The changing hydroclimatology of Southeastern U.S.

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1 Abstract

The allocation of the water resources of Southeastern United States have given rise to inter-state political conflicts for decades. The limited water resource are not only required to satisfy the demand of rapidly growing urban areas, but also the power industry, recreational needs and the environment. Although water resource variability has been attributed to various teleconnections,
knowledge of long-term water resource availability is limited. In this paper historical (1952-
2014) precipitation and streamflow data from 18 basins in southeast United States are analyzed
for long-term changes in the hydroclimatology, possibly brought by urbanization, climate change
and/or changed precipitation patterns. A Pettitt test indicates a change in the precipitation-runoff
relationship in the late 1990s. After the shift, basin records indicate decreased precipitation
storage and consequently increased streamflow.

Keywords: Southeast United States; hydroclimate; hydrology; water resources

2 Introduction

Hydroclimatological variability in the southeast United States (U.S.) can be partly explained by
the phase of various teleconnections (Dracup & Kahya, 1994; Johnson et al., 2013; Kahya &
Dracup, 1993; Katz, 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 U.S. 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 southeastern part of the country (Alabama, Georgia, North Carolina, South Carolina and Tennessee), a region that thus far has been underrepresented in hydroclimatic research but struggle with water related conflicts. 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 the water of 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). 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 southeast U.S. (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 which is used to intense summer rainstorms, winter snowfall, spring floods and water related conflicts.

3 Material and methods

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

Precipitation = Runoff + Evapotranspiration +/- 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 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
Petitt’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
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 &
4 Results

Figure 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 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 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 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 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 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 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 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>
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</thead>
<tbody>
<tr>
<td>DJF</td>
<td></td>
<td>-</td>
<td>-</td>
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<tr>
<td>MAM</td>
<td>0.016</td>
<td>-</td>
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<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>
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</table>

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.

4.1 Increased precipitation

Seager et al. (2009) project a trend of increasing precipitation and evapotranspiration in the southeast U.S. 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 nonlinear 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 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 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.
4.2 Climate change

Groisman et al. (2001) found a weak declining trend in the number of days with snow cover in the southeast U.S. 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 U.S. 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 southeast U.S. 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).

4.3 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.

5 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.
6 Acknowledgements

Presenting the preliminary findings of this paper at the American Geophysical Union’s Fall Meeting in San Francisco in 2015 led to significant insights and feedback from the wider scientific community that greatly enhanced the quality of this paper. Specifically the first author would like to thank Dr. Michelle Ho for encouragement and Dr. Anna Barros for sharing insights on the hurricane climatology of the Southeast U.S.

7 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


detection for the annual stream-flow series of the Karun River at the Ahvaz hydrometric

Sampson, R. N. (2004), Southern forest: Yesterday, today, and tomorrow, in Southern Forest
Johnsen, pp. 5–13, U.S. Dept. of Agric. For. Serv. S. Res. Station, Asheville, N. C.


causes, variability over the last millennium, and the potential for future hydroclimate
change*. *Journal of Climate, 22*(19), 5021-5045. DOI: 10.1175/2009JCLI2683.1

teleconnections. *River research and applications, 28*(5), 630-636. DOI: 10.1002/rra.1473

change. *Science, 347*(6225), 953-954. DOI: 10.1126/science.1261824

Geological Survey Streamflow Data Set for the United States for the study of climatic variation,
Washington, DC.


Figure Captions

Figure 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 2. Spatial patterns of estimated seasonal RCs across the study area.

Figure 3. Annual standardized monthly maximum, median and minimum flows averaged over the eighteen study basins.

Figure 4. Difference in the slope between precipitation and streamflow (RCs) before and after the identified breaks in seasonal relationships.

Figure 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 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 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 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. The map to the left 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 right map shows the 1952-2011 (excluding the three last years after the AMO phase change) record relative to the base case.
Figure 8
Highlights

- Longterm hydroclimatological changes are identified.
- Natural basin records show decreased precipitation storage and increased runoff.
- Observed changes are most significant during the summer and fall seasons.
- Possible drivers of observed hydroclimatological changes are evaluated.