7-16-2008

Improving Summer Drought Prediction in the Apalachicola-Chattahoochee- Flint River Basin with Empirical Downscaling

John Robert Dean

IMPROVING SUMMER DROUGHT PREDICTION IN THE APALACHICOLA-CHATTAHOOCHEE-FLINT RIVER BASIN WITH EMPIRICAL DOWNSCALING

by

JOHN R. DEAN

Under the direction of Dr. Jeremy E. Diem

ABSTRACT

The Georgia General Assembly, like many states, has enacted pre-defined, comprehensive, drought-mitigation apparatus, but they need rainfall outlooks. Global circulation models (GCMs) provide rainfall outlooks, but they are too spatially course for jurisdictional impact assessment. To wed these efforts, spatially averaged, time-smoothed, daily precipitation observations from the National Weather Service cooperative network are fitted to eight points of 700 mbar atmospheric data from the NCEP/NCAR Reanalysis Project for climate downscaling and drought prediction in the Apalachicola-Chattahoochee-Flint (ACF) river basin. The domain is regionalized with a factor analysis to create specialized models. All models complied well with mathematical assumptions, though the residuals were somewhat skewed and flattened. All models had an R-squared > 0.2. The models revealed map points to the south to be especially influential. A leave-one-out cross-validation showed the models to be unbiased with a percent error of < 20%. Atmospheric parameters are estimated for 2008–2011 with GCMs and empirical extrapolations. The transfer function was invoked on both these data sets for drought predictions. All models and data indicate drought especially for 2010 and especially in the south.

INDEX WORDS: Empirical downscaling, Global circulation model, Synoptic climatology, Apalachicola-Chattahoochee-Flint river basin, Drought prediction, Water resource management.

IMPROVING SUMMER DROUGHT PREDICTION IN THE APALACHICOLA-CHATTAHOOCHEE-FLINT RIVER BASIN WITH EMPIRICAL DOWNSCALING

BY

JOHN R. DEAN

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Arts

in the College of Arts and Sciences

Georgia State University

2008

IMPROVING SUMMER DROUGHT PREDICTION IN THE APALACHICOLA-CHATTAHOOCHEE-FLINT RIVER BASIN WITH EMPIRICAL DOWNSCALING

by

John R. Dean

Committee Chair: Dr. Jeremy E. Diem

Committee: Dr. John W. Matthews
Dr. Jeremy W. Crampton

Electronic Version Approved:

Office of Graduate Studies
College of Arts and Sciences
Georgia State University
August 2008

ACKNOWLEDEMENTS

I would like to thank my wife Sara Dean for making this project possible and my son Sam Dean for his unending patience and resignation.

TABLE OF CONTENTS

TABLES

FIGURES

ABBREVIATIONS

ACF	Apalachicola-Chattahoochee-Flint river basin
CD	Climate Division
GCM	Global Circulation Model or Global Climate Model
FRDPA	Flint River Drought Protection Act
GDMP	Georgia Drought Managament Plan
GIS	Geographic Information System
EPA	Environmental Protection Agency (Federal)
EPD	Environmental Protection Division (Georgia)
ESRI	Environmental Systems Research Institute
IPCC	Intergovernmental Panel on Climate Change (4th assessment)
NCEP/NCAR	National Center for Environmental Prediction – Atmospheric Research
NCDC	National Climatic Data Center
NNDC	NOAA National Data Center
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
(M)PDSI	(Modified) Palmer Drought Severity Index
PCA	Principal Components Analysis
SPI	Standardized Precipitation Index
USACE	United States Army Corps of Engineers
VIF	Variance Inflation Factor

INTRODUCTION

1.1 Purpose

This is an applied research project using the previously developed tools of climate downscaling for drought forecasting in the Apalachicola-Chattahoochee-Flint (ACF) river basin in the face of increased societal demand for water and possible climate change. Raw global climate models are deficient due to scale and precision limitations, but downscaling can provide sub-grid prediction skill. There have been efforts to forecast drought in the ACF Basin such as by tailoring output from the Climate Prediction Center (Steinemann 2006), but none have employed a direct approach of downscaling global climate models. This work demonstrates how precipitation predictions can be improved over raw model output with climate downscaling.

1.2 Concept of Drought

There are varying ways to assess drought severity throughout the world because different places have different dependencies and expectations for water availability (see Wilhite and Buchanan-Smith 2005). A universal definition of drought is elusive, yet there are some very thoughtful attempts. Drought can be thought of as a catastrophic non-event (Weber and Nkemdirim 1998). Redmond (2002) comments, ". . . a system is in drought when supply does not meet demand." There are generally four categories that climatologists use to discuss drought: (a) meteorological drought, which is purely rainfall deficiency, (b) hydrologic drought, which considers stream flow, reservoir, and ground water levels, (c) socioeconomic drought, which is a shortage for some group or activity, and (d) agricultural drought, which occurs when plants

struggle to draw water from the ground fast enough to meet potential evapotranspiration (see Keyantash and Dracup 2002).

1.3 Issue Overview

It is axiomatic that you are less vulnerable if you know something is coming. Water resource managers in the Apalachicola-Chattahoochee-Flint river basin (ACF) need a sentinel to warn them of impending socioeconomic drought. Redmond (2002) comments, “A set of early warning indicators is needed to alert us that societal adjustments may be needed”. As in many parts of the country, drought management history in the ACF basin has been one of reaction rather than proaction. Nationwide, drought management has historically been crisis management, “hastily prepared and executed during the peak of drought severity with little effect on impact” (Wilhite 1997). Policy-makers increasingly, however, view this as a type of subsidy for unsustainable behavior. They emphasize impact mitigation through proactive water conservation measures rather than emergency relief. Drought is a creeping phenomenon, and there is always opportunity to brace for the oncoming effects.

One possible reason for the inattentiveness to drought forecasting by ACF water resource managers is that the spring is wet with wet soil conditions. This typically does not evoke foreboding feelings of drought even as rainfall deficits accrue, however, spring rainfall deficit is a precursor to summer drought as the sun angle increases and environmental conditions feed back with the atmosphere circulation. Water resource managers have paid little mind to spring rainfall deficits, preferring instead to react to receding, summer reservoir pools. A better approach is to forecast drought years in advance.

