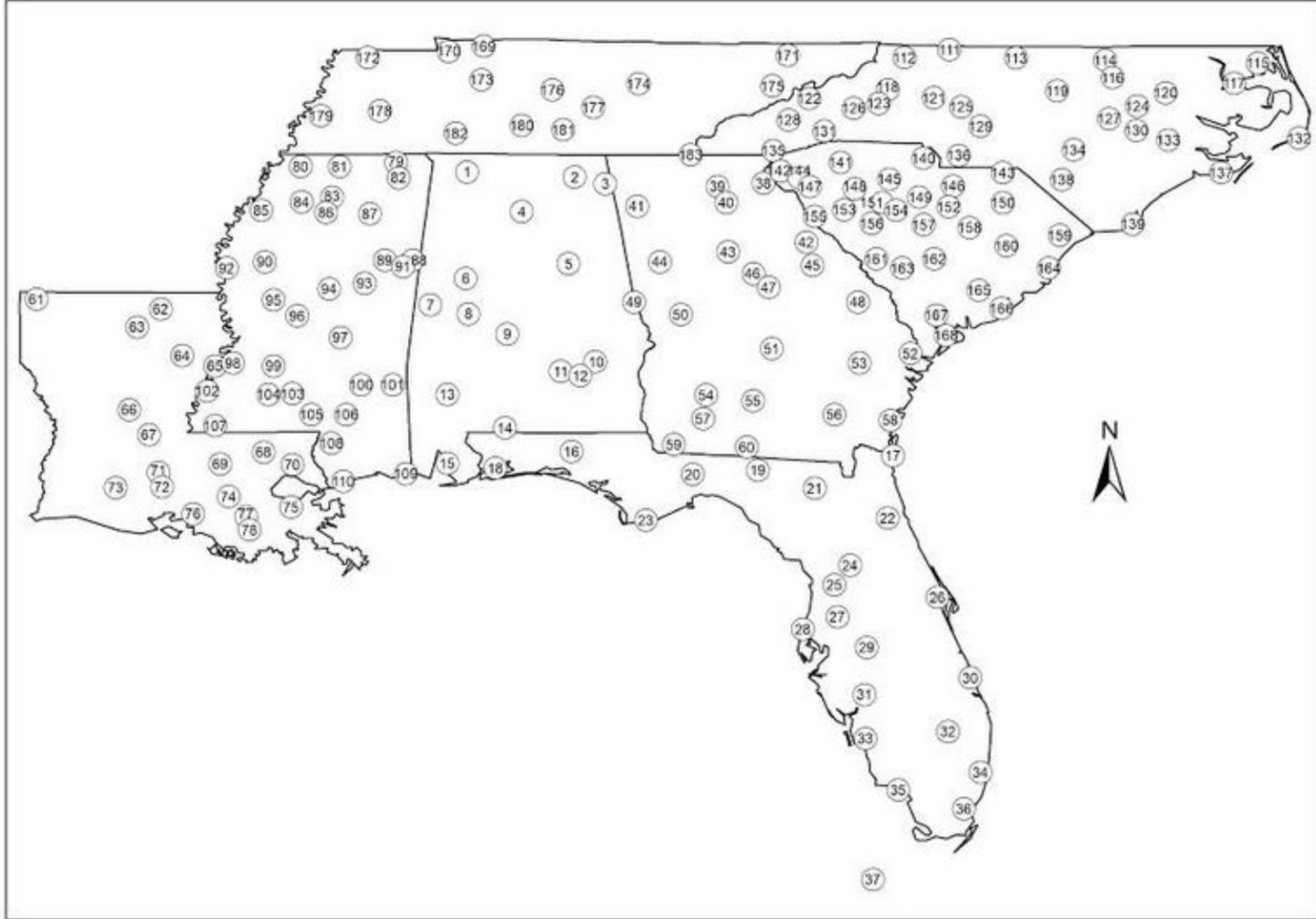


Figure 1. Gauge Location Map. Map of NOAA precipitation gauges in the southeast U.S. used in the study. Gauge locations are marked with numbered circles.

## 2.2 INTERANNUAL (ENSO)

According to Beebee and Manga (2004), there is no data set that is universally accepted for the measurement of ENSO years. Tootle et al. (2005) was used to identify the 1969-2001 ENSO years. NOAA ([http://www.cpc.ncep.noaa.gov/products/analysis\\_monitoring/ensostuff/ensoyears.shtml](http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml)) was used to identify ENSO years post-2001. Table 1 lists the years identified as warm (positive) and cold (negative).

