THE INFLUENCE OF LARGE-SCALE CLIMATE DRIVERS ON THE HYDROCLIMATOLOGY AND HYDROPOWER PRODUCTION IN SOUTHEASTERN UNITED STATES

By

JOHANNA ENGSTRÖM

A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

2017
To Ivar, my grandfather, who wanted a higher education but never got the chance
ACKNOWLEDGMENTS

There are many people I would like to thank for being part of this journey:

My dissertation committee, Dr. Peter Waylen, Dr. Christopher Martinez, Dr. Corene Matyas and Dr. Joann Mossa, have shown me great support and encouragement. I am especially thankful for Dr. Peter Waylen and Dr. Joann Mossa for encouraging me to apply to the PhD program, and their continued mentoring of me, both as a researcher and instructor.

University of Florida and its Geography Department’s faculty and staff has supported me both academically and professionally. The fellow geography graduate students have also played a crucial role. Together we have shared worries, stress, crammed conference hotel rooms, and endless laughter. Thank you for making an international student feel welcome, and for making my years as a PhD student a great time!

Ryan Good and Qianyi Kuang, for housing me during my returns to Gainesville.

Cintia B. Uvo and Göran Loman, who were the ones that opened my eyes to the fascinating worlds of teleconnections and renewable energies and remain true role models.

The U.S. Army Corps of Engineers personnel in Mobile and Savannah districts who’s shared insights have been beneficial for the success of this project.

My dear family: My brother Philip and his family, my mother, who introduced me to hydropower and whose curiosity for science I have inherited, my father, who’s positive spirit I always carry with me, and who once, in reference to my research, uttered the words “don’t quit this, what you’re doing is important”, probably without having a clue how much those words would come to mean to me, and David, who is both my greatest distraction and supporter.

Finally, I want to thank my wonderful friends. Many of you are far away, but your love and support means everything, without it I would not be where I am today.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Acknowledgments</th>
<th>List of Tables</th>
<th>List of Figures</th>
<th>List of Abbreviations</th>
<th>Abstract</th>
</tr>
</thead>
<tbody>
<tr>
<td>page 4</td>
<td>page 7</td>
<td>page 8</td>
<td>page 10</td>
<td>page 11</td>
</tr>
</tbody>
</table>

## CHAPTER

1. **INTRODUCTION** .......................................................... 13
   - Teleconnections ................................................................ 15
   - History of Hydropower in the Southeast ............................ 16

2. **DRIVERS OF LONG TERM VARIABILITY OF PRECIPITATION AND RUNOFF IN THE SOUTHEAST** ......................................................... 20
   - Data .................................................................................. 23
     - Teleconnection Indices .................................................... 23
     - Precipitation and Runoff Data ........................................ 23
   - Methods ............................................................................. 24
   - Results ............................................................................... 25
     - PC Loadings .................................................................... 25
     - Identifying the Relationships ........................................... 27
   - Discussion ......................................................................... 29
   - Conclusion ........................................................................ 33

3. **THE CHANGING HYDROCLIMATE OF THE SOUTHEAST UNITED STATES** ........ 46
   - Material and Methods ....................................................... 47
   - Results ............................................................................... 50
     - Increased Precipitation ................................................... 52
     - Climate Change .............................................................. 54
     - Urbanization and Land Cover Change ............................... 55
   - Conclusion ........................................................................ 56

4. **HYDROPOWER IN THE SOUTHEAST: A HYDROCLIMATOLOGICAL PERSPECTIVE** ................................................................. 66
   - Data and Methods ............................................................ 67
   - Results and Discussion .................................................... 70
     - Potential Production ...................................................... 70
### LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>Potential economic and environmental winnings.</td>
<td>19</td>
</tr>
<tr>
<td>1-2</td>
<td>Overview of the dams included in this project.</td>
<td>19</td>
</tr>
<tr>
<td>3-1</td>
<td>Resulting P-values from the Kolmogorov-Smirnov test.</td>
<td>57</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>1-1</td>
<td>The study area</td>
<td>18</td>
</tr>
<tr>
<td>2-1</td>
<td>Location of the uncontrolled river basins included in the analysis</td>
<td>34</td>
</tr>
<tr>
<td>2-2</td>
<td>Seasonal variation of percentage of variability explained by P1, PC2 and PC3</td>
<td>35</td>
</tr>
<tr>
<td>2-3</td>
<td>Spatiotemporal variation of basins in PC1 for precipitation</td>
<td>36</td>
</tr>
<tr>
<td>2-4</td>
<td>Same as Figure 2-3, but for runoff</td>
<td>36</td>
</tr>
<tr>
<td>2-5</td>
<td>Lag correlation between PC1 (precipitation) for each season and the AMO index</td>
<td>37</td>
</tr>
<tr>
<td>2-6</td>
<td>Same as Figure 2-5 except lag correlation between PC1 (precipitation) and the AO</td>
<td>38</td>
</tr>
<tr>
<td>2-7</td>
<td>Same as Figure 2-5 except lag correlation between PC1 (precipitation) and the NAO</td>
<td>38</td>
</tr>
<tr>
<td>2-8</td>
<td>Same as Figure 2-5 except lag correlation between PC2 (precipitation) and the NAO</td>
<td>39</td>
</tr>
<tr>
<td>2-9</td>
<td>Same as Figure 2-5 except lag correlation between PC1 (precipitation) and ENSO</td>
<td>39</td>
</tr>
<tr>
<td>2-10</td>
<td>Same as Figure 2-5 except lag correlation between PC2 (precipitation) and ENSO</td>
<td>40</td>
</tr>
<tr>
<td>2-11</td>
<td>Same as Figure 2-5 except lag correlation between PC1 (precipitation) and the PNA</td>
<td>40</td>
</tr>
<tr>
<td>2-12</td>
<td>Same as Figure 2-5 except lag correlation between PC2 (precipitation) and the PNA</td>
<td>41</td>
</tr>
<tr>
<td>2-13</td>
<td>Same as Figure 2-5 except lag correlation between PC1 (runoff) and the AMO</td>
<td>41</td>
</tr>
<tr>
<td>2-14</td>
<td>Same as Figure 2-5 except lag correlation between PC2 (runoff) and the AMO</td>
<td>42</td>
</tr>
<tr>
<td>2-15</td>
<td>Same as Figure 2-5 except lag correlation between PC1 (runoff) and the AO index</td>
<td>42</td>
</tr>
<tr>
<td>2-16</td>
<td>Same as Figure 2-5 except lag correlation between PC1 (runoff) and the NAO</td>
<td>43</td>
</tr>
<tr>
<td>2-17</td>
<td>Same as Figure 2-5 except lag correlation between PC1 (runoff) and the ENSO</td>
<td>43</td>
</tr>
<tr>
<td>2-18</td>
<td>Same as Figure 2-5 except lag correlation between PC2 (runoff) and the ENSO</td>
<td>44</td>
</tr>
<tr>
<td>2-19</td>
<td>Same as Figure 2-5 except lag correlation between PC1 (runoff) and the PNA</td>
<td>44</td>
</tr>
<tr>
<td>2-20</td>
<td>Same as Figure 2-5 except lag correlation between PC2 (runoff) and the PNA</td>
<td>45</td>
</tr>
<tr>
<td>3-1</td>
<td>Basins included in the analysis</td>
<td>58</td>
</tr>
<tr>
<td>3-2</td>
<td>Spatial patterns of estimated seasonal RCs across the study area</td>
<td>59</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>ACE</td>
<td>United States Army Corps of Engineers</td>
<td></td>
</tr>
<tr>
<td>ACF</td>
<td>Apalachicola-Chattahoochee-Flint River Basin</td>
<td></td>
</tr>
<tr>
<td>ACT</td>
<td>Alabama-Coosa-Tallapoosa River Basin</td>
<td></td>
</tr>
<tr>
<td>AMO</td>
<td>Atlantic Multidecadal Oscillation</td>
<td></td>
</tr>
<tr>
<td>AO</td>
<td>Arctic Oscillation</td>
<td></td>
</tr>
<tr>
<td>ENSO</td>
<td>El Niño-Southern Oscillation</td>
<td></td>
</tr>
<tr>
<td>NAO</td>
<td>North Atlantic Oscillation</td>
<td></td>
</tr>
<tr>
<td>PNA</td>
<td>Pacific-North American Pattern</td>
<td></td>
</tr>
<tr>
<td>SAV</td>
<td>Savannah River Basin</td>
<td></td>
</tr>
</tbody>
</table>
This project takes a holistic view of the hydroclimatology of Southeastern United States, analyzing what large-scale atmospheric patterns influence it, how the influence varies over time and what this means for hydropower production. The study area consists of five states; Alabama, Georgia, North Carolina, South Carolina and Tennessee, of which three (Alabama, North Carolina and Tennessee) are among the top ten hydropower producing states in the U.S. Water availability varies from year to year, which can partly be explained by the phase of various large-scale atmospheric anomalies referred to as teleconnections. The teleconnections included in the analysis are the Atlantic Multidecadal Oscillation (AMO), Arctic Oscillation (AO), El Niño-Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), and the Pacific-North American (PNA) pattern.

Through the application of Principal Components Analysis to historical precipitation and natural streamflow records, and using multiple different time lags linking the leading modes of variability to teleconnections, the AMO and ENSO are identified as the strongest drivers of hydroclimatic variability, while the atmospheric-based patterns show more sporadic influences. Using a Pettitt Change Point Analysis test, a breakpoint in the runoff coefficients of the
Southeast is identified. The shift to higher runoff coefficients throughout the region happened in the late 1990s and is explained by increased hurricane impact on the region. Teleconnection variability also affects hydropower production in the Southeast. Analyzing seasonal production data from the Apalachicola-Chattahoochee-Flint, Alabama-Coosa-Tallapoosa and Savannah River basins, the strongest and most widespread influence is asserted by the cold phase ENSO that decrease both reservoir inflow and production throughout the region. Considering teleconnection interaction also proved useful, as did the application of time lags, which makes the findings useful for water resource and hydropower production forecasting.
CHAPTER 1
INTRODUCTION

The water resources of Southeastern U.S. (hereafter “the Southeast”) are dominated by conflicting interests. The annual precipitation should not only satisfy the natural ecosystems, but also the drinking water needs of rapidly growing metropolitan areas such as Atlanta and Charlotte, recreational use, and power hydroelectric plants. The disputes stem in lingering water resource scarcity, a result of rapid development, and include, but are not limited to, the “Tri-State Water dispute” (between Alabama, Florida and Georgia) over the Apalachicola-Chattahoochee-Flint and Alabama-Coosa-Tallapoosa rivers, the U.S. Supreme Court Case over water allocations from the Catawba-Wateree River which is shared between North and South Carolina, and the increased groundwater pumping around Memphis (Tennessee) that has led to dropping groundwater levels in Mississippi (American Rivers, 2008; Bryan, 2008; Cameron, 2009; Walton, 2011; Upholt, 2015). This study includes the states of Alabama, Georgia, South Carolina, North Carolina and Tennessee, of which three (Alabama, Tennessee and North Carolina) are among the top-ten hydropower producing states in the country (Figure 1-1) (National Hydropower Association, 2013). As population pressure is increasing and the demand for renewable energies is greater than ever before, there is a desperate need for a more profound understanding of the hydroclimatology of this region in order to improve forecasting, reduce conflicts and make the society more resilient. Climate drivers (teleconnections) can provide valuable information for long term forecasting of water resources (Hamlet et al, 2002; Poveda et al. 2003) and, as the climate is changing (IPCC, 2014), hydrological forecasts and projections based on stationary historical records use assumptions that are no longer valid (Pal et al., 2015), but need to be re-evaluated. The understanding of this changed relationship’s impact on water availability might be even more important as a changing climate brings new normals.
(Dominguez, Cañon, & Valdes, 2010), diverging from those that have been the dominant patterns for decades to centuries and upon which modern water management infrastructure is built.