The Georgia General Assembly has recently responded to the need for drought impact mitigation with urban and agricultural conservation protocols. They are most effective, however, with a lead-time: particularly with the agricultural protocols that rely on crop suspension and irrigation abatement. Georgia has considerable coverage of arable land, close to markets and under considerable production pressure, but certain soils and row crops are irrigation-intensive. These can be taken out of production if water shortages are anticipated.

The current political and socioeconomic backdrop has created a need for drought forecasting. In this work, the approach to the problem falls under the category of synoptic climatology: a research field that measures and understands the relationship between circulation and environment. There are other branches of climatology that address drought, such as paleoclimatology, and other academic disciplines such as geography, geology, agriculture, anthropology, and history that have their own approaches towards drought.

1.4 Global Circulation Models

Most people are familiar with numerical weather predictions from meteorologists. These are from deterministic and dynamic models using codified laws of nature to replicate the troposphere and its processes: such as the Equation of State and Newton's Laws of Motion. They forecast the weather up to a week in advance. Climate models are different from meteorological models in that they consider the average thermodynamic and hydrodynamic statistical relationships of the atmosphere, soil, snow, ice, sea, orbital oscillations and radiation balance for the entire earth system for decades in advance. All climate models are called general circulation models or global climate models: interchangeably abbreviated GCMs.

GCMs are too course in spatial resolution to be of much use for drought prediction in small areas like the ACF basin. Randall et al. (2007, 596) list current GCM properties and show that grid cells tend to be larger than 2º latitude by 2º longitude. The ACF Basin is much smaller than this, and it is inappropriate to make inferences from larger scale forecasts. Furthermore, if cells were created smaller, the accuracy of the output would be degraded because the precision does not exist in the underlying functions. Moreover, cells typically collocate poorly with river basins, complicating uncertainty; indeed, the 2º latitude by 2.5º longitude scheme from the Geophysical Fluid Dynamics Laboratory (fig. 1) corresponds very poorly to the ACF basin. Hewitson and Crane (1996) offer a cogent discussion of how GCM hydrological skill decreases with finer-scale production: in direct opposition to societal needs.

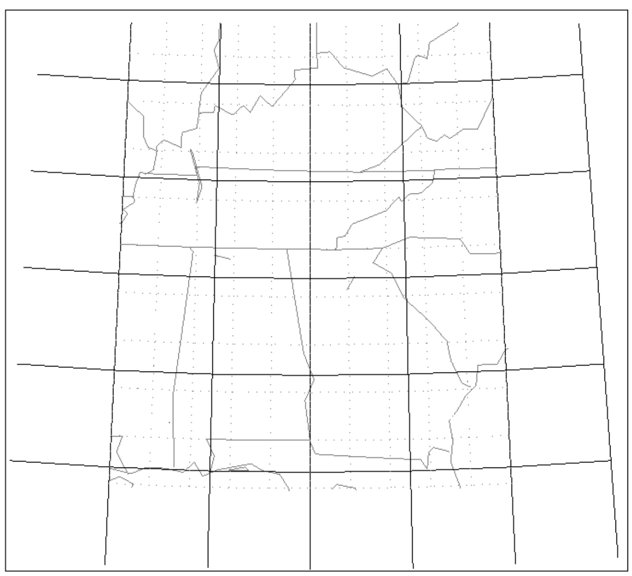


Figure 1. 2º by 2.5º grid scheme for Geophysical Fluid Dynamics Laboratory's global CM2.1 model.

1.5 Solving the Scale Problem

Interrelationship across scale is not a new research problem in geography. Geography offers various solutions to transform large-scale data to small-scale uses, and for GCMs, the remedy is climate downscaling. All climate downscaling approaches infuse extra climate information to sharpen GCMs for sub-grid prediction skill (see Hewitson and Crane 1996; Crane and Hewitson 1998; Yarnal et al. 2001). Downscaling in the ACF Basin will enable water resource managers to interpret what general circulation models mean in terms of the hydrologic impact on their jurisdiction.

1.6 Two Types of Downscaling

General circulation models are increasingly skilled at predicting large-scale circulation patterns, but skill levels decrease when drilled down for finer-scale production (Hewitson and Crane 1996). Researchers attempt to translate course global model output to finer scales with two approaches: dynamic downscaling and empirical downscaling. Dynamic downscaling—the technically superior approach—drives (nests) a regional model at mesoscale resolution within the larger model. It is based on a deterministic understanding of processes and requires additional information in the form of a detailed, quantitative study of the weather systems of that region. It incurs considerable research and computational cost. Empirical downscaling is an economical alternative (see Hewitson and Crane 1996). The additional information needed for empirical downscaling is a measurement of historical, atmosphere-environment, statistical relationships called specification that is used as a transfer function to produce smaller scale forecasts. Specification is typically measured with multiple linear regression. Studies in Norway

have shown empirical downscaling to compare well in general with dynamic downscaling, but less so when applied to warm-season precipitation (Hanssen-Bauer et al. 2003).

1.7 Specification

As outlined by Yarnal (1993, 126), specification experienced a sort of revival in the 1980s and evolved into empirical downscaling during the 1990s (Yarnal et al. 2001). Klein (1983) reported using a grid of 133 map points of 700 mbar geopotential height to predict 75 percent of the variance in temperature at U.S. cities. Using multiple linear regression, he was able to whittle the predictors down to just three to nine map points per city. Klein and Bloom (1987) regressed spatially averaged, monthly, winter precipitation onto map-point data, noting that spatial averaging provides better results. They were able to compress the domain of predictors, noting that closer points were more important and verified the importance of lower latitude points (20º–25º N). Harnack and Lanzante (1985) used a similar domain of 700 mbar heights to specify precipitation for U.S. area-averaged climate divisions, but reported less skill. Keables (1988) used a 5º by 5º grid to relate monthly 700 mbar height to a spatially averaged summer rainfall frequency in the Upper Mississippi River basin. Stahle and Cleaveland (1992) correlated Atlantic Coastal Plain growing-season rainfall to gridded points of sea-level pressure, and indeed, there are many examples of specification using surface parameters. For example, Conway, Wilby, and Jones (1996) used just three indices—wind speed, direction, and vorticity—at the surface as predictors of rainfall in the British Isles. All climate downscaling assumes that circulation-environment conditions will remain stable over time, and all results are dependent upon the integrity of the GCM being downscaled. Furthermore, climate downscaling is usually (1) better

with precipitation frequency, (2) weaker with precipitation totals, (3) better with spatial and temporal smoothing, (4) better during the cool season, and (5) optimal in the mid-latitudes.