## 2.3 INTERDECADAL (PDO AND AMO) OCEANIC DATA

The study provided by Tootle et al. (2005) was used for the 1969-2001 AMO and PDO warm (positive) or cold (negative) years. The post-2001 PDO phases used in this study were obtained from the website provided by Nate Mantua via the University of Washington's College of the Environment (<http://research.jisao.washington.edu/pdo/>). The PDO was in a cold (negative) phase from 1969-1976 and 2000-2013. During the years 1977-1999, the PDO was in a warm (positive) phase. NOAA ([http://www.aoml.noaa.gov/ocd/ocdweb/ESR\\_GOMIEA/amo.html](http://www.aoml.noaa.gov/ocd/ocdweb/ESR_GOMIEA/amo.html)) was used to establish post-2001 AMO phases. The AMO was in a cold (negative) phase from 1969-1994 and shifted to a warm (positive phase) in 1995 (Tootle et al. 2005 and McCabe et al. 2004). The warm phase continued through the final year used in this study, 2013 (Table 1).

	<b>ENSO</b>	<b>PDO</b>	<b>AMO</b>
<b>Warm (Positive)</b>	1969, 1972, 1977, 1982, 1987, 1991, 1993, 1994, 1997, 2002, 2004, 2006, 2009	1977-1999	1995-2013
<b>Cold (Negative)</b>	1970, 1971, 1973, 1974, 1975, 1981, 1988, 1998, 1999, 2000, 2007, 2008, 2010, 2011	1969-1976, 2000-2013	1969-1994

Table 1. ENSO, AMO and PDO Identified Years. Years identified for warm/positive or cold/negative for the ENSO, PDO and AMO.

## 2.4 STATISTICAL SIGNIFICANCE TESTING

The warm (positive) and cold (negative) years were identified for the year prior to the precipitation data to evaluate the influence for both the interannual (ENSO) and interdecadal (PDO and AMO) oceanic-atmospheric climate phenomenon. Three statistical significance tests (1) two-sample t-test (2) rank-sum and (3) effect-size were used to evaluate precipitation response of the individual phases (warm/positive vs. cold/negative) effects on annual and seasonal (three-month periods) precipitation variability. Code via Octave was written to perform the three significance tests (Appendix B).

For the two-sample t-test, Octave analyzes the data sets and provides a p-value (pval) output based on the t-statistic and degree of freedom of the annual and monthly precipitation data for each oceanic-atmospheric influence (ENSO, PDO and AMO). The significance percentage was then obtained through the equation  $(1 - pval) \times (100\%) = \textit{Significance}$ . The threshold of 90% significance for the two-sample t-test was used to retain consistency between the two-sample t-test and the rank-sum test. The two-sample t-test significance levels for each gauge are provided in Appendix B. For example, if the p-value were equal to .1 then the significance would have been measured at 90% and qualified as an observed signal. Similar to Tootle et al. (2005) and Hunter et al. (2006), the threshold of 90% significance was used to determine a positive or negative signal for the rank-sum test. Octave provided p-value outputs, which were then used to find the significance percentage in an identical fashion as the two-sample t-test. The non-parametric rank-sum significance levels for each gauge are provided in Appendix B. The raw precipitation data was used to determine whether the significance difference detected was positive or negative.

Octave was also used to perform the effect size test by first computing the pooled

standard deviation of the considered precipitation data sets, using the equation:

$$SD_{pooled} = \sqrt{\frac{SD_1^2 + SD_2^2}{2}}$$

Where  $SD_1$  was the standard deviation of the first data set and  $SD_2$  was the standard deviation of the second data set. Cohen's d was then calculated using the equation:

$$d = \frac{M_1 - M_2}{SD_{pooled}}$$

Where  $M_1$  was the mean of the first data set and  $M_2$  was the mean of the second data set.

According to Khalilzadeh (2017), a Cohen's d value of 0.8 is the recommended cut-off point for a "large effect." For the purposes of this study, a Cohen's d of +0.8 was used to determine a positive signal and a Cohen's d of -0.8 was used to determine a negative signal. The values for the Cohen's d for each gauge can be found in Appendix B.