This dissertation provides a holistic overview of the teleconnections influencing the hydroclimatology of the Southeast. Unlike earlier research that focuses on one climate driver’s influence on either precipitation or runoff, often during a limited time of the year, this project includes multiple climate drivers and analysis of both precipitation and runoff throughout the year. This way it adds to our understanding of the relative influences different climate drivers have on the hydroclimatology on varying temporal scales. As a region that is facing increased population pressure and urbanization it is imperative to investigate how available water resources can be forecast in order to provide efficient distribution. This doctoral dissertation is a combined study that considers how the climate and hydrologic variables interact and tries to quantify how this interaction may have changed over time. The findings can be applied to many forms of water resource management, but for this dissertation the application is limited to hydropower production. Scholarly research binding hydroclimatology to hydropower has traditionally focused on the hydropower intensive regions, such as Northwest U.S., neglecting the hydroelectricity production of the Southeast. This project aims to fill that gap by advancing knowledge of the complex hydroclimatology of the Southeast and its ties to hydroelectricity generation.

In a similar study of the Columbia River Hamlet et al. (2002) found that including El Niño-Southern Oscillation in water resource forecasting, to complement traditional forecasting based on mountain snow pack, could increase the annual hydropower production of the Columbia River by 9.6%. Considering federally installed dams on the Columbia River only, this
increase would lead to the production of an additional 5.5 million MWh of electricity and $153 million in increased revenues to the federal government per year.

This project aims to investigate what large scale atmospheric drivers influence the hydrology and hydropower production in the Southeast, and hence would be useful in forecasting. Table 1-1. shows how a 9.6% increase in production from the U.S. Army Corps of Engineers’ dams in the region would benefit the environment and economy of the United States.

**Teleconnections**

Teleconnections are large-scale atmospheric anomalies that bring abnormal weather conditions over vast geographic regions (Barnston & Livezey, 1987). These anomalies appear on interannual, decadal and interdecadal timescales as a result of changed atmospheric pressure patterns, such as the relation between the semi-permanent pressure centers Azores High and Icelandic Low, which constitutes the North Atlantic Oscillation (NAO) index, influencing the zonal flow over the North Atlantic (Hurrell et al. 2001, Visbeck et al. 2001). Another example are the pressure centers over North America and East North Pacific that make up the Pacific-North American Pattern (PNA), regulating the strength and location of the jet stream over North America, where the negative (positive) phase is associated with a more zonal (meridional) flow over the continent (Leathers et al. 1991). Other teleconnections are coupled ocean-atmospheric patterns, such as El Niño-Southern Oscillation (ENSO), which is linked to changed ocean circulation patterns and associated temperature anomalies in the Tropical Pacific Ocean. ENSO events happens every two to seven years and the warm phase is referred to as El Niño while the cold phase is called La Niña (Deser & Wallace 1987, Trenberth, 1997). The Atlantic Multidecadal Oscillation (AMO) is a 60-80 year cycle of temperature variability in the North Atlantic Ocean (Enfield et al. 2001). Such a large body of water changing temperature influences the energy balance and hence the weather patterns of the surrounding continents.
As the teleconnections bring abnormal weather conditions, studies have shown that they have a strong influence on global and regional water resources (Poveda et al. 2003, Tootle et al. 2005, Boening et al. 2012, Johnson et al. 2014) and therefore can be useful to consider in water resources planning and management.

**History of Hydropower in the Southeast**

Hydropower covers approximately 7% of the electricity needs of the U.S. (U.S. Energy Information Administration, 2013). Although hydropower has been associated with environmental and societal concerns such as river bed erosion (Graf, 2006) changed wildlife habitats (Young et al., 2011; Harnish et al. 2014), greenhouse gas emissions (Rudd et al, 1993; Teodoru et al. 2012) and loss of human lands and livelihoods (Jackson & Sleigh, 2000; Plateau, 2006; Ziv et al. 2012), it still remains the most available, affordable and reliable option of all the renewable energies in the U.S. Despite the local environmental concerns, the use of hydropower significantly decreases electricity production related emissions of carbon dioxide and particles, which have an adverse effect on both climate and people’s health. Recognizing the benefits of hydropower and as the U.S. is a net importer of electricity, it is of interest to the nation to further increase hydropower production, and decrease non-domestic electricity dependence. Work on investigating the potential for and promoting the development of hydropower has been of great interest in the U.S. during the last few years:

- The Department of Energy has started a Water Power Program promoting the development of hydro, wave and tidal energy extraction with the goal that 15% of the nation’s electricity needs should be generated using these energy sources by 2030 (U.S. Department of Energy, 2013).
- In 2014 Oak Ridge National Laboratory released a report on the potential for further developing hydropower in the United States in rivers where there are none, or only a limited number, of hydropower stations ("New Stream-reach Development: A
Comprehensive Assessment of Hydropower Energy Potential in the United States”), showing that there is potential to almost double the current annual hydropower production in the Southeast. This report is a follow up to the “Non-powered Dam Resource Assessment” (2011) which evaluated the potential of hydroelectric installation in currently non-powered dams (U.S. Department of Energy, 2013)

- In 2013 the “Hydropower Regulatory Efficiency Act” was signed by President Barack Obama. This act is meant to promote and facilitate the development of hydroelectric power in the U.S. by streamlining the permission process and raising the small-hydro license exemption from 5 to 10 MW installed capacity.

- In 2016 the Hydropower Vision was released. This is an analysis of current and future potential hydropower production in the U.S., created by the U.S. Department of Energy’s Wind and Water Power Technologies Office in cooperation with non-federal agencies, concluding that installed hydropower capacity could be increased by 50% by 2050 (U.S. Department of Energy, 2016).

In the Southeast (Alabama, Georgia, North Carolina, South Carolina and Tennessee) hydropower produces about 11% of the total electricity. This is more than the national average, but in-depth analysis of how the hydropower production in this region is affected by climate variability has been neglected in favor of more hydropower intensive regions, such as the Pacific Northwest.

Approximately 50% of the dams in the Southeast are federally owned and operated (U.S. Department of Energy, 2016) by the U.S. Army Corps of Engineers (ACE) and the Tennessee Valley Authority. Among the non-federal there are numerous agencies of which Southern Company and Duke Energy are the largest cooperations. In this study the focus will be on the federal dams operated by ACE.

Most ACE dams are multipurpose projects, originally designed to improve navigation and provide flood control and hydropower. In more recent times purposes have been expanded to include water supply, recreation, and fish and wildlife management. There were plans to build dams in the Southeast already in the early 1940s, plans that were put on hold due to World War II. After the war construction started on the Allatoona dam in the northern part of the ACT basin,
which was completed in 1950 and it was soon followed by others, many of which were authorized by the Flood Control Acts of 1941 and 1944 or Rivers and Harbors Act of 1945, 1946. (U.S. Army Corps of Engineers, 2017). Commencement years for the dams included in the analysis can be found in Table 1-2.

The possibility to reach full production within minutes is an advantage that sets hydropower apart from both renewable and traditional energy sources. The ACE’s hydropower plants in the Southeast are sometimes referred to as “peaking” plants meaning they are operated to meet peak electricity demands, typically occurring in the middle of the day during weekdays.

Figure 1-1. The study area, including the states of Alabama, Georgia, North Carolina, South Carolina and Tennessee, is outlined in black. In the insert map the top-ten hydropower producing states in the U.S. are highlighted in blue and the geographic location of the study area marked with a black box.
Table 1-1. Potential economic and environmental winnings based on a 9.6% increase in annual production.

<table>
<thead>
<tr>
<th>Annual benefits from a 9.6% increase in annual production</th>
<th>8 dams included in this analysis</th>
<th>All Army Corps of Engineers’ Dams in SE US****</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased production (MWh) 9.6% of average annual production</td>
<td>244,705</td>
<td>569,952</td>
</tr>
<tr>
<td>Additional number of households that could be powered (based on an electricity use of 12 MWh/year)</td>
<td>20,392</td>
<td>47,496</td>
</tr>
<tr>
<td>Decreased CO₂ emissions (metric tons)* (Coal 40%, Natural gas 40%, Fossil free 20%)**</td>
<td>145,844</td>
<td>339,691</td>
</tr>
<tr>
<td>Increased revenue ($) ***</td>
<td>8,148,692</td>
<td>18,979,402</td>
</tr>
</tbody>
</table>

* This number does not include emissions resulting from extraction and transport of fuel
** Average electricity mix for the study area (EIA, 2016)
*** Based on average 2014 electricity prices (Army Corps of Engineers, 2015)
**** Mobile, Nashville and Savannah Districts.

Table 1-2. Overview of the dams included in this project. The bottom three are found in the analyzed basins but excluded.

<table>
<thead>
<tr>
<th>Dam</th>
<th>Operation start</th>
<th>Installed Cap (MW)</th>
<th>River basin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buford Dam</td>
<td>1958</td>
<td>126</td>
<td>ACF</td>
</tr>
<tr>
<td>Walter F George Dam</td>
<td>1963</td>
<td>168</td>
<td>ACF</td>
</tr>
<tr>
<td>West Point Dam</td>
<td>1975</td>
<td>87</td>
<td>ACF</td>
</tr>
<tr>
<td>Allatoona</td>
<td>1950</td>
<td>85</td>
<td>ACT</td>
</tr>
<tr>
<td>Millers Ferry Dam</td>
<td>1970</td>
<td>90</td>
<td>ACT</td>
</tr>
<tr>
<td>Robert F Henry Dam (Jones Bluff)</td>
<td>1975</td>
<td>82</td>
<td>ACT</td>
</tr>
<tr>
<td>Hartwell</td>
<td>1963</td>
<td>42</td>
<td>SAV</td>
</tr>
<tr>
<td>J. Strom Thurmond Dam (Clarks Hill)</td>
<td>1952</td>
<td>380</td>
<td>SAV</td>
</tr>
<tr>
<td>Jim Woodruff Dam</td>
<td>1957</td>
<td>43.35*</td>
<td>ACF</td>
</tr>
<tr>
<td>Carters Dam</td>
<td>1975</td>
<td>280**</td>
<td>ACT</td>
</tr>
<tr>
<td>Richard B Russel</td>
<td>1985</td>
<td>300**</td>
<td>SAV</td>
</tr>
</tbody>
</table>

* No storage
** Does not include installed capacity for reversed pumping
CHAPTER 2
DRIVERS OF LONG TERM VARIABILITY OF PRECIPITATION AND RUNOFF IN THE SOUTHEAST

The water resources of the Southeast are dominated by conflicting interests. The average annual precipitation of 1,000-1,500 mm (Kunkel et al. 2013) is required to not only satisfy the natural ecosystems, but also the agriculture and drinking water needs of the rapidly growing metropolitan areas such as Atlanta and Charlotte, recreational use, and hydroelectricity power plants. In response to increasing population and pressures to switch to renewable energy sources, this research is part of a broader project investigating climate drivers of hydropower output in the Southeast. The current study investigates interannual variability in precipitation inputs to, and runoff outputs from, eighteen basins in the region and whether that variability can, in part, be explained by the influence of various ocean-atmosphere teleconnections. The study area includes the states of Georgia, South Carolina, Alabama, North Carolina and Tennessee, of which the last three are among the top-ten hydropower producing states in the country (National Hydropower Association 2013).