1.8 Non-Downscaling Approaches

There has been work on drought prediction that does not employ climate downscaling: sometimes relying on persistency and positive feedback. Cancelliere et al. (2007) reported success in Sicily using the Standardized Precipitation Index to forecast monthly precipitation. Lohani and Loganathan (1997) used precipitation deficit for the first five months of the year with Palmer Drought Severity Index to forecast the possible evolution of ongoing drought in Virginia.

Anne Steinemann (2006) translates and formats output from the Center for Climate Prediction to develop an early warning drought index for the Georgia EPD. She calls it the Forecast Precipitation Index and claims, ". . . positive skill for most of the critical months and lead times . . ." The index is an early warning, drought predicton tailored for southeastern U.S. water managers. Steinemann reports that the index is used by the Georgia Department of Natural Resources to activate the Flint River Drought Protection Act. When the state invoked it in 2001 and 2002, they felt they had "called it right" each year and that the drought forecasts were primary determinants in the decision.

1.9 Research Question

Many parts of the world have been subject to empirical downscaling, and Georgia has been the subject of drought prediction and, like many states, has enacted pre-defined, comprehensive, drought-planning apparatus that rely on forecasts. No research to date, however, has provided drought forecasting in the form of climate downscaling in the ACF Basin. Global climate models

can provide outlooks, but they are based on a very course grid cells that cannot resolve rainfall for small, irregular, socially relevant areas like a river system. They can be down scaled for sub-grid prediction skill, but the most economical climate downscaling approach, empirical downscaling, requires a statistical measurement of the circulation-environment relationship called specification. The first objective of this research is to provide specification for the ACF Basin. The research question then becomes, "How does one down scale for summer drought in the ACF Basin and what are the results?" The question is answered by rigorously applying the specification to a GCM and generating forecasts for upcoming seasons.

1.10 Policy Backdrop

Barring some prophetically accommodating change in the climate of the region, water resources in the Apalachicola-Chattahoochee-Flint river basin will need more intense management in coming decades. In fact, it is believed that status quo water policy will fail the Atlanta area by 2030 (Metropolitan North Georgia Planning District 2003a). The 16 March 2000 NPR Morning Edition reported that Georgia administrators feared surface-water stores would run out by 2030 or become polluted. One of the various responses to this situation is the 2001 Metropolitan North Georgia Water Planning Act, which amends most of Chapter 5 of Title 12 of the Official Code of Georgia (O.C.G.A. § 12-5-570-585). It mandates a regional water resource planning entity for the 16-county Atlanta area called the Metropolitan North Georgia Water Planning District: hereinafter referred to as Metro Planning District. This regional planning organization uses information and technology to craft choices for regional water provision and offers guidance and expertise on how to implement those choices. The region has recently become a subject of high-profile media coverage. By 21 November 2007, the Gwinnett Daily

Post reported that the pool level at Sidney Lanier had receded below the previous nadir of 1052.66 feet above mean-sea-level of December 1981 (source: U.S. Army Corps of Engineers).

The 2004 Comprehensive Statewide Water Management Planning Act (O.C.G.A. § 12-5-522) mandates a statewide water plan in Georgia that supports sustainable consumption while protecting the economy and natural systems and enhancing the quality of life. This is a tall order, and Georgia must craft a water allocation formula with other states, intensify water conservation measures, construct at least five new reservoirs, devise inter-basin transfer, and develop a way to reuse treated effluent. Even with this renewed and comprehensive approach, water supplies are projected to squeak by demand by only ten percent in 2030 (Metro Planning District 2003a).

The diversion of water, especially during drought, has serious consequences to stream flow and aquatic habitat downstream. It is always an issue and high-profile cases include the Rio Grande, the Jordan River, and the Tigris-Euphrates River. Worldwide, agriculture accounts for 73 percent of all water consumption (Encyclopedia of Environmental Science, s.v. "water use."), and in Georgia, agriculture is a $5.1 billion per year industry: the largest in the state (Georgia Department of Agriculture).

Reducing water consumption is an obvious response to drought, and water conservation has proven effective for short-term drought mitigation (see Vickers 2005). Since 2000, the Georgia General Assembly has empowered water resource managers with two apparatus to conserve water and constrain seasonal withdrawals. The Georgia Drought Management Plan (GDMP) is mostly a municipal and industrial conservation protocol that reaches a little further into reservoir release and sewer-leak surveillance issues. The Flint River Drought Protection Act (FRDPA) is an agricultural conservation protocol to compensate farmers for irrigation abatement. Both are

implemented according to drought-trigger criteria, and both are dependent upon some way to predict upcoming summer drought with a significant lead-time.

The state Climatologist's Office and Georgia Environmental Protection Division (EPD) look to stream flows, precipitation, lake levels, ground water, and, increasingly, drought prediction for triggers. The Director of the Georgia EPD is empowered to announce each 1 March whether drought conditions will occur during the upcoming summer (Cummings, Norton, and Norton 2001). A survey by Steinemann (2006) showed that water quantity managers in the Southeast need a lead-time of about three months to invoke drought response mechanisms, and furthermore, showed that managers are most interested in the summer months because this is when drought conditions have maximal impact.

Georgia is part of a growing trend to integrate climate data and drought detection with water policy. The Western Governors' Association is actively promoting early detection as an important component of water policy (Western Governors' Association 2004). As of 2006, only seven states nationwide had yet to invoke a comprehensive, statewide, drought management plan: Alaska, Arkansas, Michigan, Mississippi, Tennessee, and Wisconsin (Goodrich and Ellis 2006; see Kundell, DeMeo, and Myszewski 2000). Jacobs, Garfin, and Morehouse (2005) comment, "serious drought conditions over the last eight years [in Arizona] have raised awareness of a comprehensive, statewide, drought management plan" and ". . . the revised New Mexico drought plan has an extremely well defined and specific set of mitigation and response actions."