### 3. RESULTS

The results provided were limited to annual and winter (JFM) season signals ENSO and AMO, and winter (JFM) and summer (JAS) for PDO. This was based on the strength of the climate signals observed. The results for the remaining seasons (AMJ, JAS, OND) can be found in Appendix C.

#### 3.1 RESULTS (ENSO)

The results of all three significance tests for the effects of the ENSO are shown in figures 2 and 3. The results reaffirm Enfield et al. (2001), indicating an ENSO annual signal in the southeastern United States (Figure 2). For all figures in the results section, a filled (or open) circle represents a statistically significant positive (or negative) difference in the precipitation values, respectively. For example, in Figure 2, the open circles, which were predominantly in the gulf coast region, were associated with decreased annual precipitation for the first phase listed [ENSO cold (La Niña) for this case]. With that, the filled circles were associated with an increase in precipitation for the first phase listed. Thus, the well-established ENSO signal in that increased moisture occurs following an El Niño while decreased moisture occurs following a La Niña was observed.

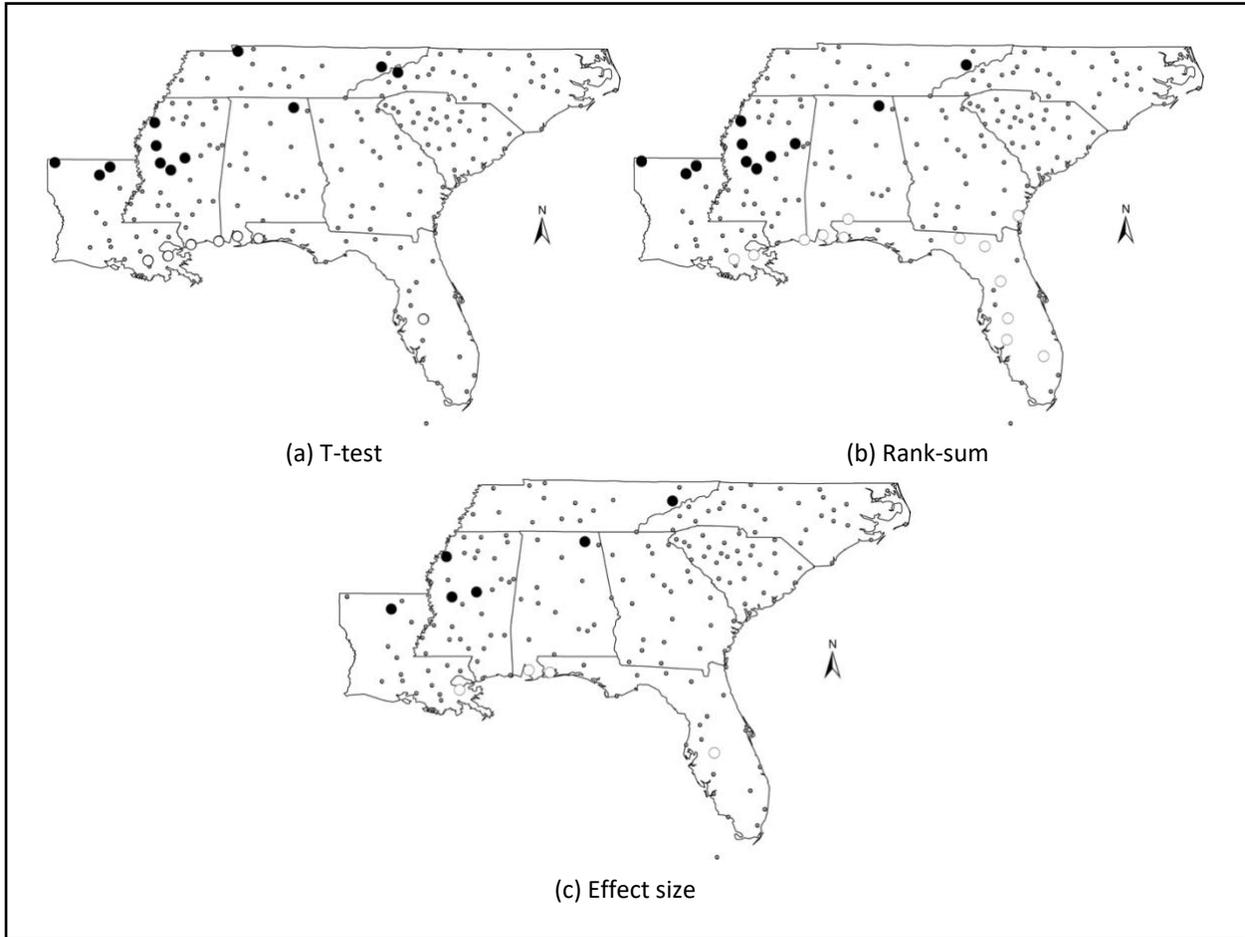


Figure 2. Annual ENSO Results Maps. Significant difference in annual precipitation for ENSO cold (La Niña) – ENSO warm (El Niño). Positive (negative) significance represented by filled (open) circles.