The form, as well as the spatial and temporal variability of precipitation in the region can be attributed to three main factors: distance to the sea (Atlantic or Gulf of Mexico), elevation, and latitude (Kunkel et al. 2013). Areas located closest to the Atlantic and Gulf of Mexico receive the bulk of their annual precipitation during the summer months as a result of convection, sea breezes and tropical cyclones (Giemeno et al. 2010; Kunkel et al. 2013; Brun and Barros 2014). Further inland the difference between summer and winter precipitation diminishes. The influence of summertime sea breezes and tropical cyclones decreases and that of the passage of precipitation-bearing cold fronts increases (Kunkel et al. 2013).

Latitude and elevation influence the form of precipitation during the winter months. Snow is common at higher altitudes in Tennessee and North Carolina, while falling sparsely in
continental portions of Alabama, Georgia and South Carolina (Kunkel et al. 2013). The likelihood of precipitation falling as snow during the winter season controls the quantity of snow storage. Subsequent melt is a determinant of the timing and quantity of flows in spring and seasonal losses to evapotranspiration (Vanrheenen et al. 2004; Carmona et al. 2014).

While the general intra-annual pattern of spatial and temporal variability of precipitation regime can be explained by the physical features described above, prior research has indicated a number of potential external drivers (teleconnections) of hydroclimatic variability in the region. In their extensive mapping of the influence of Pacific Ocean-based El Niño-Southern Oscillation (ENSO) on the streamflow in the continental United States Kahya and Dracup (1993) and Dracup and Kahya (1994) indicate that ENSO’s influence is relatively weak in the Southeast (excluding Florida and the coast of the Gulf of Mexico), with warm phase ENSO events leading to higher flows and the cold phase to lower flows. Several authors (see for example, Hastenrath 1990) posit that the analysis of streamflow rather than precipitation records is a preferable means of detecting such long-run drivers of climatic variability. The drainage basin acts as spatial filter of the noise inherent in precipitation data and the non-linear nature of the hydrologic system and comparative consistency of losses through evapotranspiration (Bonan 2008, p. 171; Peel et al. 2010) may amplify the signal of climate drivers in the streamflow record.

There is limited research showing linkages between the North Atlantic Oscillation (NAO) and streamflow in the study area. Coleman and Budikova (2013) conclude that the influence of the NAO is strongest in the Northeastern United States, but positive relationships also can be found between the NAO and summer streamflow in parts of the Southeast. Temperatures, which may play a key role in determining the type of precipitation (Kang et al. 2016) and controlling
evapotranspiration, have been shown to be associated with both the NAO and ENSO in the Southeast (Rogers 1984).

Katz et al. (2003) identified the Pacific-North American (PNA) pattern as an additional control of winter precipitation, confirming the earlier findings by Serreze et al. (1998), and foreshadowing those of Sen (2012). PNA is negatively correlated with wintertime temperatures throughout the Southeast, while its direct negative influence on wintertime precipitation is limited to the continental portion of the region (Katz et al., 2003). These associations between climate drivers and winter precipitation and temperatures highlight the need to incorporate the use of lag-times in regional studies linking teleconnections to seasonal flows. It has been suggested (Enfield et al. 2001) that the Atlantic Multidecadal Oscillation (AMO) displays no significant connection to streamflow in the Southeast (excluding Florida). Subsequently Ortegren et al. (2011, 2014) found that warm phase AMO is associated with summer droughts in the Southeast, a finding that was further confirmed by Johnson et al. (2013) that detected AMO signals in the flow of the Apalachicola–Chattahoochee–Flint river (draining parts of western Georgia, eastern Alabama and northwestern Florida).

The Arctic Oscillation/Northern Annular Mode index (AO) impacts the location and strength of the Polar Jetstream (Thompson and Wallace 1998; Wallace 2000, Feldstein and Franzke 2006). Less well known, and arguably indistinguishable from the NAO index (Deser, 2000; Feldstein and Franzke 2006), the AO has been more or less excluded in the study of the climatology of the United States, in favor of the longer established NAO (Walker and Bliss 1932). Since it is considered by some to be the dominant mode of variability in the extratropics (Higgins et al. 2000; Wallace 2000; Feldstein and Franzke 2006) and has been linked to temperature variations throughout the Northern Hemisphere (Thompson and Wallace 1998) the
AO is also included in this analysis. Labosier and Quiring (2013) take a holistic view of the regional hydroclimatology of the Southeast, concluding that variability in regional hydroclimatology is controlled by ENSO, the Pacific-North American pattern, the strength and location of the Bermuda High and tropical cyclones. All of these teleconnections are explicitly included as possible drivers of seasonal precipitation and runoff in the Southeast with the exception of the Bermuda High, which can be considered as represented by the NAO, and tropical storms, which are important local meteorological phenomena, driven by larger scale variability governed in part by the various teleconnection indices (Goldenberg et al., 2001; Elsner 2003; Xie et al., 2005).

Data

Teleconnection Indices

The following teleconnection indices are included in this analysis:

- The NAO and PNA indices, derived by the methods described by Barnston and Livezey, (1987) are obtained from National Oceanographic and Atmospheric Administration (NOAA) (2013a, 2013b). The AO index is also obtained from NOAA, but emerges when an Empirical Orthogonal Function (EOF) is applied to the 1000 hPa height anomalies 20-90°N, using the standard deviation of the 1979-2000 monthly index as the base period (NOAA, 2005).

- ENSO is represented by the Bivariate ENSO Timeseries (BEST), a combination of the Southern Oscillation Index (SOI), and the Niño 3.4 index (Smith and Sardeshmukh 2000).

- The AMO index consists of the 121 months smoothed version of the Kaplan SST V2 data (Kaplan et al. 1998; Enfield et al. 2001; NOAA 2002)

Precipitation and Runoff Data

Estimates of historic precipitation inputs to the basins of interest are derived from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) 4x4 km gridded dataset. The eighteen basins included (Figure 2-1.) range in size from 300 to 7300 km², thus due
to their large size, influence of any highly localized geographical differences may be minimized. PRISM interpolates precipitation data from almost 13,000 stations in the continental United States by applying a climate-elevation regression (Daly et al. 1994) and has been widely used in long term climate variability research (Hamlet et al. 2005; Kennedy et al. 2009; Latysh and Wetherbee 2011; Yang and DelSole 2012; Ciancarelli et al. 2014; Nag et al. 2014). Monthly streamflow data are available from the United States Geological Survey (USGS) (2013). The gage sites and basins are all part of the Hydro-Climatic Data Network Streamflow Data Set (Slack et al. 1993).

Methods

The Southeast could be divided into a number of different climate regions depending on the scope of the research (Kunkel et al. 2013; Ortegren et al. 2014). However, the focus here is on longer-term (seasonal) influences of teleconnections on the overall water resource of the region, and a number of generalizing and smoothing methods are employed.

The gridded PRISM data are converted to time series of monthly precipitation inputs (mm) to each basin, and discharge data converted to runoff (mm) to facilitate comparisons between variables and basins (Figure 2-1). Both variables are converted to seasonal averages by creating 3-month running mean time series, which are entered into a Principal Components Analysis (PCA). The PCA identifies spatial patterns of variability of all the time series (eigenvectors), their variation in time (orthogonal time series of the PCA) and their rank (modes), where the first mode explains the largest fraction of the variance (Lorenz 1956, Bretherton et al. 1992, Wilks 2011). The sizes of the basins, the 3-month running mean and the PCA work together to reduce local geographical and short-term temporal variability to make any findings useful for long-term forecasting.
The new time series of the PCA are entered in a Spearman rank correlation to determine any relationship between the precipitation/runoff and the teleconnections, employing a number of different time lags, recognizing that the influence of a teleconnection on the hydroclimatology need not be synchronous but can be lagged up to several months (Ropelewski and Halpert 1986, Kahya and Dracup 1993, Dracup and Kahya 1994, Hamlet et al. 2002, Su et al. 2005, Engström and Uvo 2015).

Many different philosophies exist regarding how many PCs should be considered and included in further analysis. One alternative is to consider all PCs, starting with the highest ranked, until together they explain a predetermined percentage of the variance of the original dataset. Another approach is to construct scree-plots, which portray the ranks of the PCs on the x-axis and their associated eigenvalues on the y-axis and to include all those PCs with an eigenvalue >1 meaning that they explain more of the variance in the dataset than any single input vector of data.

In this study only the first two PCs are examined, since the PC3 in this case typically explains less than 10% of the variance of the original dataset. Such small variances explained are not considered useful in correlating the PCs with the teleconnection indices. The influence of the teleconnection on precipitation/streamflow is the product of the explained variance of the PC and r². For example, PC3 would typically explain <1% of the hydroclimate variability, and was therefore considered too small to be useful for water management purposes.

Results

PC Loadings

Figure 2-2 shows the temporal variability of variance explained by the first three Principal Components (PC1, PC2 and PC3) for precipitation and runoff. PC1 explains more of the variability in precipitation than in runoff, but similar patterns of seasonality appear in both
graphs. In general there is less homogeneity in both precipitation and runoff during the summer months, which is reflected by a smaller fraction of the variability of the datasets explained by the PC1 during this part of the year. PC2 compensates for this by explaining a larger fraction of the variability during the same part of the year. The most uniform behaviors are found during the cold part of the year where PC1 explains 60-70% of the variability in precipitation and 60-65% of the variability in runoff. PC3 is illustrated in Figure 2-2. only as reference and is not included in further analyses.

Figure 2-3. depicts the spatial patterns of the significant loadings of the PC1, and complements Figure 2-2. by illustrating spatiotemporal variability. The radar plot in the middle of Figures 2-3 and 2-4 shows how many basins (of eighteen) are significantly correlated to PC1 on a seasonal basis. The surrounding maps describe the locations of those basins throughout the year. Those significantly correlated with PC1 are represented by a filled point, while those related to PC2 and PC3 are marked with an empty point. Emerging from Figures 2-3 and 2-4 is a “heartland” of basins that dominate PC1. This central cluster is surrounded by a couple of clusters of stations that are better explained by PC2 during parts of the year. One such cluster on the precipitation maps (Figure 2-3) appears in the northwest. These basins show little to no association with PC1 during the winter, as they receive significantly more precipitation during this part of the year than the other basins in the analysis (Figure 2-1.). During the summer another cluster of basins appears in the northeast. Not unexpectedly a similar pattern emerges in the patterns of runoff and PC1 (Figure 2-4), with small clusters behaving differently appearing seasonally in the northwest and northeast. Runoff in the Satilla basin in the southeastern corner of the study area is also markedly different from most basins with no specific seasonality (its double mass curve is displayed in Figure 2-1., bottom row, second from the right). This basin is
dominated by marshland, in which hydrologic storage might produce differing lagged responses to seasonal precipitation.

**Identifying the Relationships**

The complete results (correlation coefficients and associated significance levels) of the Spearman rank correlations between teleconnection indices and precipitation and streamflow respectively, are shown as correlation charts in Figures 2-5 – 2-20. The AMO’s association with variations in precipitation (Figure 2-5) is limited to the late fall through spring seasons, where a positive phase of the AMO leads to decreased precipitation ($r \geq -0.34$), supporting the findings of Enfield et al. (2001). The influence of the AMO persists for much longer than that of any other teleconnection, with significant time lags longer than a year. This can be explained by the AMO’s long cycles (typically 60-70 years) of variability. Significant correlations between precipitation and the AMO are mainly prevalent in PC1 of the precipitation data, while the second shows a limited relationship with precipitation.

Significant positive correlations between AO and precipitation appear sporadically throughout the year (Figure 2-6) but are concentrated in the late fall-winter, with a time lag of about one year, when the phase of the AO during the previous fall and winter exhibits a high correlation ($r \leq 0.52$). The teleconnection’s influence on PC2 is more limited and not displayed.