1.11 Political and Physical Geography

The ACF is a regulated, four-reservoir river system—in order of downstream progression—Lake Sidney Lanier, West Point Lake, Walter F. George Lake (locally known as Lake Eufaula,), and Lake Seminole. They were filled in 1956, 1975, 1963, and 1957 respectively (fig. 2). The lakes are federal impoundments built by the U.S. Army Corps of Engineers (hereinafter referred to as USACE). The river system is effectively one body of water and can be thought of as an aggregate stock of surface water. All the federal impoundments are on the Chattahoochee River; the first 150 miles of the Flint River are free flowing (Crews and Dowling 2002). The lakes are operated by the USACE for navigation, flood control, and hydroelectric power generation. Columbus and Bainbridge have been the heads of navigation on the Chattahoochee and Flint rivers respectively since 1945 (see U. S. Army Corps of Engineers, Mobile District)—meaning that the river is navigable up to that point. Though there is market demand for the Bainbridge port, neither of the ports at Columbus or Bainbridge are currently operating at capacity, to the considerable economic disadvantage to southwest Georgia, which would effectively be commercially connected to Chicago. The culprit is constraint to navigation on the Apalachicola River, which is related to ecological concerns but is more immediately a political impasse due to disunity between Florida and USACE. An ecological compromise is assessable and has been proposed by the Development Authority of Bainbridge and Decatur County—and this includes an acknowledgement of the natural hydrograph issue—but dredging and thus barge traffic is currently impaired on the Apalachicola waterway (Martin 2008, personal communication).

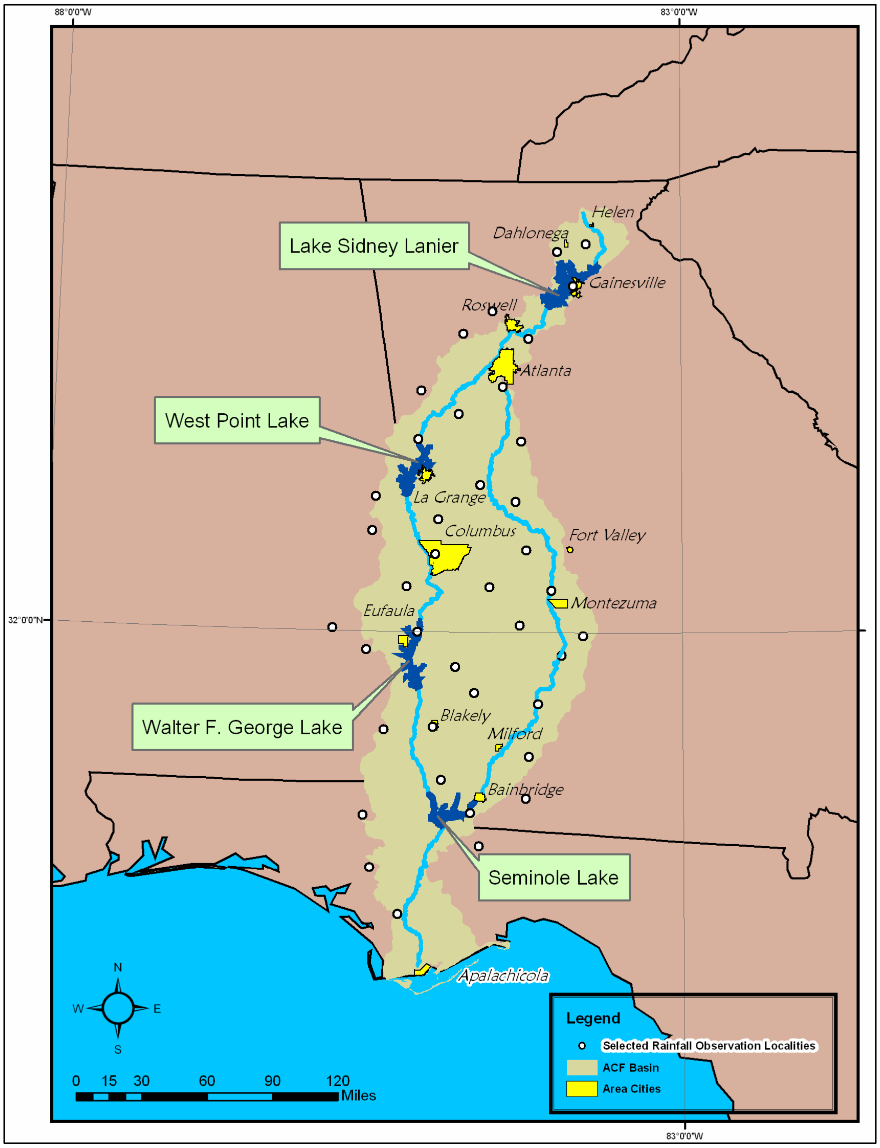


Figure 2. The Apalachicola-Chattahoochee-Flint river system and
a network of 40 rainfall observation localities.

Unlike the western United States, which is governed by the doctrine of prior appropriation—meaning that if somebody was pumping the water, they can continue to pump regardless of whether they own land adjoining the stream—the ACF river system is governed by riparian rights, which only gives landowners adjacent to a stream the use of water, and that right is subject to any damaging downstream externalities (Edgens 2001). Of course, there are damaging

downstream externalities: such as reduced stream flow and degraded water quality. Since title to the water in the ACF Basin is not clear, a long-running dispute between Georgia, Alabama, and Florida over water in the basin has degenerated into an acrimonious, interstate allocation controversy. No one state clearly owns specific stretches of river (see Adams, Crews, and Cummings 2004); consequently, conflict over water allocation has become an intractable source of contention through various governorships since about 1992. Known as the “Tri-state Water Wars”, Alabama’s argument mostly concerns hydropower and water quality (Melton and Silliman 2005), and Alabama officials have repeatedly stated that they will not allow Atlanta to grow at Alabama’s expense. Georgia cites municipal and industrial consumption, recreation, agricultural consumption, and barge traffic as vital to economic growth (Lipford 2004).

Florida’s argument is much more ecological (see Ruhl 2005). Florida is highly vigilant of the balance between fresh-water flow and salt-water intrusion in the estuaries of Apalachicola Bay. Officials make a pointed ecological defense that the quality and quantity of discharge from the Apalachicola River bears the full brunt of upstream water policy. Florida strenuously argues for a guaranteed hydrograph called the “natural flow regime”, which approximates the natural ebb and flow of the river. The Tallahassee Democrat reported on 18 April 2003 that stream flow on the Apalachicola River should be 50 percent more on wet years. The NPR Morning Edition reported on 16 March 2000 that Florida fears Georgia’s “minimum guarantee” would also become the maximum stream flow. Florida maintains that a minimum flow policy is not ecologically sound and insists on a cap to Georgia’s water consumption: a move viewed by Georgia as an assault on the state’s political sovereignty (see Hardin 2002).