The three significance tests used to evaluate the precipitation data were the t-test (90% significance), rank sum (90% significance) and effect size (threshold of .8). A smaller black circle represents a precipitation gauge where no significant difference was found. The results in Figure 2 display an ENSO signal from the Louisiana gulf coast that extends into Florida. The results are consistent for the three significant tests used.

The results indicate a very strong ENSO winter (JFM) signal throughout much of the southeastern United States (Figure 3). As seen with the results for the annual precipitation, the winter (JFM) results show an ENSO signal across the gulf coast and down through Florida with

the decrease in precipitation associated with ENSO cold (La Niña) as compared to ENSO warm (El Niño). The ENSO winter signal (JFM) was much stronger than the annual signal for the southeastern United States. The ENSO signal extends up eastern Atlantic coast into Georgia and South Carolina, which was not observed with the annual data. An opposite pattern of increased precipitation due to a La Niña was observed in clusters located in Tennessee and the northern parts of Mississippi and Alabama. The results were consistent for all three significance tests, with the strongest correlation along the gulf coast, extending southward through Florida. Highlighted by Straus and Shuckla (1997), this ENSO signal was due to the eastward extension and southward shift of the jet stream during El Niño winters, which was accompanied with similar migration of precipitation.

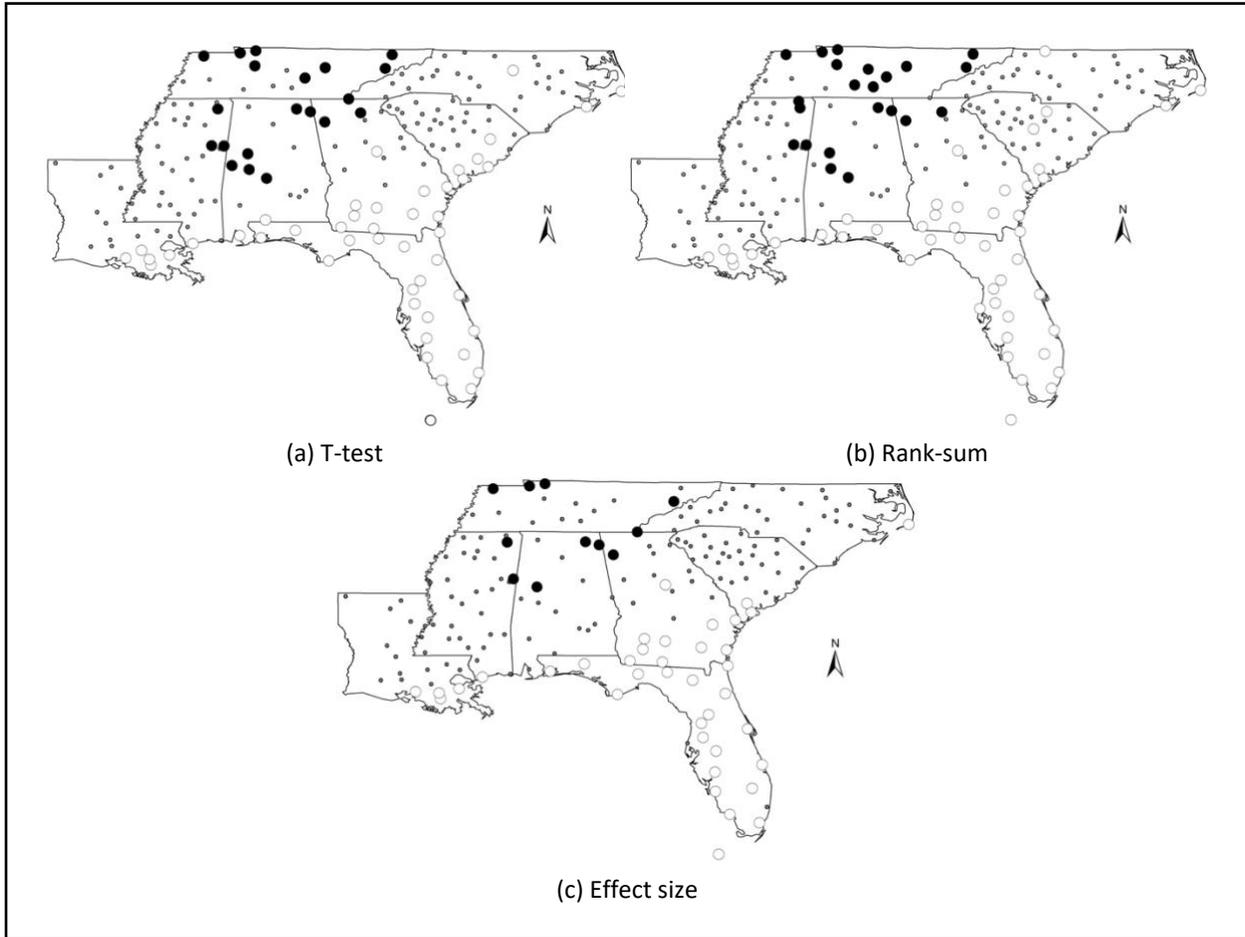


Figure 3. Winter (JFM) ENSO Results Maps. Significant difference in winter (JFM) precipitation for ENSO cold (La Niña) – ENSO warm (El Niño). Positive (negative) significance represented by filled (open) circles.

### 3.2 RESULTS (PDO)

The results did not indicate a statistically significant PDO signal in the annual precipitation data. Thus, the figures were not provided in this study but can be found in Appendix C. Figure 4 presents the winter (JFM) results and Figure 5 presents the summer (JAS) results from the three significance tests for PDO.