Despite earlier indications that the NAO influences the temperature and hydrology of the Southeast (Rogers 1984, Katz et al. 2003), only a temporally scattered influence on precipitation is revealed here. The association is sometimes stronger ($r \leq 0.4$) but shows no consistency of seasonality or “direction” in association in the first nor the second mode of the PCA (Figure 2-7, 2-8).

Variability in fall and winter precipitation can be explained partially by ENSO, which is positively correlated with the first mode of the precipitation PCA from OND through JFM,
reflecting the common observation that a warm phase ENSO leads to increased precipitation (and vice-versa) in the Southeast (Figure 2-9). The second mode of the PCA (Figure 2-10) is also significantly correlated with ENSO, but in contrast to the first mode the sign of the correlation varies, and several consecutive months of negative correlations appear during the second half of the year. This is a result of the perpendicular relationship between the PC1 and PC2, but might also indicate that on rare occasions the warm phase ENSO leads to decreased precipitation. Further, this could be the consequence of other contemporary large scale patterns, perhaps the noted association between tropical cyclones in the North Atlantic basin and the phase of ENSO (Gray, 1984; Goldenberg et al., 2001). This would also explain the lack of consistency during the spring, in which the PCA does not manage to identify any dominant pattern of influence. Just like the impact of the AMO, the influence of ENSO events persist for relatively long periods as the El Niño/La Niña events occur over many months, and therefore have a long-lasting influence on the regional hydroclimatology.

The association of the PNA and regional precipitation is scattered. In the first mode of the PCA it appears as negative ($r \geq -0.3$) in the early summer through winter seasons (Figure 2-11). The second mode of the PCA displays a less coherent association, concentrated into the late winter-spring seasons (Figure 2-12).

Compared with precipitation, associations of teleconnections with streamflow are generally stronger. AMO shows up as the strongest driver, affecting the runoff during more than half of the year, its influence ranging from contemporary to up to 24 months’ time lag in the first mode of the PCA (Figure 2-13) and is a negative correlation, suggesting that a warmer Atlantic Ocean correspond to periods of reduced regional runoff. The influence of the AMO in the second mode is limited (Figure 2-14).
The AO has restricted positive association to the winter runoff (Figure 2-15) and its association is not synchronous being linked to the phase of the AO in the previous year, similar to the association detected with precipitation (Figure 2-6). Few and scattered significant correlations appeared with the time series from the second mode of the AO PCA.

Despite earlier research linking the NAO and regional hydroclimatology, this analysis suggests a more complex set of interactions (Figure 2-16). The association of the teleconnection with runoff is lagged. Of particular note are the positive correlations of runoff at the beginning of the year \((r \leq 0.41)\) with the teleconnection’s phase during the following summer and early fall.

ENSO exhibits an association with runoff in both the first and second mode of the PCA, but of differing signs. The first mode is positively correlated with ENSO \((r \leq 0.42)\), indicating that a warm ENSO phase leads to more runoff in accordance to the observations concerning precipitation (Figure 2-9). The influence of ENSO can be detected in the winter months in lags ranging from the preceding summer through to the following May-June (Figure 2-17). The second mode of the PCA, displayed in Figure 2-18, matches the second mode of the precipitation shown in Figure 2-10, indicating a negative correlation \((r \geq -0.53)\).

The PNA is mainly negatively correlated with river discharge in the Southeast. In the first mode of the PCA (Figure 2-19), the summer-fall PNA has a slight dampening effect on the wintertime river discharge the coming year. These patterns are similar to the PNA’s influence on precipitation (Figure 2-11), indicating that the teleconnection mainly influence precipitation amounts, while having little effect on temperatures. In the second mode of the PCA the influence of the PNA is limited to the early spring (Figure 2-20).

**Discussion**

Association between teleconnection indices and observed streamflow is useful from a water resource management perspective. Analysis of the phase of these indices can give an
indication of expected hydroclimatic conditions months ahead, which facilitates water resource
distribution and decreases the risk of water related conflicts.

The basins included in the analysis are all part of the Hydroclimate Data Network (Slack at al. 1993). The authors realize that the basin flows might have been altered since the publication of Slack et al. (1993), but as long-term time series analysis is not part of this paper, removal of basins displaying a changing hydrologic behavior leads to an incomplete depiction of the actual water balance (Rice et al. 2015) as there is widespread human influence in the region.

As suggested in earlier research (Hastenrath 1990), the teleconnection signals often appear more strongly in streamflow than precipitation data. From a holistic water resource perspective, the teleconnections considered in this analysis have limited value in forecasting precipitation. However, the results can be usefully incorporated into surface water forecasting for those industries and organizations that depend on that resource for their activities.

The ocean-atmosphere based teleconnections ENSO and AMO have the strongest and most persistent influences on the hydroclimatology in the Southeast based on these findings. During the warm-phase of ENSO an enhanced subtropical jetstream causes southwesterly winds to dominate over the Gulf of Mexico bringing warm, moist air in over land which leads to above normal precipitation in the Southeast. During the cold phase the wind shifts to the northwest, bringing drier air and below normal precipitation (Ropelewski & Halpert 1986, Katz et al. 2003). The warmer Atlantic sea surface temperatures associated with the warm phase of the AMO offers more favorable conditions for tropical cyclone development and to an increased number of tropical cyclone landfalls along the U.S. east coast, and hence more precipitation (Goldenberg et al., 2001). Despite this, the general pattern of influence of the AMO is that the warm phase leads to relatively dry conditions in the Southeast. Analyzing the 500 hPa geopotential heights
anomalies in the warm vs the cold phase of AMO, Enfield et al. (2001) find that the winter ridge-trough pattern over Northern U.S. is flattened during the warm AMO phase. The weaker ridge of the Pacific Northwest leads to an increased number of winter cyclones, while the North Central-East region gets a reduced number of cyclones. The cold phase AMO shows the opposite with a strengthened ridge in the Northwest and a deepened trough in the North Central-East. The southwestern region gets increased 500 hPa heights during the warm phase while the Southeast experiences decreased geopotential heights, leading to increased precipitation. Considering the very long cycles of variability of the AMO, the usefulness of including this index in intra-annual forecasts is questionable. It is however an important teleconnection to consider when planning for future water availability in the longterm and construction of infrastructure as its influence is strong and long lasting.

Associations to ENSO events vary on a shorter term basis than the AMO, but typically persist from fall through early spring. For this reason it is more useful from an intra-annual water resource planning perspective. As a warm (cold) phase ENSO event is predicted or appears in the central equatorial Pacific during late boreal summer, water managers can conclude with greater certainty that the winter and early spring will bring above (below) normal precipitation and runoff and can thus plan accordingly.

Atmosphere-based teleconnection indices included in this analysis display scattered influences on the hydroclimatology of the region. The PNA, which through its variability influences the location and height of atmospheric ridges and troughs over the United States, and hence has direct influence on wintertime temperatures (Wallace and Gutzler, 1981), shows a negative correlation with both precipitation and runoff. The PNA’s influence shows varying time
lags and little consistency and its usefulness in water resource forecasting is therefore considered limited.

Researchers debate whether the AO and NAO are the same or separate atmospheric phenomena. In a general sense the NAO can be described as partly controlling the strength and location of the midlatitude jet stream over the North Atlantic. During positive conditions North Atlantic cyclones are tunneled towards Northwestern Europe that gets excess amounts of precipitation. During the negative phase the North Atlantic storm track is shifted slightly south, causing increased precipitation throughout the Mediterranean. On the western side of the Atlantic basin the Southeast show a similar relationship to the NAO as Northwest Europe with positively correlated winter temperatures and precipitation anomalies (Barnston and Livezey, 1987, Hurrell 1995). The AO could be described as an expanded NAO with oscillating pressure centers on multiple longitudes around the Arctic, where a positive phase leads to stronger subpolar westerlies (Thompson and Wallace, 2001), which could be expected to have a similar influence on the Southeast as the positive phase of the NAO. Results suggest that their relative associations are different to the hydroclimatology of the Southeast, primarily because of differences in the periods over which the indices are seen to vary. Secondly, the AO shows a stronger association with precipitation, and the NAO with runoff. The implication is that AO changes precipitation, but that change is not transmitted as markedly to the rivers. Thompson and Wallace (1998) showed that phases of the AO are positively correlated to warmer temperatures throughout the Northern Hemisphere. This observation, in combination with the timing of the strong correlation between AO and precipitation (SON-DJF), suggests that increases/decreases in precipitation may be offset by the opposite change in evapotranspiration, thereby dampening any signal in the rivers.
By contrast to the AO, positive phase of the NAO leads to more winter time runoff, despite lack of association with increased precipitation. Approximately the same amount of precipitation is leading to more runoff, which would imply that winter time temperatures would be higher during the positive phase of the NAO, decreasing snow and ice storage, which is confirmed by Katz et al. (2003) as well as Thompson and Wallace (1998). It is also noteworthy that the NAO shows an inverse lead/lag relation to the runoff, meaning that the winter and spring runoff are correlated with the phase of the NAO later in that same year. This fact implies that the rivers in the Southeast experience some kind of precursor of the NAO, before the index itself actually changes. Similar patterns of inverted responses have been observed in conjunction to other teleconnections, such as ENSO (Ropelewski & Halpert, 1987; Waylen & Caviedes, 1996).

**Conclusion**

This paper confirms the significant influence of various teleconnections upon the hydroclimate of southeastern United States. The most significant external contributors to variability in the region are the ocean-atmosphere based teleconnections AMO and ENSO, which strongly influence the hydroclimate in the fall through spring with several months’ time lag. The atmospheric-based teleconnections AO, NAO and PNA show more sporadic influences. In general, the teleconnection signal can be more clearly identified in streamflow than precipitation records. This fact, in combination with the temporal lag between the teleconnection indices and the hydroclimatic response make teleconnection indices useful parameters to include in surface water forecasts.
Figure 2-1. Location of the uncontrolled river basins included in the analysis. Surrounding diagrams of monthly mean (Jan-Dec) double mass curves (with a 1:1 line for reference) for the rivers A) Buffalo, B) Emory, C) French Broad, D) Deep, E) Conecuh, F) Sweetwater, G) Satilla, H) Lynches, give an idea about the varying hydrology of the region. The precipitation and runoff have been converted to monthly average millimeters (mm) for ease of comparison.
Figure 2-2. Seasonal variation of percentage of variability explained by P1, PC2 and PC3 (outer, middle and inner polygons respectively).
Figure 2-3 Spatiotemporal variation of basins in PC1 for precipitation. Basins significantly correlated with PC1 are represented by a filled point, while those related to PC2 and PC3 are marked with an empty point.

Figure 2-4 Same as Figure 2-3, but for runoff.
Figure 2-5. Lag correlation between PC1 (precipitation) for each season and the AMO index. The labels along the x-axis indicate the season (monthly triad) considered and the strength of only significant correlations for that season on a scale ranging from -0.7 to 0.7 (for clarity the first digit (zero) of the correlation coefficient has been removed, hence the number 5 indicates a correlation coefficient of 0.5). The nature of each significant correlation is indicated with a grey bar for negative correlation and black for positive. Filled bars indicate a correlation with a p-value of <0.05, while empty bars display correlations with p-values of <0.1. The y-axes show the triads in which the corresponding teleconnection index is computed. Alternating triads are printed on the right and left of the chart. The diagonal line of boxes indicates periods of contemporary precipitation/runoff and teleconnection index. As an example, at the far left, the box is centrally located, indicating a negative correlation of synchronous JFM values of precipitation and the AMO index. Precipitation is also negatively correlated with the AMO index in the twelve preceding months (vertically above the box) and with that in eleven subsequent months (below the box), acknowledging the fact that the association of a teleconnection with precipitation/runoff need not be instantaneous. This type of figure not only highlights the specific strength of the correlations, but also indicates temporal extents of the association to the teleconnections.
Figure 2-6. Same as Figure 2-5 except lag correlation between PC1 (precipitation) and the AO index.