Ostensibly, Florida cites the Endangered Species Act, which protects five species of mussel in the area, and the Environmental Protection Agency (EPA), which is studying the Gulf striped

bass and Gulf sturgeon that use the rivers for thermal sanctuary. Bass, sturgeon, mussel, habitat, the EPA, and low stream flow all transcend state boundaries, however, and all are present in the Flint River basin as well. The upstream neighbors do not operate with ecological impunity.

Florida would be alone, however, in bearing the burden of a damaged Apalachicola oyster yield. Apalachicola Bay supplies ten percent of all U.S. oyster consumption (Ruhl 2005; McDowell et al. 2006; see U.S. Fish and Wildlife Service, Panama City, Florida). So, presumably, Florida is concerned about its economy as well as its ecology.

The governors of Georgia, Florida and Alabama signed the Apalachicola-Chattahoochee-Flint River Basin Compact in February of 1997, and it was activated by President Clinton on 1 January 1998. The ACF Compact did not stipulate a water allocation formula; it was anticipated that the states would convene and submit an agreement for equitable apportionment of surface water within a year. Unfortunately, in six years, they could not, and on 1 September 2003, the compact was dissolved (Melton and Silliman 2005). The case has since been referred to the U.S. District court in Florida. For the time being, The USACE is operating the river system according to an interim plan, which has caused considerable consternation with the Georgia governor.

1.12 Water Resource Planning in Georgia

In Georgia, water *quantity* planning and provision decisions are done at the state level, and water quantity managers are mostly officials at the Metropolitan North Georgia Planning District and the Georgia EPD, who intervene in the relationship between humans and the hydrologic cycle. Navigation, flood control, hydroelectric power, and water *quality* issues are the purview of the Federal Government. Municipal wastewater treatment service has devolved to the local level (Kundell, DeMeo, and Myszewski 2000).

CHAPTER 2

DROUGHT

2.1 Earth's Droughts and Spatial Scale

Droughts occur at a fine-grain scale (50 km) while the long-term atmospheric subsidence over the stricken area is a large-scale phenomenon (1000 km–6000 km). This cross-scale relationship is not lost upon synoptic climatology (Yarnal 1993, 6); in fact, translation across spatial scale is a central theme (see Hewitson and Crane 1996). Studies on quasi-stationary dipoles of action in the hemispheric circulation show that interactions between the local environment and the greater atmospheric circulation may cascade all the way to the hemispheric scale (Harman 1991; Turner, Dale, and Garner 1989). Researchers have successfully used the Southern Oscillation Index to forecast local precipitation across the globe (Nicholls, Coughlan, and Monnik 2005). Curtis (2006) found La Niña inhibits extratropical storm formation in the western Gulf of Mexico. Alexadrov and Hoogenboom (2001) found El Niño is associated with above normal, cool-season precipitation in Georgia. Henderson and Vega (1996) found a strong correlation to rainfall in the mid-South with the continental-scale Bermuda High Index. Henderson and Robinson (1994) found a connection between rainfall frequencies in the Southeast with the Pacific North America Index. Diem (2006) performed a north Georgia precipitation-to-circulation classification of the average warm-season precipitation falling on spatially cohesive areas during prescribed 13-day intervals. He found the position of local, synoptic-scale, mid-tropospheric troughing to be associated with dry episodes, and a different troughing pattern to be associated with wet episodes (and he compensated for tropical

aberrations). Stahle and Cleaveland (1992) found evidence that growing-season rainfall on the Atlantic Coastal Plain is strongly modulated by synoptic-scale protrusions in the Bermuda high.

2.2 Drought Feedbacks

Rainfall deficiency in the January–June period in the ACF Basin is often succeeded by further rainfall deficit in the July–September period (table 1). There are two feedback mechanisms that might explain this: (1) environmental forcing, and (2) recycling. Environmental forcing reinforces drought when dry soils under high sun angle heat up and cause positive thermal inequalities over the surface of the earth that perturb the westerlies (see Harman 1991). Recycling reinforces drought when dry soils suppress rainfall yields by denying mid-latitude storms of their incoming moisture. Extratropical storms draw up to 30 percent of their moisture from surface evaporation that comes from about five times their radii (Trenberth et al. 2003).

Spring moisture deficiency is equivalent to incipient summer drought. Moisture charged soils normally remain cool into the summer. Rind (1982) comments, “During times when the ground receives an excess of radiation, moist earth will lose heat through latent heat fluxes and remain cool . . .”. With a deficit, however, soils become dry and hot, which initiates positive feedback. The sensitivity of the general circulation to soil moisture is evident in global models (see Fennessy and Shukla 1999). Lohani and Loganathan (1997) seem like-minded about the importance of spring rainfall deficit to summer drought. This self-perpetuating nature of drought has been coined “Drought begets drought”.

Table 1. Bottom five basin-wide 1 July rainfall deficits for the year (mm) and the subsequent SPI for the three-month interval July–September.

YEAR	DEFICIT	SUBSEQUENT DROUGHT
1954	315.85	-1.89
2007	289.79	-0.57
1986	274.62	-0.28
2000	252.04	-0.26
1968	209.77	-0.58

2.3 The Risk of Drought in the Southeast

The climate of the Southeast poses a drought hazard. Barber and Stamey (2000), using stream discharge data, identified several hydrologic drought episodes during the 20th century, most notably in the 1930s, 1950s, and 1980s. Sharp periods of drought are a normal aspect of the climate in the Southeast. Throughout the 20th century, the Palmer Drought Severity Index shows a propensity for sharp but brief episodes of meteorological drought (fig. 3). In Georgia, precipitation over the 20th century has shown no statistically significant year-round trend, but warm-season precipitation has waned significantly, especially since the 1970s, and especially in the late spring (Alexandrov and Hoogenboom 2001). The 1117 mm, five-year accumulated rainfall deficit in Atlanta from 1998-2002 was certainly a paltry premier to the 21st century; 2007 was the second driest year on record in Atlanta (source: National Weather Service Forecast Office, Peachtree City keyword: rainfall scorecard).