The results for the PDO indicate a similar signal to what was observed in the winter (JFM) ENSO results (Figure. 4). There was a very strong signal along the southern area of the southeastern U.S., specifically along the gulf coast from Louisiana to Florida. When evaluating

the t-test and rank sum test for the PDO, we saw a signal of decreased precipitation for the PDO cold as compared to the PDO warm throughout sections of Georgia, South Carolina and North Carolina. However, this was not observed by the effect size test. This was likely attributed to the high threshold used for effect size ( $\pm .8$ ). When evaluating the gauges for the three aforementioned states and Florida, it was evident that there was a moderate signal ( $\pm .5$ ) throughout this region. The effect size results indicate a signal along the gulf coast of Louisiana, Mississippi, Alabama and Florida. Highlighted by Tootle et al. (2005), these findings are due to the intensification of the Aleutian Low in the North Pacific at higher sea level pressures in the western U.S., resulting in both a southerly shift in the jet stream and an intensification of the subtropical jet stream which influences the southern U.S. (Mantua and Hare 2002).

Unlike what was seen for ENSO and AMO, the PDO results indicate a strong summer (JAS) signal (Figure 5). We saw the strongest signals in Louisiana, Mississippi and Alabama. We saw a pattern of increased precipitation in this area for the PDO cold as it compares to the PDO warm. Like the PDO results for the winter (JFM) season, we saw the strongest results in the t-test and rank sum test, but a much weaker signal was indicated by the effect size.



Figure 4. Winter (JFM) PDO Results Maps. Significant difference in winter (JFM) precipitation for PDO cold – PDO warm. Positive (negative) significance represented by filled (open) circles.