Figure 2-7. Same as Figure 2-5 except lag correlation between PC1 (precipitation) and the NAO index.
Figure 2-8. Same as Figure 2-5 except lag correlation between PC2 (precipitation) and the NAO index.

Figure 2-9. Same as Figure 2-5 except lag correlation between PC1 (precipitation) and the ENSO index (BEST).
Figure 2-10. Same as Figure 2-5 except lag correlation between PC2 (precipitation) and the ENSO index.

Figure 2-11. Same as Figure 2-5 except lag correlation between PC1 (precipitation) and the PNA index.
Figure 2-12. Same as Figure 2-5 except lag correlation between PC2 (precipitation) and the PNA index.

Figure 2-13. Same as Figure 2-5 except lag correlation between PC1 (runoff) and the AMO index.
Figure 2-14. Same as Figure 2-5 except lag correlation between PC2 (runoff) and the AMO index.

Figure 2-15. Same as Figure 2-5 except lag correlation between PC1 (runoff) and the AO index.
Figure 2-16. Same as Figure 2-5 except lag correlation between PC1 (runoff) and the NAO index.

Figure 2-17. Same as Figure 2-5 except lag correlation between PC1 (runoff) and the ENSO index.
Figure 2-18. Same as Figure 2-5 except lag correlation between PC2 (runoff) and the ENSO index.

Figure 2-19. Same as Figure 2-5 except lag correlation between PC1 (runoff) and the PNA index.
Figure 2-20. Same as Figure 2-5 except lag correlation between PC2 (runoff) and the PNA index.
CHAPTER 3
THE CHANGING HYDROCLIMATE OF THE SOUTHEAST UNITED STATES

Hydroclimatological variability in the Southeast can be partly explained by the phase of various teleconnections (Dracup & Kahya, 1994; Johnson et al., 2013; Kahya & Dracup, 1993; Katz et al., 2003; Labosier & Quiring, 2013; Ortegren et al. 2014). However, the hydroclimate should not be treated as a static, but rather a constantly evolving system (Milly et al. 2008; Schindler & Hilbron, 2015). Groisman et al. (2001) find a general trend of increased runoff during the twentieth century throughout the U.S. Instead of calling it a longterm trend, McCabe & Wolock (2002) describes this change as an abrupt shift in the early 1970s, a pattern that show up significantly mainly in sites located in Eastern U.S. The authors speculate that this increase is linked to increased Fall season precipitation reported by Karl & Knight (1998). Wang & Hejazi (2011), using the same temporal breakpoint, argue that human impacts play a more important role in reported streamflow changes than have yet been acknowledged. They only identify minor streamflow increases in the Southeast that could be attributed to a changed climate, while finding a just as strong opposite pattern of decreased streamflow linked to human impacts. While the above-mentioned research consider the continental U.S., this paper focuses solely on the Southeast part of the country (Alabama, Georgia, North Carolina, South Carolina and Tennessee), a region that thus far has been underrepresented in hydroclimatic research. By limiting the geographical area of study, a deeper analysis and subregionalization is possible, leading to more detailed results that are useful and applicable to regional water management.

No obvious warming trend has been identified in the Southeast (Misra et al., 2012; Pan, 2004; Portmann et al., 2009), yet identified hydroclimatological changes include weak decreases in the number of snowcovered days in the Southeast (Groisman et al. 2001). Seager et al. (2009) on the other hand find that there have been no significant changes to the hydroclimate of the
Southeast during the period of anthropogenic forcing of climate, but that climate change may lead to increased precipitation and evaporation, resulting in higher risk of drought. In their study of the hydroclimatology of the U.S. Sankarasubramanian & Vogel (2003) find that for most of the Southeast a 1% increase in precipitation leads to 1.5-2.5% increase in runoff, while some areas in the Southeast of our study area get up to 4% increase in streamflow, implying less evaporation and/or storage capacity.

Evidently, there are many different aspects and contradictory findings regarding trends in the regional hydroclimatology of the Southeast U.S. In this paper we aim to investigate if and how the translation of precipitation to streamflow has changed over time by examining historical data. The non-stationarity in the translation between precipitation and runoff is likely to be more pronounced as a changing climate brings new normals that diverge from the historically dominant patterns upon which modern water management infrastructure is built. The findings of this paper would be of greatest interest to water managers in a region that is used to intense summer rainstorms, winter snowfall, spring floods and water related conflicts.

**Material and Methods**

The approach employed is based on a simple seasonal water balance equation where

\[ \text{Precipitation} = \text{Runoff} + \text{Evapotranspiration} +/- \text{Storage}. \]

Mean seasonal runoff and estimates of mean seasonal precipitation are available from historic records. The residual is assumed to represent losses to evapotranspiration and or changes in basin storage. Streamflow data from the Hydro-Climatic Data Network (Lins 2012; Slack et al, 1993) are supposedly minimally affected by human interventions and are as such frequently used in hydrologic analyses (Frei et al, 2015; Henn et al, 2015; Sagarika et al. 2014; Stewart et al. 2005). For this paper historic monthly discharge observations (1952-2014) from 18 gauges (Figure 3-1.) drawn from the U.S. Geological Survey’s Hydro-Climatic Data Network are analyzed. The extent of the basins are
defined by a 100 m resolution Digital Elevation Model (DEM) (U.S. Geological Survey, 2014). Basins range in size from as little as 299 to 7370 km$^2$, although it should be noted that the second and third largest basins are only half the size of the largest. Discharge data are converted to depth units (mm) to facilitate comparison to precipitation data by normalizing by watershed area. Estimates of historical precipitation input (mm) to the basins of interest are taken from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) 4x4 km gridded data (Daly et al, 1994), a dataset that is widely used in hydroclimatic research (Kennedy et al, 2009; Nag et al, 2014; Yang & DelSole, 2012). The introduction of the 100 m resolution DEM to create the outlines of the basins based on the location of the gage leads to some generalizations. However, a comparison between the basin sizes reported by U.S. Geological Survey and the sizes defined in this analysis shows a maximum difference of 4%, while the average difference is less than 0.5%. This is recognized as a limitation of the analysis, but since the size is constant through time it is not considered as being an influential factor upon the findings of this research.

The approach taken assumes a simple, seasonally varying linear relationship between precipitation and runoff described by the slope of a fitted regression line (the runoff coefficient, RC). While accepting that this assumption runs contrary to the basic non-linear nature of rainfall-runoff relationships, at this level of temporal aggregation and within this environment, empirical evidence suggests that the assumption is a reasonable first step in such a spatio-temporal analysis. The improvement in fit resulting from the use of second order functions was generally small and most apparent during the summer and fall seasons in years of very low precipitation input when baseflow-dominated runoff appeared more insensitive to changes in precipitation input. Given the small changes in goodness of fit and the associated loss of meaningful interpretation of results, the RC derived from the slope of the first order fit is preferred.
A Pettitt Change Point Analysis is employed to identify any changes in seasonal time series of RCs viewed through a 30 year moving windows of precipitation and runoff. The window is used to smooth any interannual variability that might arise through the influence of atmospheric drivers such as El Niño-Southern Oscillation, The North Atlantic Oscillation and Pacific North American Pattern, all found to significantly change seasonal precipitation and runoff in southeastern U.S. (Engström & Waylen, 2017; Sen 2012; Katz et al. 2003), while detecting inter-decadal scale changes in rainfall-runoff relations. The coefficients give an indication of the proportion of the precipitation exported as runoff. The moving window is constructed as such that the estimated coefficient is assigned to the last calendar year of the 30 year period. The Pettitt’s Change Point Problem (Pettitt, 1979) is similar to the Kruskal Wallis non-parametric test comparing populations, but the Pettitt test employs a different approach, identifying the year in which a data series breaks, leaving the data series before and after that break-year significantly different. The null hypothesis of the Pettitt test is that there is no breakpoint. The test has successfully been employed to detect breakpoints in both rainfall and streamflow data (Alghazali & Alawadi, 2014; Gao et al. 2011; Harrigan et al. 2014; Ma et al. 2008; Salarijazi et al. 2012)

Following Mallakpour & Villarini (2015), a sensitivity analysis is performed on the Pettitt test. The test is run 100 times on constructed time series with means and standard deviations from two of the basins included in the analysis. The spread of the break years identified varies by season with the most spread in the summer months and the least spread in fall, but the correct break year was identified the majority of the time in all seasons and the Pettitt test is therefore considered to have a high sensitivity to breakpoints in time series of means, as confirmed by Mallakpour & Villarini (2015).
Results

Figure 3-2. shows the seasonal variation of RCs in the study area. In DJF the lowest RCs are found in the mountains, where there some years is a significant snow storage (Keighton et al. 2009; Sugg et al. 2014). The rest of the region has relatively high RCs during this season due to the limited evapotranspiration. The coefficients are highest in MAM following snowmelt and as temperatures are still relatively low, limiting evaporation and vegetation growth. In JJA RCs are at their minimum due to high temperatures accompanied with intense vegetation growth. The mountain region stands out in this season as having slightly higher RCs, which can be explained by the higher elevations experiencing milder temperatures, hence evapotranspiration is less pronounced in this region. SON shows a north-south pattern where the northerly and continental basins pick up the first signals of the approaching colder season, which is reflected in higher RCs, while the southern and eastern basins still have high evapotranspiration levels.

Following the approach of McCabe & Wolock (2002), Figure 3-3. depicts annual standardized min, median and max flow for the 18 basins included in this analysis. The reported break in 1970-71 (McCabe & Wolock, 2002; Wang & Hejazi, 2011), is not visually apparent. Rather Figure 3-3. shows that the basins experience considerable interannual variability in these three particular streamflow characteristics.

This paper focuses on longer term changes than those identified as being associated with teleconnections. The Pettitt test identifies any such significant breaks in the pattern of RCs in all seasons. Estimated coefficients before and after the breaks are compared and displayed in Figure 3-4. clearly indicating higher RCs after the breaks. In only 17 of the 72 cases (24%) are increases not experienced. The pattern is most pronounced during the summer (JJA) and fall (SON).

Figure 3-5. displays the observed changes in RC geographically. Each season is represented separately by an arrow, emanating from the gauge site. The shade and the length of
the arrow indicate the nature (positive/negative) and magnitude of the observed change in RC before and after the break. The summer and fall stand out as displaying the greatest change in RC in the mountains and in some of the eastern coastal basins. Spring shows the least difference pre- and post-break, while winter shows increased RCs of varying strength throughout the study area.

The years of the breaks (Figure 3-6.) are represented by pie charts for easier identification of spatial clusters of basins exhibiting similar timings. DJF displays no distinguishable spatial patterns. In MAM two trends emerge with the majority of the station records breaking in the late 1980-early 1990s, while a couple of stations show changes in the early 2000s. With few exceptions most stations break earlier in MAM than in other seasons. In JJA the western stations indicate a shift in the late 1990s, while the central mountainous region tends to elicit a change a little later. East coast basins show a lot of variability. SON returns the most uniform pattern of break years and the majority of the basins experience a change in the late 1990s. The southernmost basins stand out as breaking in the early 2000s. The diversity in the observed break years reflects the hydroclimatic heterogeneity of the region as recognized by Carmona et al. (2014).