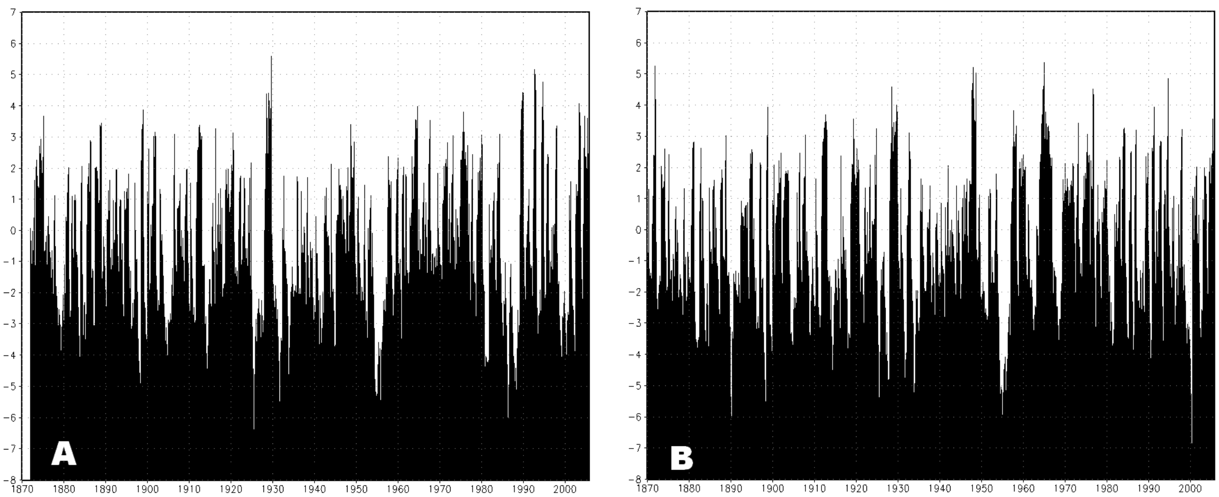


Figure 3. Palmer Drought Severity Index (PDSI) computed monthly for 1870–2006 for data grid cells representing the northern half of the basin (A) and the southern half (B). PDSI is non-dimensional with -3 representing severe drought and -4 extreme drought.

Long-term trends in population and job growth make the region increasingly vulnerable to socioeconomic drought. Fulton and Gwinnett counties in Georgia are projected to be millionaire counties by 2030, and Forsyth, Cherokee, and Bartow counties will triple employment between 2000 and 2030. Metro Atlanta population in the ACF basin alone will be near 3.5 million by 2030 (Metro Planning District 2003a). The population of the whole basin is already approaching 7 million (Ruhl 2005). This is compounded by the fact that the ACF is a net exporter of approximately 90 million gallons per day (Mgal/d) to the Ocmulgee River basin (Metro Planning District 2003a, ES-8). Unfortunately, the northern part of the ACF basin does not have the geological option of a groundwater yield, which would be of great utility during short-term drought.

Trends in farming practice also make the region increasingly vulnerable to agricultural drought. In descending order of significance, the ACF basin irrigates 600,500 acres of cotton, peanuts, corn, vegetables, and pecans (McDowell et al. 2006). Recent trends are toward more intensive crops such as vegetables, which demand more irrigation. As agricultural demand

increases, sandy areas may come more into production, which need more irrigation than loamier soils.

Related to water quantity are water quality issues created by urbanization. Urbanization increases polluted runoff and decreases clean runoff (see Metro Planning District 2003b, 2-1). The 12 August 2007 Atlanta Journal Constitution reported that surface runoff from suburban sprawl is contaminating Lake Sidney Lanier. Urbanization also removes riparian vegetation, which exposes water courses to sediment and pollution. Healthy watersheds are essential for clean water supply.

Risk is often codified as Risk = Vulnerability * Hazard. This formula suggests increased risk for the ACF basin due to increased vulnerability from poor growth management. Wilhite, Svoboda, and Hayes (2007; see National Drought Mitigation Center) comment that society worldwide is mounting pressure on natural systems to deliver more clean water. The *Intergovernmental Panel on Climate Change 4th Assessment Report* (IPCC) reports:

> Vulnerability to extended drought is increasing across North America as population growth and economic development create more demands from agricultural, municipal and industrial uses, resulting in frequent over-allocation of water resources . . . (Field et al. IPCC 2007).

Consistent with an acceleration of the hydrologic cycle, global climate predictions are for both increased evapotranspiration and precipitation. The Clausius-Clapeyron equation indicates that, as the atmosphere warms, it can hold 7 percent per degree Kelvin more water vapor. Hence, a very robust finding of all climate models is that potential evapotranspiration will increase with climate warming. In the absence of precipitation, this leads to increased drought hazard (Trenberth et al. 2003). Climate models indicate increased summer precipitation in the high latitudes but decreased precipitation in low latitudes with a pivotal line running roughly through

the ACF basin, perhaps drifting north in the summer (IPCC 2007 Working Group I, Chapter 10, fig. 10.9). This is substantiated by Alexandrov and Hoogenboom (2001), who found a distinct warm-season drying in Georgia over the 20th century and especially since the 1970s. Lettenmaier et al. (1999) summarized several general circulation models and reported much-increased potential evapotranspiration north of the ACF basin; however, the ACF might completely compensate evapotranspiration with increased rainfall, at least in earlier decades. Thus, the outlook for the ACF basin is mixed, but the IPCC fourth assessment generally foresees an increased hazard throughout the middle latitudes:

> A long-standing result from global coupled models noted in the Third Assessment Report is a projected increase in the chance of summer drying in the mid-latitudes in a future warmer climate with associated increased risk of drought (Meehl et al. IPCC 2007).

The instrumental record, of course, does not extend much beyond 100 years. The extraction of a proxy record of climate signals from the myriad of factors that affect tree-ring growth is a developing branch of climatology called dendrochronology. These results show a long-standing drought hazard in the Southeast that seems to wax and wane through the epochs. Stahle and Cleaveland (1992) conducted a critical analysis of bald cypress in the Southeast and reported the reconstruction of a millennium-long rainfall chronology. They find, ". . . decade-long regimes of spring rainfall have been an important aspect of the natural background climate of the Southeast during the late Holocene . . ." Knight (2004) reported a reconstruction of stream flow in the Flint River near Albany, Georgia using longleaf pine. He found enduring episodes of very low flow around 1756–1760, 1853–1857, and 1896–1900.