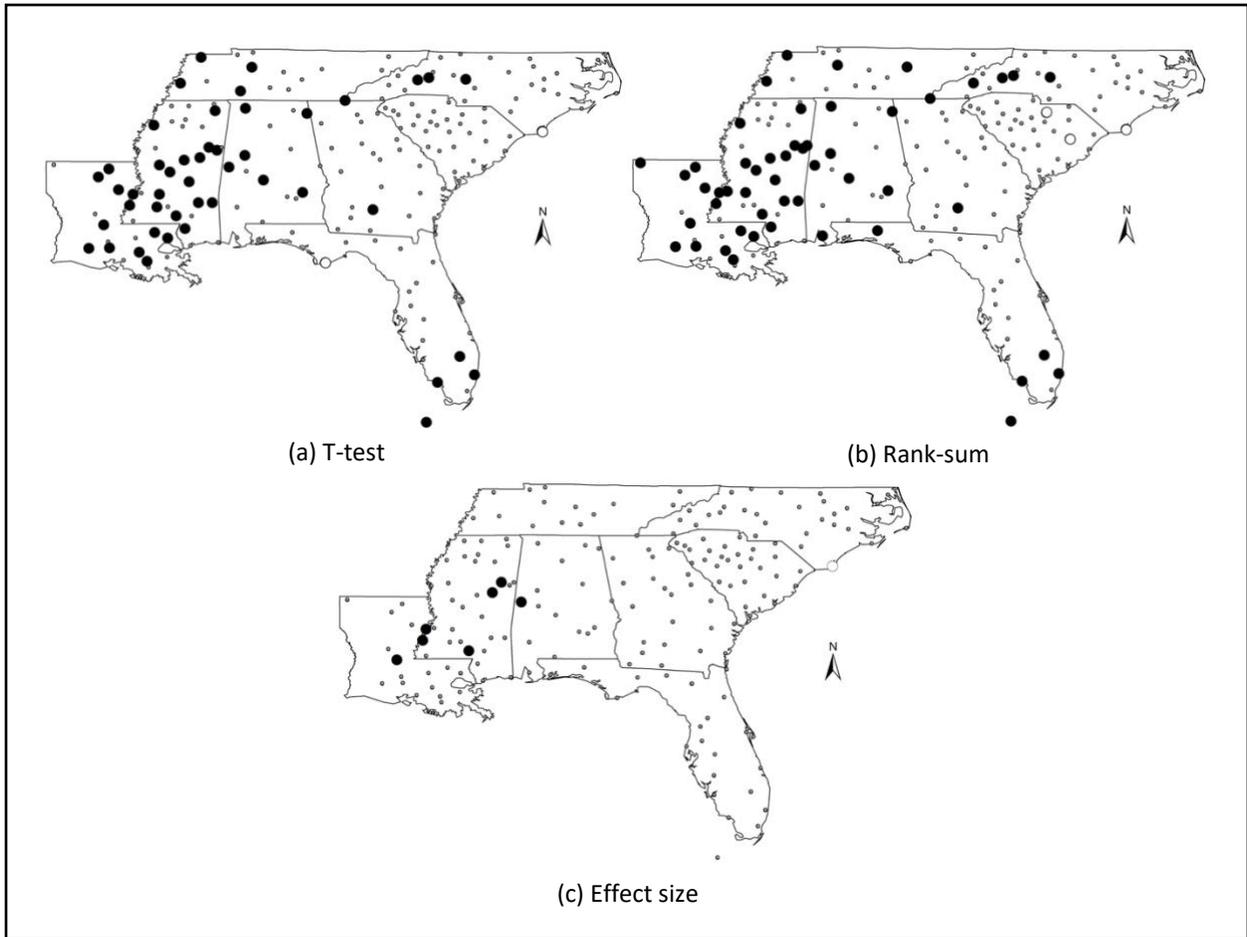


Figure 5. Summer (JAS) PDO Results Maps. Significant difference in summer (JAS) precipitation for PDO cold – PDO warm. Positive (negative) significance represented by filled (open) circles.