The 30-year averages entered into the Pettitt analysis are constructed such that a break in 1970-71, as reported by (McCabe & Wolock, 2002), would appear in 1999-2000 (in the end of the 30 year time series). Figure 3-7. displays the observed cumulative frequency of break years by season. 50 percent of the basins have already experienced their break in JJA RCs by the year suggested by these authors; 65% of MAM, 75% of DJF and 90% of SON. Only coefficients for JJA show any large number of changes 1998-2002. A Kolmogorow-Smirnov test comparing the empirical cumulative distributions of the seasonal breaks reveals that the spring season is significantly different from all the other seasons (0.05 level). The spring season break years are
typically earlier (average year 1997); while the other seasons break in 1998-1999 (Table 3-1.). Due to the nature of how the 30 year averages are constructed, a reported change in the late 1990s could also mean that the actual change was in the beginning of that 30 year time window, which would be in the late 1960s, close to the break identified by McCabe & Wolock (2002). To ensure the timing of the actual breakpoints the analysis replicated using 20 year moving averages. If the actual breakpoints were in the beginning of the moving window (late 1960s), these changed settings would lead to that the reported break year would be 10 years earlier than previously reported. No such changes appeared.

Identified changes in seasonal runoff coefficients and slopes potentially suggest increased (decreased) proportions if seasonal water being released from (input to) seasonal hydrologic stores and/or decreased losses to evapotranspiration. Several different explanations for this change in runoff coefficient are possible, the principle ones of which are analyzed below.

**Increased Precipitation**

Seager et al. (2009) project a trend of increasing precipitation and evapotranspiration in the Southeast Kunkel et al (2013) on the other hand, write that the regional annual precipitation has not changed significantly over the period 1895-2011, but that there has been a shift in the timing of the precipitation with a smaller fraction falling during the summer and increased precipitation in the fall months.

Considering the geographic location of the study area and the observed seasonality of changes in the precipitation-runoff relationship, tropical storm frequency was investigated as possible driver of observed changes. Generally the occurrence of tropical storms not only increases the seasonal precipitation total, but it also tends to increase the proportion of both precipitation input and runoff output to and from the basin in just a few days, thereby amplifying the essential non-linear nature of the relationship between precipitation and runoff, which is
generally linearized by taking seasonal totals. Application of a 500 km radius of influence
(Barlow, 2011; Brun & Barros, 2014; Zick & Matyas, 2015) around North Atlantic tropical
storm track data (IBTrACS by Knapp et al. 2010) revealed that there has been a significant
increase in the number of tropical storms exerting a potential influence on the basins before and
after the breaks identified by the Pettitt test. Considering all seasons, sixteen of the eighteen
basins intersected more frequently with the “circle of influence” around tropical storms after the
break in the time series. The average increase in frequency was 21%. Klotzbach et al. (2015)
show that the number of Atlantic hurricanes has decreased since 2012. If only data up to year
2011 (1952-2011) are considered all eighteen basins report increased frequencies of potential
interactions with tropical storms averaging 36% more. Considering the JJA and SON seasons as
the main hurricane season twelve of the eighteen basins get more hurricanes after the break. On
average all the basins get hit 18% more often during JJA and SON after the break when the full
record is included. If the record is shortened, excluding 2012-2014, the basins get hit by
hurricanes on average 41% more often (Figure 3-8.).

An increase in the number of tropical storms in the North Atlantic basin, following a
change in the phase of the Atlantic Multidecadal Oscillation (AMO) in 1995, has been reported
by Goldenberg et al. (2001) and Webster et al. (2005). The warmer phase of the AMO
constitutes more favorable conditions for tropical cyclone development, while the cold phase has
the opposite effect. The influence of the AMO is most obvious when studying landfalls along the
U.S. east coast and in the Caribbean, and less so around the Gulf of Mexico, where the sea
surface temperatures do not show the same type of interannual or interdecadal variability as
those in the North Atlantic (Goldenberg et al., 2001). During the warm phase of the AMO, when
tropical storms are more likely to form and grow stronger, there is also a higher risk of them
moving further inland, as a stronger tropical storm survives longer over land than a weak. The *difference* in storm impact frequency is therefore larger inland than in coastal areas (Figure 3-8.), even though the coastal areas always get hit by a higher number of tropical storms than the more continental basins.

Xie et al (2005) applied a Principal Components Analysis to a hurricane track density function, confirming the findings of Goldenberg et al. (2001) as the first mode of variability was significantly correlated with the AMO as well as El Niño-Southern Oscillation. The second Principal Component on the other hand showed significant correlation with the AMO, Arctic Oscillation and North Atlantic Oscillation; hence the AMO is identified as one of the strongest drivers of tropical storm variability. The AMO returned to its cool phase in 2012, which has led to a decrease in tropical storm activity (Klotzbach et al. 2015; McCarty et al. 2015). This is reflected as a distinct decrease in the number of tropical storms impacting the study basins during the last two years of the historical time record. In the SON seasons of 2013 and 2014 no storms came within 500 km of the basins – an occurrence unique in observations of consecutive years throughout the current historic data.

**Climate Change**

Groisman et al. (2001) found a weak declining trend in the number of days with snow cover in the Southeast during the last century, which might be an indicator of warmer temperatures. A Mann-Kendall test is performed on seasonal PRISM mean temperature data to identify increased temperatures, which would explain changes in RCs as a result of changes in hydrologic storage (snow and snowmelt) during DJF and MAM and changes in evapotranspiration losses. No significant temperature change trends appeared in SON, DJF and MAM, while a couple of basins in the southeastern section of the study region show a warming trend through JJA. These findings concur with the literature, which identifies the Southeast as part of what Pan (2004)
termed “the Warming Hole”, - a region of the U.S. that show less, or no, warming connected to climate change than the rest of the country. Later studies confirm that the Southeast thus far is one of the few places where an obvious warming temperature trend related to climate change cannot be detected (Misra et al., 2012; Portmann et al., 2009).

**Urbanization and Land Cover Change**

The study region underwent substantial land cover changes during the last century. The natural forest cover was largely denuded for agriculture in the late 19th and early 20th centuries. Following the Great Depression of the 1930s much of the farmland was abandoned and forest returned through natural restoration, silviculture and a lucrative forestry industry. Today some areas are experiencing rapid urbanization and have done so for several decades (Liu, 2011; Sampson, 2004). Despite the fact that the watersheds included in this analysis are supposedly minimally affected by man in terms of flow regulation structures, it must be recognized that the basin landscapes may have been modified during the time period studied. Changes in land cover could influence the translation of precipitation to runoff as urbanization typically involves removal of vegetation and the installation of impervious surfaces and storm drains. Hence, in the absence of any remedial measures increasing runoff and decreasing infiltration, transpiration and interception might be expected. Further such changes can alter local and regional surface energy fluxes through changed albedos and decreased latent heat exchange, which in turn affect evapotranspiration. However, most of these basins are sufficiently large that the urbanization still only constitutes a small portion of the basin area, and the requirement that they be free of major flow regulation also increases the probability of occupying more rural settings. Moreover, if urbanization would be the answer to why the precipitation-runoff slopes of the study region are changing one would expect to see the similar changes all seasons. No such pattern emerges.
Conclusion
This study finds that there has been a significant change in the hydroclimatology of the Southeast U.S. during the last half-century. A general pattern of increased streamflow per unit of precipitation occurs, especially in JJA-SON, but also in DJF, indicating decreased precipitation storage. Changed temperatures, urbanization and land cover change, and increased hurricane generated precipitation were factors analyzed as potential drivers of the observed change in the precipitation-runoff relationship. Considering the timing of both the seasonal and long-term observed changes, and the fact that the frequency at which the basins are hit by hurricanes increase post observed breaks, hurricane generated precipitation is concluded to be the major driver of the changed hydroclimatology of the southeast US. It is however important to note that the changed frequency in land falling hurricanes is tightly linked with the phase of the Atlantic Multidecadal Oscillation, which hence is a useful indicator in long-term water resource forecasting in the region.
Table 3-1. Resulting P-values from the Kolmogorov-Smirnov test comparing the cumulative distributions in breaks identified in the seasonal series of runoff coefficients by the Pettitt test. Significant differences at 0.05 level are bolded.

<table>
<thead>
<tr>
<th></th>
<th>DJF</th>
<th>MAM</th>
<th>JJA</th>
<th>SON</th>
</tr>
</thead>
<tbody>
<tr>
<td>DJF</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>MAM</td>
<td>0.016</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>JJA</td>
<td>0.43</td>
<td>0.044</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SON</td>
<td>0.64</td>
<td>0.016</td>
<td>0.47</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 3-1. Basins included in the analysis. The location of the USGS gauging stations are indicated by black dots. The basin sizes in the table to the right are defined using a DEM.
Figure 3-2. Spatial patterns of estimated seasonal RCs across the study area.
Figure 3-3. Annual standardized monthly A) maximum, B) median and C) minimum flows averaged over the eighteen study basins.
Figure 3-4. Difference in the slope between precipitation and streamflow (RCs) before and after the identified breaks in seasonal relationships.
Figure 3-5. Difference in the seasonal RCs before and after the identified breaks. Black arrows represent a positive difference, indicating increased runoff per unit of precipitation after the identified break. Grey arrows represent decreased runoff. The magnitude of the change is indicated by the length of the arrows.
Figure 3-6. Visual depiction of identified break years. The pie charts are filled according to their break years, a key is given on the left side of the figure. Basins where no significant break was identified are represented with a black dot. The most uniform break year pattern emerges in SON, which is also the only season in which all basins show significant breaks, while the other seasons show more regional variations.
Figure 3-7. Cumulative distribution of break years. Basins typically break the earliest in MAM and the latest in JJA. The break in 1970-71 identified by McCabe & Wolock (2002) is marked with a line and an asterisk.
Figure 3-8. Comparisons of how frequently tropical cyclone tracks and zones of influence intersect with the basins before and after the identified breaks in the time series. A) includes the full time series and the full North Atlantic hurricane season and is considered “the base case”. In this record the more continental basins show an increase in hurricane frequency, while the coastal show a slight decrease. The map in B) shows the 1952-2011 (excluding the three last years after the AMO phase change) record relative to the base case.
CHAPTER 4
HYDROPOWER IN THE SOUTHEAST: A HYDROCLIMATOLOGICAL PERSPECTIVE

Water allocation for hydropower in the Southeast competes with several conflicting interest for the region’s limited water resources. This competition could be expected to become more severe in the face of burgeoning demands from an increasing population for domestic, industrial, and agricultural consumption, contemporary to a growth in interest in cheap renewable energy sources.

All these societal changes are to be played out against the backdrop of a climate that is facing extended periods of drought, such as 1986-1988, 1998-2002 and 2006-2009 (Pedersen et al. 2012, Seager et al. 2009) and excess precipitation brought by warm El Niño-Southern Oscillation (ENSO) events (Johnson et al., 2013; Dracup & Kahya, 1994; Kahya & Dracup, 1993) or tropical storms (Brun & Barros, 2014; Ortegren & Maxwell, 2014).

The Southeast is a region not typically associated with hydropower, but three out of the nation’s top 10 hydropower-producing states are located within: Alabama, North Carolina and Tennessee (National Hydropower Association, 2013). As seen in Figure 4-1., the three watersheds included in the analysis drain Alabama, Georgia and minor parts of North Carolina, South Carolina and Tennessee. They contain multiple hydroelectric dams, of which a portion is managed by the Army Corps of Engineers (ACE). The ACE dams commenced operation between the early 1950s-mid 1970s and are operated to provide peak power, i.e. meet peaks in demand with short notice and operate during parts of the day when the demand typically is the highest. On average hydropower produces approximately 11% of the regions’ electricity, but it exhibits great year-to-year variability (Figure 4-2.).

This paper examines how hydropower in the Southeast responds to large scale climate drivers (teleconnections). Through this analysis we add to the research on the utility of including
teleconnections in forecasting of hydropower and water resources. Recognition of teleconnections as important drivers of water availability and market behavior could benefit hydropower production, and would allow it to make up a larger proportion of the energy mix in the Southeast. This could lead to the two-fold benefits for the U.S. as a country as more hydroelectric production by the ACE leads to increased revenue for the Department of the Treasury. At the same time increased hydroelectric production would allow decreases in the production of electricity using traditional resources such as oil, coal and gas, which would benefit the health of both people and the environment.