2.4 Seasonality of Drought in the ACF Basin

The Southeast enjoys the Köppen climate category of "subtropical humid" meaning that rainfall is generally reliable and there is no pronounced dry season (Trewartha and Horn 1980). There are annual cycles of supply and demand, however, and the annual oscillation of human water consumption reaches its apex in the summer while the annual cycle of stream recharge reaches its nadir. Thus, socioeconomic drought is a summertime phenomenon in the Southeast. While median September stream flows near Dahlonega and Milford fall to less than half their February values (figure 4), historical water use time series in metropolitan Atlanta show increased residential water use in the summer months (Metro Planning District 2003a, 4-8). Moreover, the oscillation is even more peaked in dry years due to increased agriculture demand (Landers and Painter 2007). As the basin's water balance—the residual between human consumption and natural recharge—sways from positive to negative, reservoirs in the ACF basin experience warm-season drawdown. The situation is more severe in a drought year when the two forces are in greater opposition. Socioeconomic drought occurs when the pendulum swings too far, and water stocks are depleted. Exceptionally dry years are feared for their rapidly receding reservoir pools. For example, the pool level at Lake Sidney Lanier fell from 1064 to 1055 feet above mean-sea-level between 13 May 1986 and 6 October 1986 (U.S. Army Corps of Engineers n.d.)

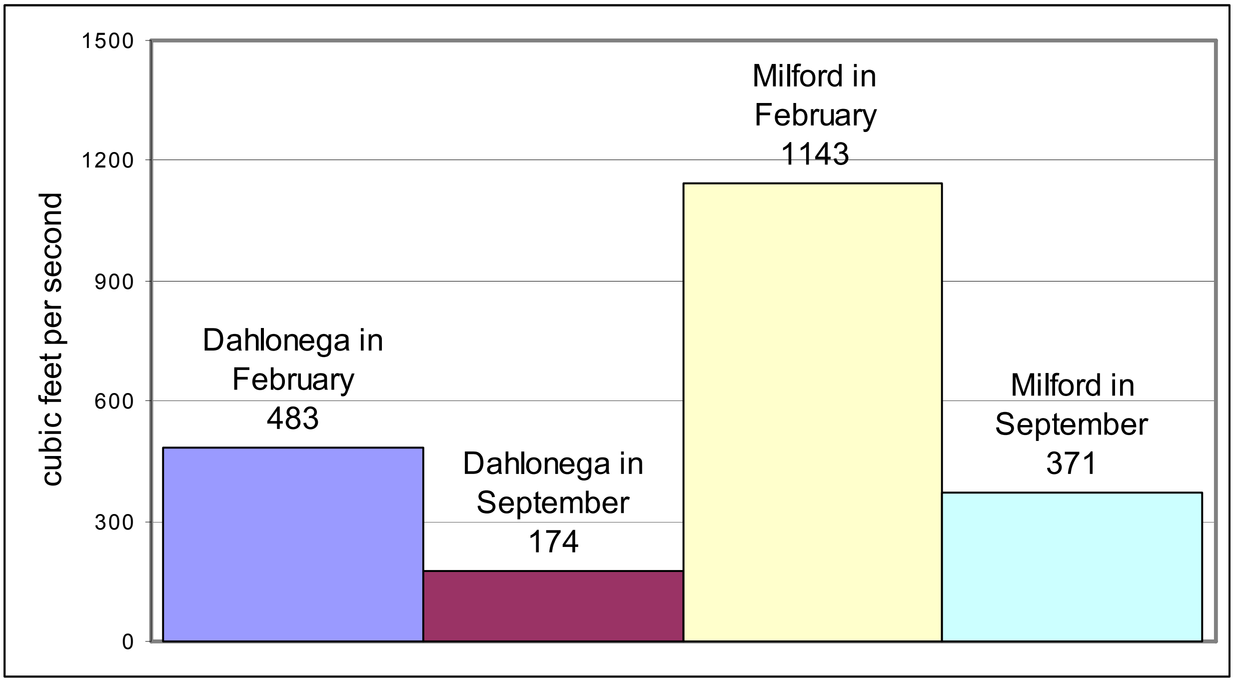


Figure 4. Median 1940–2006 stream discharge (ft^3/s) for the Chestatee River near Dahlonega, Georgia (North) and Ichawaynochaway Creek near Milford, Georgia (South) for the bimodal months of the year.

Municipal consumption is a residual between water withdrawn and water recharged back into the basin. In Georgia, about 55 percent of public water withdraw is treated and returned (Chakravorty and Fisher 2005). The figure varies with time, place, circumstances, and source. For the year 1990, Couch (1993) placed the figure at 20 percent for the ACF basin. Landers and Painter (2007) placed it at between 18 and 34 percent for the year 2000 above West Point Lake. The Metro Planning District (2003a) places it at 58 percent for metro Atlanta. According to Ruhl (2005), Atlanta draws about 500 Mgal/d, returning about 350 Mgal/d downstream as treated effluent leaving a residual of 150 Mgal/d as municipal consumption.

Agricultural withdrawal is purely consumptive, so agricultural consumption might seemingly be the number of gallons withdrawn from pipes in streams. The fact that surface water can intermingle with aquifers, however, convolutes the final figure. In South Georgia, 70 percent of