### 3.3 RESULTS (AMO)

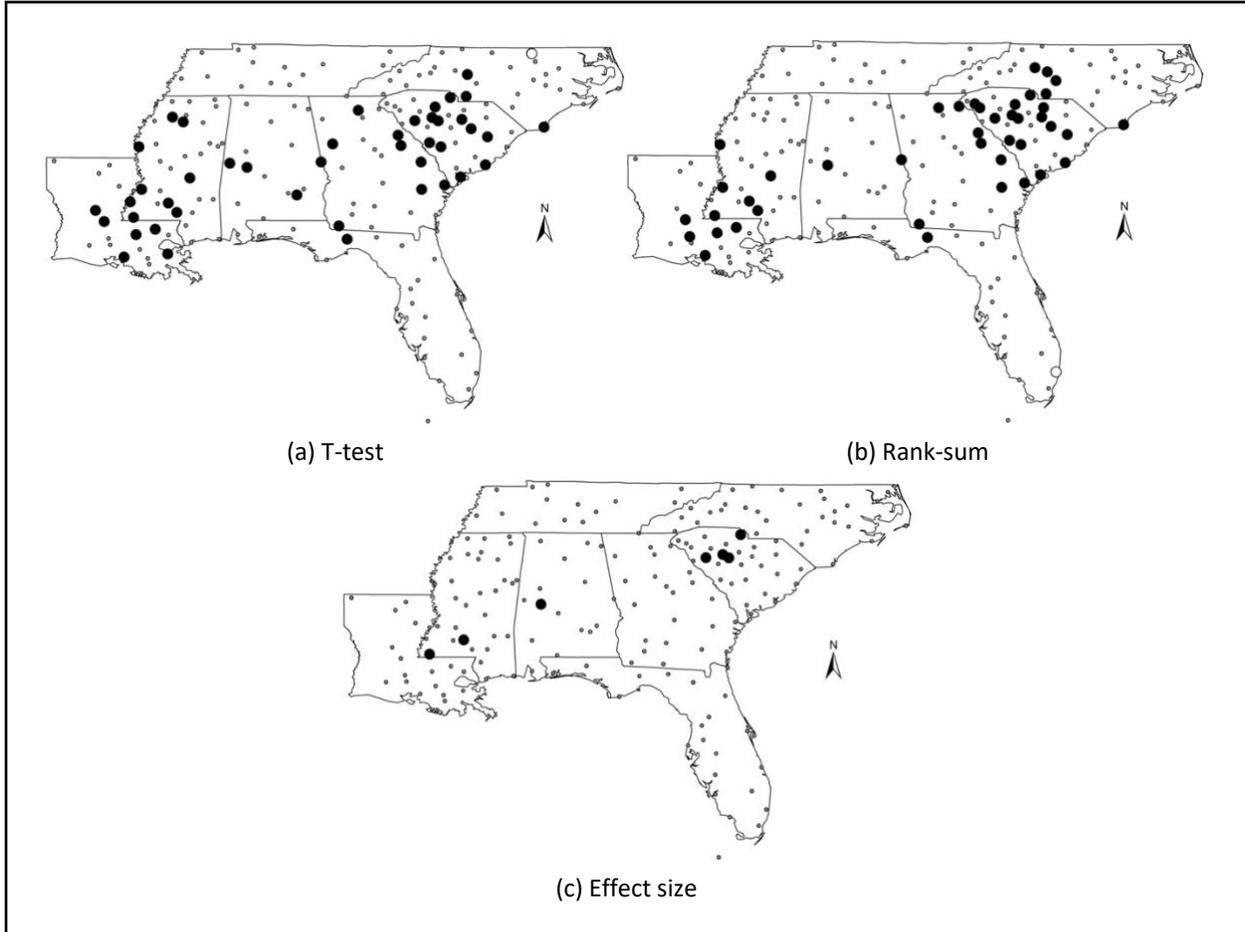


Figure 6. Annual AMO Results Maps. Significant difference in annual precipitation for AMO cold – AMO warm. Positive (negative) significance represented by filled (open) circles.

Figures 5 and 6 display the results of all three significance tests for the AMO for both the annual and winter season (JFM) precipitation. Per Enfield et al. (2001), the annual results indicate an increase in precipitation for the AMO cold as compared to the AMO warm, stretching west to east throughout the central region of the southeastern United States. The signal ranges from eastern Louisiana into southern North Carolina (Figure 5), but the strongest signals are seen in Louisiana, Mississippi and South Carolina. Both the annual and winter (JFM) results for the t-test and rank sum were consistent, with the effect size showing a much lower signal (Figure 6,

Figure 7). Similar to the results of the PDO, this was also attributed to the high threshold ( $\pm .8$ ) of the effect size test.