Linking hydropower production to large-scale atmospheric drivers (teleconnections) is a new field of study in the Southeast, but similar studies have been completed elsewhere. The NAO has been identified as the dominant driver of the hydropower in Scandinavia (Cherry et al. 2005, Engström and Uvo, 2015), and a valuable index for the electricity companies to monitor to have a good idea of expected water resources. Poveda et al. (2003) found that if the phase of ENSO would have been considered, the country of Colombia could have saved $10 million/year in energy costs between the years of 1977-1994. Hamlet et al. (2002) suggest that large economic gains can be made if teleconnections were to be included in the water resource forecasting of the Columbia River in the Pacific Northwest of the United States. If ENSO and the Pacific Decadal Oscillation were to be included in the water resource forecasting the annual electricity production could be increased by 9.6% (Hamlet et al. 2002). Table 1-1. provides an overview of what a 9.6% increase of hydropower production would mean for the ACE dams in the Southeast.

**Data and Methods**

The motivation for the inclusion of teleconnections included in this analysis are based on the comprehensive overviews of teleconnections influencing the hydrology of the Southeast
described by Labosier and Quiring (2013) and Engström and Waylen (2017). The influence of
ENSO in the Southeast is well documented (Kahya & Dracup, 1993, Dracup & Kahya, 1994,
Kunkel et al. 2013, Labosier & Quiring, 2013). Typically the warm phase brings increased
winter precipitation to the west part of the region due to strong south westerly winds over the
Gulf of Mexico. This pattern of increased precipitation is less marked along the east coast as the
strong southwesterly flow tends to keep moisture-bringing tropical cyclones off-shore,
amplifying the tendency for greater vertical shear over the North Atlantic basin to produce fewer
such events. The cold phase of ENSO is generally associated with drier conditions. In this study
the Bivariate ENSO Timeseries (BEST), a combination of the Niño 3.4 index and the Southern
Oscillation Index (SOI), is used to represent ENSO (Smith and Sardeshmukh 2000).

Due to its cycle of variability being 60-80 years, the Atlantic Multidecadal Oscillation
(AMO) has a longer-lasting influence on the hydroclimate of the Southeast relative to other
teleconnections. Its positive phase brings drier conditions (Tootle et al. 2005, Johnson et al.
2013), especially during the summer (Enfield et al. 2001, Ortegren et al. 2011, 2014), while the
negative phase is associated with increased precipitation and streamflow. The AMO index
utilized here is the smoothed version of the Kaplan SST V2 data (Kaplan et al. 1998; Enfield et
al. 2001; National Oceanographic and Atmospheric Administration, 2002).

There is limited research showing linkages between the NAO, precipitation and
streamflow in the study area. Coleman and Budikova (2013) conclude that its influence is
strongest in the Northeastern United States, but positive relationships can also be found in
summer streamflow in parts of the Southeast. Surface temperatures, which play a key role in
determining the type of precipitation (Kang et al. 2016) and controlling evapotranspiration, have
been shown to be associated with both the NAO and ENSO throughout the Southeast (Rogers,
1984; Katz et al. 2003). In this study we use the NAO index as it is defined by Barnston and Livezey (1987).

Katz et al (2003) also found significant relationships between the SO, NAO, and Pacific-North American pattern (PNA) and the wintertime precipitation across the Southeast. The positive link between the PNA and the wintertime snowfall in the Appalachians identified by Serreze et al. (1998) highlights the need for time lags when analyzing the effect of teleconnections on water resources in the Southeast. In this study we use the PNA index as it is defined by Barnston and Livezey (1987).

Hydrologic data consists of seasonal water availability (reservoir inflow and outflow) and hydroelectric power generation for eight dams managed by the ACE. The dams are located in three different watersheds: Alabama–Coosa–Tallapoosa (ACT, three dams), Apalachicola–Chattahoochee–Flint (ACF, three dams) and Savannah River (SAV, two dams) (Figure 4-1.). As dam operation downstream relies heavily on discharge from upstream reservoirs the analysis is made at the watershed level, including all ACE hydroelectric dams on the river. Plants in which water is sometimes pumped back into the reservoir (so called pumped storage) to meet peak demands excluded from the analysis as the re-use of the water resource is less dependent on water resource availability and the relationship with production is instead mainly driven by demand.

The original data contains some extreme outliers that are excluded, as they tend to distort the further statistical analysis. Hurricane related precipitation data are obtained from Zhou & Matyas (2017), however, exceptionally high seasonal flows couldn’t be linked to tropical cyclones alone. Instead outliers are defined as being more than two standard deviations from the mean inflow (the standard deviation was inflated due to a few extreme outliers and therefore two
standard deviations are used instead of the more common practice of using three). Seasonal inflow and hydropower production data are sorted depending on the phase of the various teleconnections. The variables are associated with a teleconnection if they occur in the upper tercile of the teleconnection index range included in this analysis (1988-2013). Teleconnection interactions are also considered as, depending on season and teleconnection, the teleconnections sometimes amplify or cancel out the effect of each other (Enfield et al. 2001, Tootle et al. 2005). To account for interactions between teleconnections, the analysis includes all inflow and hydropower production data that match the set criteria (ex. positive AMO and positive NAO coincide).

A total 45 different combinations of teleconnections are considered. Due to the rare occurrence of certain teleconnections, 31 teleconnections and combinations are entered into the analysis. T-tests determine if the seasonal inflow and/or hydropower production that are influenced by any of the teleconnections are significantly different from those that aren’t influenced by that same teleconnection. A t-test is chosen as it allows the populations to be analyzed separately, hence acknowledging that the variables might not respond the same way under teleconnection influence.

Results and Discussion

Potential Production

Figure 4-3. shows the seasonal average inflow and production for the three basins over the study period. Production is strongly associated with inflow in the ACF and SAV basins, indicating that long-term storage is limited. This observation is further confirmed by a simpler analysis of outflow data (not displayed). In the ACT basin MAM and DJF production does not correspond as well to the inflow. Maximum monthly potential production is shown as an insert in each diagram of Figure 4-3. This number is computed as the product of the installed capacity
(MW) and the number of hours in a 30 day month. At most the ACF basin produces 56% of its potential monthly production, the ACT basin 57% and SAV 90%. Figure 4-3a suggests the ACF basin production is closely linked to inflow. Based on these data, it appears that a lack of sufficient water resource may be a contributing factor, the maximum production only reaches 56% of its potential, i.e. there is overcapacity in the dams. The ACT basin plot (Figure 4-3b) suggests that the production is capped in some way around 110,000 MWh, despite its maximum potential production of 185,000 MWh. There is also significant variability in production during the periods of higher inflow, indicating that the inflow-production relationship at these volumes is far more complex than what is seen at lower flow volumes and in the other basins. These high inflows occur mainly in the winter and spring. In the ACF and SAV basins the electricity to inflow ratio is slightly higher during the summer and fall, indicating that more electricity is produced than with equivalent inflow volumes during the winter and spring. This might be an indicator of short-term storage during the cooler part of the year and/or higher electricity demand during the summer and fall seasons.

Two different approaches are taken to estimate potential production based on inflow for the ACT basin. The first, more conservative approach, applies the average summer inflow-production ratio onto the inflow. Considering that the powerplants may have to close down for scheduled maintenance, etc. a max powerplant availability of 90% is applied. This modification leads to a 46% increase in annual production. The greatest changes are found in the winter and spring seasons, when production would increase by 82%. A second, more optimistic approach uses the ten highest inflow-production ratios and applies those to the ACT inflow. This results in a 67% increase in annual production, and a 101% and 99% increases respectively in winter and spring seasons. In both approaches, the ACT basin reaches 90% of maximum potential
production multiples times, an indication that if the water volumes alone controlled production there would be room for additional installed capacity.

**Influence of the Teleconnections**

Nineteen out of the 38 teleconnections and their combinations significantly altered inflow and/or hydropower production.

ENSO, identified as one of the main driver of hydrologic variability in the region, significantly alters both inflow and hydropower production in its cool phase, while a warm phase signal only appears to have an impact in the ACT basin (Figure 4-4.).

Results indicate that the influence of teleconnections is sometimes lagged, for example Figure 4-5. illustrates how ENSO phases in MAM significantly change inflow and hydropower production in following JJA in the SAV basin.

The interaction of teleconnections sometimes leads to amplified responses in the basins. Figure 4-6. indicates that neither warm phase AMO nor cool phase PNA alone, exert any significant influence on the SAV summer inflow or production, however when they coincide both inflow and the production decreases significantly.

Figure 4-7. shows examples of different responses in inflow and hydropower production, indicating that management is not always linked to water availability. Significantly higher hydropower production, despite lack of significant change in inflow, as depicted in Figure 4-7a, could be an indication that stored water resources are used to meet the market demands, while Figure 4-7b indicates significantly lower hydropower production, despite abundant water availability. An analysis of inflow and total outflow through the basin does not indicate any long-term storage.

The heat maps in Figure 4-8. summarize the influence of the nineteen significant teleconnections and combinations per basin. The strongest influence across all basins and all
seasons of inflow and hydropower production is brought by the wintertime cold phase ENSO, which significantly lowers both inflow and production (top row of Figure 4-8.). Cold phase ENSO events occurring in the fall, have the second strongest influence, bringing lower inflow and production throughout the fall and winter. Fall cold phase events also affects the summer production (but not inflow), which might be an indicator that water management operates the powerplants to conserve water following information on expected dry conditions from the National Weather Service. The third strongest influence and most pervasive is brought by the combination of a year of warm phase AMO (AMO Y+) and a year with negative NAO (NAO Y-), conditions that bring lower inflow and production during the cold seasons and higher rates in the summer, a response that is particularly pronounced in the ACT basin. As can be seen in Figure 4-8, many of the teleconnections show up in the inflow and production record with a lagged response. Good examples are the influence of springtime ENSO events on the SAV basin as well as the coupled influence of summertime AMO and cold phase ENSO in the ACF basin. This kind of lagged behavior is useful in terms of water resources planning. Figure 4-9. summarizes the heat maps of Figure 4-8., giving an overview of the overall influence of the teleconnection on the region.

Discussion

Results show that the ACF and ACT basins in general behave more similar to each other than the SAV basin. This can be explained by the geography of the basins, both the ACF and the ACT originate from the southern end of the Appalachian Mountains and run southwards, draining into the Gulf of Mexico. SAV on the other hand drains from the southeastern flank of the Appalachians and discharge into the Atlantic Ocean. It is hence more affected by easterly atmospheric flows than ACF and ACT that are strongly influenced by south-westerly winds, regulating the northwards transport of moisture from the Gulf of Mexico. In some cases, west-
east geographical trends can be seen in the inflow and hydropower production response to the teleconnections in Figure 4-8. One example is the influence of springtime warm phase ENSO on the basins (row 7 in Figure 4-8). The teleconnection phase brings slightly higher inflow and production to the ACT basin, the response is somewhat stronger in the ACF basin and the strongest and longest lasting effect is found in the SAV basin that is furthest to the east.

Conversations with ACE Water Managers in the region revealed that despite general knowledge of teleconnections, they are not accounted for in water resources planning. Instead, production planning is based on seven-day weather forecasts, which are updated daily. Overall monthly production goals are set annually by the Southeastern Power Administration, that sell ACE hydropower electricity, in response to anticipated demand from their customers. In this paper we find that, disregarding other constraints, hydropower production at the plants included in this analysis could be increased. This is based on insights from ACE personnel who stated that even during non-flood conditions water is sometimes let through the spillways instead of going through the turbines. Data on how much water is discharged like this, with what frequency it happens, and how much potential electricity is lost is not available.

Even without considering the influence of teleconnections the powerplants in the ACT basin could significantly increase their production, providing the region with cleaner energy and the nation with additional revenues. The way the ACT basin behaves at the moment, there seems to be a “cap” of some sort in the production. Splitting Figure 4-3a up by its three sub-basins (powerplants) reveals that the production of the first powerplant on the river (Allatoona) has a similar response to inflow as the ACF and SAV basins (high inflow= high production). However, the two downstream powerplants R.F. Henry and Millers Ferry (that the authors note have six non-federal dams in between them and Allatoona) show a very different behavior as
production at these dams do not peak at high inflows, but instead production decreases at times
of high inflows (Figure 4-10.). This kind of response cannot be explained by the power curve of
the turbine (Sammartano et al. 2014) but is possibly due to management strategies. The author
speculates that the decrease in production at high inflows might be due to the monthly
production goals set by the Southeast Power Administration. When there are ample water
resources throughout the entire basin the set production goal is met by maximizing production at
the uppermost dam and capping it downstream once the set goal is achieved. One could argue
that the additional electricity that could be produced could still be sold to bring extra income to
the Department of Treasury and decrease the use of fossil fuels. However, there are thirteen
hydropower dams in the ACT basin (U.S. Army Corps of Engineers, 2017), hence at high flows
the total hydropower output is high and might exceed market electricity demand, i.e. there might
not be need for additional electricity and since reservoir storage is limited, the water is
discharged to prevent flooding and/or dam failure. Following along the same line of high water
levels and high hydropower production throughout the basin, it is possible that the limiting factor
is not the market, but rather the electric grid that might not have the capacity of transporting
simultaneous maximized production from all dams in the basin, and hence production levels are
decreased downstream.

Teleconnections also show strong linkage to inflow and/or hydropower production during
parts of the year. Acknowledging this linkage would allow water managers to make more long-
term plans for the water resources and would also allow hydropower to become a more
competitive electricity alternative in this region.

**Conclusion**

Inflow and production analysis revealed that based on water resource availability,
hydropower production in the ACT basin could be increased 46-67% per year. For the ACF
basin, available water resources was the limiting factor for increased hydropower production. The SAV basin reaches 90% of its maximum production.

The teleconnections AMO, ENSO, NAO and PNA proved to be significantly linked to variations in inflow to hydropower reservoirs as well as hydropower production in the Southeast. The strongest influence is asserted by wintertime and fall cold phase ENSO events, that bring significantly drier conditions to all basins in the study area. The influence of El Niño events was more limited but still significant. Considering teleconnection interactions as well as time lags proved useful.

The findings highlight the potential to incorporate teleconnections in water resources planning and forecasting. What teleconnections to consider varies by basin and season, but the AMO, ENSO, NAO and PNA are all significantly influencing the water resources of the Southeast. Teleconnections have potential to inform water resource forecasting and improve the efficiency of hydropower production.
Figure 4-1. Overview of the basins and hydroelectric dams included in the analysis. Pumped storage dams managed by the ACE are not included in the analysis but displayed here in lighter colors. For readers unfamiliar with the region a small scale map in the upper left corner shows the location of the study area.
Figure 4-2. Annual production anomaly in percent around the mean. In an average year the eight dams included in this analysis produce 2,500 GWh of electricity, enough to supply over 200,000 households with their total electricity needs.
Figure 4-3. Plots of average seasonal inflow and hydropower production 1988-2013 in geographical order (west to east) for the a) ACT, b) ACF, and c) SAV basins. Seasons are represented by different colored dots and the maximum potential monthly production is noted on the right-hand side of each diagram.
Figure 4-4. Plots showing the influence of ENSO events. Inflow is displayed on the x-axis and hydropower production on the y-axis. ENSO years of desired phase are indicated as filled dots. The upper row shows the influence of warm phase ENSO in the A) ACT basin, B) ACF basin, and C) SAV basin. The bottom row shows the influence of cold phase ENSO on the D) ACT basin, E) ACF basin, and F) SAV basin. Influence leading to significantly different behavior is highlighted with a red circle.
Figure 4-5. Example of lagged response. SAV summer inflow and hydropower production is significantly altered by both A) La Niña, and B) El Niño, spring events.

Figure 4-6. Example of how teleconnection interaction leads to amplified influences. Alone the A) annual (Y) positive phase of AMO and B) negative phase of PNA do not change the summertime behavior of the SAV basin, but C) shows that when they coincide inflow and hydropower production decrease significantly.
Figure 4-7. Two examples form the ACT basin where only one of the variables is significantly changed under the influence of teleconnections. In plot A) production is increased, despite lack of significantly higher inflow. In plot B) production is significantly low, despite ample water resources.
Figure 4-8. Heat maps giving an overview of the seasonal influence of the nineteen teleconnections on the inflow and hydropower production of the three basins. Every row represents a teleconnection phase or combination and its season, as displayed to the left. The columns represent the seasonal inflow and hydropower production. The heat maps are displayed in the geographical order of the basins, from west to east for easier identification of spatial patterns. A key to the colors is shown to the right.
Figure 4-9. Heat map showing the count of basins influenced by the teleconnections.
Figure 4-10. Drawings of generalized relationship between monthly reservoir inflow and hydropower production at the three ACT basins. Actual production is marked with an A, potential production with a P.
CHAPTER 5
SUMMARY AND CONCLUSIONS

For decades the water resources in the Southeast has been a topic of controversy. The water should not only satisfy natural ecosystems, but also the drinking water needs of growing urban areas, agricultural needs, and in the case of the Southeast, hydroelectric production. The hydroclimate in the region exhibits great variability, giving rise to additional political tensions in times of drought as well as floods. Through the studies presented in this dissertation, some light is shed on the drivers of natural variability of precipitation, runoff and hydropower production. The analyses are made on a seasonal basis, recognizing that influences and natural processes might vary throughout the year, as does the demand for the water resource. Knowledge of influential hydroclimatological drivers and the relationship between precipitation and runoff are some of the most fundamental ingredients for successful water resource planning and management.

The first study, presented in Chapter 1, confirms the significant influence of various teleconnections upon the hydroclimate of the Southeast. The most significant external contributors to variability in the region are the ocean-atmosphere based teleconnections AMO and ENSO, which strongly influence the hydroclimate in the fall through spring with several months’ time lag. The atmospheric-based teleconnections AO, NAO and PNA show more sporadic influences. The findings of this paper also add to the ongoing debate on whether the AO and NAO are one or separate phenomena by showing that the teleconnections’ relative influence on the hydroclimate of the Southeast differs both in seasonal timing and the form of the influence (AO influence precipitation, NAO streamflow), suggesting that they in fact are separate phenomena. In general all teleconnection signals appear more clear in streamflow than precipitation records.
In the second study, disregarding teleconnections, a significant change to the hydrological cycle in the Southeast is identified. Results show that the relationship between precipitation and runoff has changed during the last half-century. A general pattern of increased streamflow per unit of precipitation occurs, especially in JJA-SON, but also in DJF, indicating decreased hydrological storage. Changed temperatures, urbanization and land cover change, and increased hurricane generated precipitation were factors analyzed as potential drivers of the observed change in the precipitation-runoff relationship. Considering the timing of both the seasonal and long-term observed changes, and the fact that the frequency at which the basins are hit by hurricanes increase post observed breaks, hurricane generated precipitation is concluded to be the major driver of the changed hydroclimatology of the Southeast. It is however important to note that the changed frequency in land falling hurricanes is tightly linked with the phase of the AMO, which hence is a useful indicator in long-term water resource forecasting in the region, a fact that is further confirmed by the findings of studies number one and three (Chapter 2 and 4).

Chapter 4 investigates the influence of teleconnections on the hydropower production in the Southeast. Earlier, similar, studies of other geographic regions have indicated that hydropower production could be increased if teleconnection indices are considered in the production forecast. In the current study several different linkages were established between hydropower reservoir inflow, production and teleconnections:

- In some cases a time lag is observed between the teleconnection indices and the reservoir/production response. This proves that teleconnections can be useful in seasonal forecasting.

- Considering the simultaneous phase of multiple teleconnections showed that the combined influence is sometimes stronger than that asserted by the teleconnections separately.

- Sometimes a response was found in the reservoir inflow but not in the production, and vice versa. The behavior was especially pronounced in the ACT basin.
• The decreased inflow and production associated with a cold phase ENSO is more pronounced than the increases associated with ENSO’s warm phase.

There is hence many types of existing relationships between the teleconnections and hydropower, indicating that incorporating them in forecasts could be useful. Further, it is found that based on available water resources alone, and disregarding teleconnections, the annual production of the ACT basin could be increased by up to 67%. The increased production would mainly occur during the winter and spring, as this is when high inflows are observed and the inflow-production ratio of the ATC basin decreases before reaching maximum production.

The findings highlight the potential to incorporate teleconnections in water resources planning and forecasting. What teleconnections to consider varies by basin and season, but the AMO, ENSO, NAO and PNA are all significantly influencing the water resources of the Southeast. By understanding the natural drivers that influence hydropower production, reservoir management and electricity production can be optimized. Decreasing uncertainties of future water availability and demand offer potential for further development of hydropower that may ultimately decrease dependence on non-renewable resources and energy imports.

Although the findings of this project show great potential to help improve water resource management in the Southeast, further directions include incorporating teleconnections into streamflow forecasting models. There is also potential to connect their variation to electricity pricing and possibly also the economy of the region. Water quality is also a challenge throughout the Southeast, and as teleconnections affect the water quantity, they might also indirectly influence the water quality.
LIST OF REFERENCES


Mallakpour, I., & Villarini, G. (2015). A simulation study to examine the sensitivity of the Pettitt test to detect abrupt changes in mean. *Hydrological Sciences Journal*, 1-10. DOI: 10.1080/02626667.2015.1008482


U.S Army Corps of Engineers (2013) Army Geospatial Center – National Inventory of Dams


U.S. Army Corps of Engineers (2017) “Mobile District Hydropower Projects”


BIOGRAPHICAL SKETCH

Johanna Cecilia Louise Engström is born and raised in the small fishing village Lomma, just north of Malmö, in southern Sweden. This is where she went to elementary school for nine years before she started high school, specializing in social science and business, at ProCivitas Private Gymnasium in Malmö. After high school graduation Johanna continued to study business at Lund University for one semester before moving to Florence, Italy, to study Italian.

Geography always being Johanna’s favorite subject in school and having a passion for nature, made Johanna apply to the Bachelor of Science in Physical Geography and Ecosystem Analysis at Lund University in 2006. She received her Bachelor of Science in 2009 and Master of Science in 2011. Johanna has a long ranging interest in renewable energies and during her university studies she had an internship and later on also a part-time job at E.ON Wind, Malmö, which gave her valuable insights in the opportunities and challenges associated with wind power development. During her master’s program she also got the chance to study abroad for one semester and chose to go to University of Florida. After graduating from Lund University Johanna worked for one year as a consultant for Sweco Position, Malmö, before moving to the U.S. in 2012 to start the Ph.D. program in University of Florida’s Geography Department.

Apart from doing research, Johanna has also been the instructor of Geography for a Changing World, Geography of Europe and Physical Geography at University of Florida. She has presented her research at multiple national conferences, published five peer-reviewed journal articles and taken on the role as the Geography Department’s graduate student representative. The Geography Department honored Johanna’s departmental service, teaching and academic excellence by awarding her the Ryan Poehling Award in 2015.

Johanna hopes to continue her career within the field of water, climate and renewable energies after graduation.