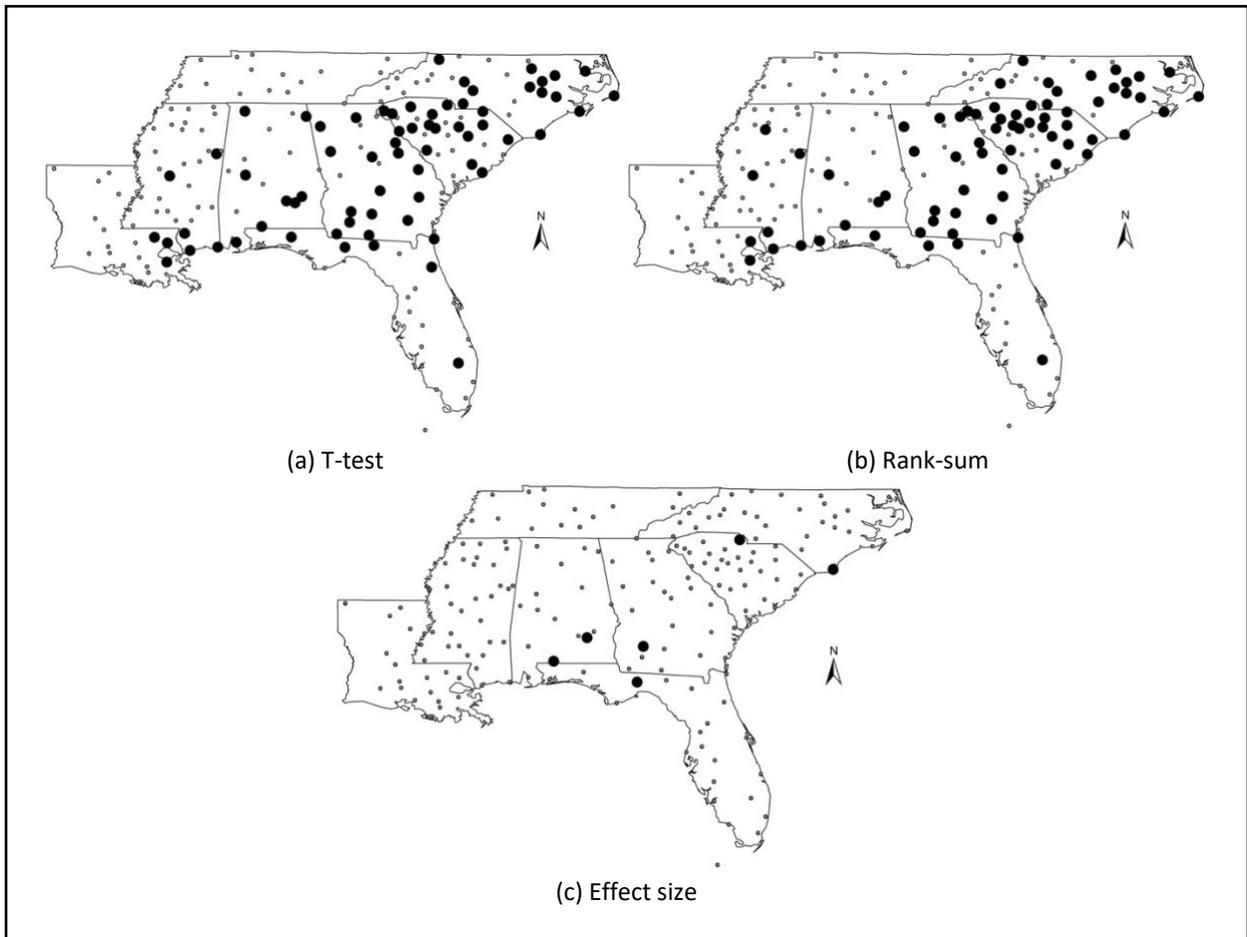


Figure 7. Winter (JFM) AMO Results Maps. Significant difference in winter (JFM) precipitation for AMO cold – AMO warm. Positive (negative) significance represented by filled (open) circles.

The AMO signal in the winter (JFM) precipitation was similar yet more robust than annual precipitation. The results indicate an increase in precipitation during the AMO cold as compared to the AMO warm (Figure 6). The main spatial clusters extend from Mississippi into Alabama and were also apparent in Georgia, South Carolina and North Carolina.

#### 4. DISCUSSION

The current research presented reaffirms previous results for past studies in regards to the influence of ENSO, PDO and AMO on southeastern U.S. hydrologic response. However, the current research provided an updated analysis, focusing on the years after the climate shift of the mid-1970s and the utilization of three different statistical tests. Additionally, both annual and seasonal precipitation were evaluated by developing an extensive, high-quality dataset of gauged Southeast U.S. precipitation. While the annual signals of each of the three oceanic-atmospheric influences were reaffirmed, the identification of climate signals in the winter months (JFM) for all three oceanic-atmospheric signals and summer (JAS) for the PDO were important findings. While the current research evaluated the effects of each oceanic-atmospheric influence separately, future research could supplement these findings by coupling the phases of the three oceanic-atmospheric influences. The current research provides water forecasters and managers vital information for their prediction and management efforts.

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