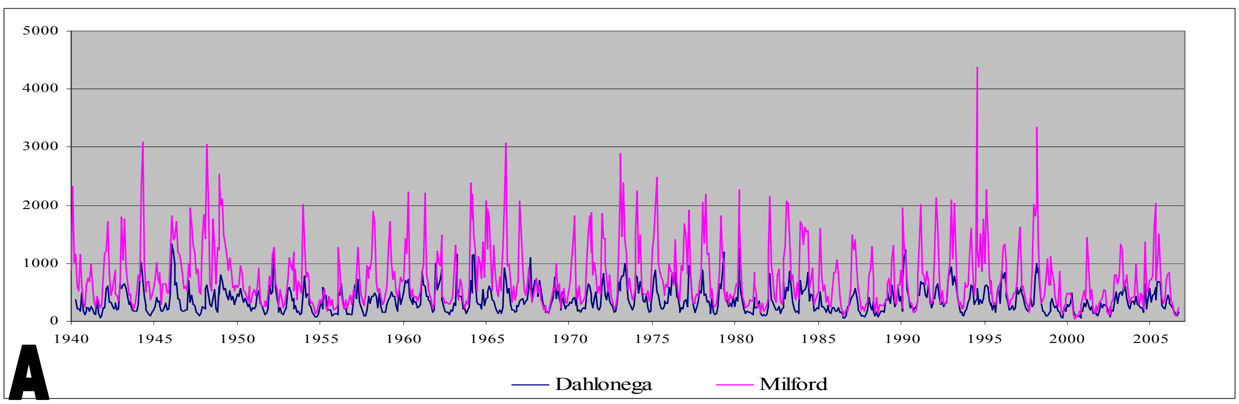
irrigation is drawn from wells (Frick et al. n.d.). Downstream of about Vienna, Georgia, however, the Flint River and some of its tributaries, to varying degrees, are hydraulically connected to the Floridan acquifer. This means that ground water and river water are not geologically distinct bodies of water: they intermingle; therefore, in South Georgia, the distinction between surface water consumption and ground water withdrawal is muddled (McDowell et al. 2006).

2.5 Regional and Temporal Concurrence of Drought in the ACF Basin

Considering that the basin has considerable meridional extent, is there really such a thing as basin-wide drought? Especially considering that Henderson and Vega (1996) split the ACF into two spatially cohesive, quasi-homogenous areas of rainfall behavior, perhaps meteorological drought in the basin is always offsetting. Furthermore, considering the diversity of factors that influence watershed response and memory to rainfall, perhaps basin-wide meteorological drought does not translate to synchronous, basin-wide hydrologic drought. Georgia streams show varying memories to antecedent rainfall (Rose 1998; see Allen 1995). Finally, perhaps human demand is less during meteorological drought, offsetting the imbalance that causes socioeconomic drought.

Two SPI and stream flow time series are superposed in figure 5. They portray a similar history of meteorological drought across the basin. Conditions on one end of the basin are generally unopposed by conditions on the other. The 1950s drought, probably the worst in the state's recorded history, was in fact a statewide event (Alexandrov and Hoogenboom 2001).

Not only is meteorological drought basin-wide, it is associated with low stream flow. A one-tailed Spearman rank correlation coefficient finds SPI time series to be significantly correlated to stream flow at the $\alpha = 0.01$ significance level, thus rejecting the null hypothesis that meteorological drought and stream flow are two unrelated phenomena. The two time series for Dahlonega and Milford show similar phasing in stream flow, indicating that hydrologic drought is synchronous across the basin. Hydrologic drought in the basin is a regional phenomenon and significantly associated with meteorological drought.



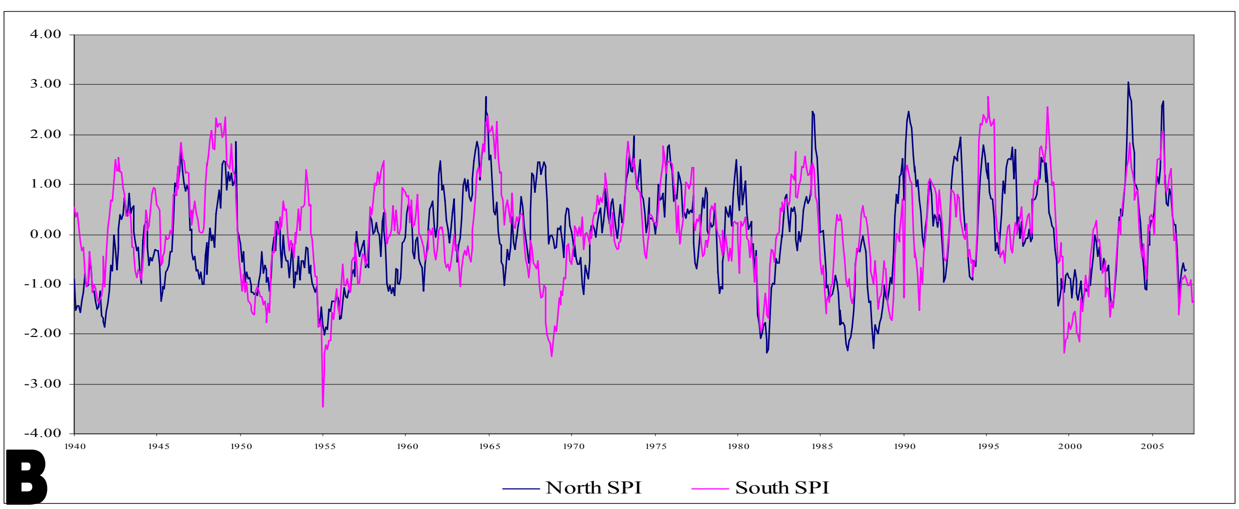


Figure 5. Superpositions of monthly average stream discharge (ft^3/s) for the Chestatee River near Dahlonega, Georgia and Ichawaynochaway Creek near Milford, Georgia (A), and Standardized Precipitation Index (12-month interval) for the climate divisions corresponding to the northern and southern ends of the basin (B).

Meteorological drought is associated with more human demand. Water use in the Flint River Basin during the growing season is 90 percent agricultural. Irrigation peaks in a drought year, (McDowell et al. 2006), though exact figures are sketchy because permits are required only if 100,000 gallons/year are used (Crews and Dowling 2002). According to Georgakakos and Yao (2003), ". . . in a drought year agricultural demand may be two to three time more . . ." and ". . . water investigations in Georgia have shown that Atlanta water demand may increase by as much as 20 percent during drought." Demand for water resources builds during dry conditions.

Since meteorological drought tends to co-occur in the north and the south part of the ACF Basin, and since two major, free-flowing streams are correlated with meteorological drought in the north and south, and since demand increases at precisely the time when supply wanes, meteorological drought, hydrologic drought, and socioeconomic drought are all regionally synchronous and concurrent.

CHAPTER 3

DATA AND STUDY AREA

3.1 Study Domain

The domain of the study is the Apalachicola-Chattahoochee-Flint river basin: a narrow hydrologic drainage basin straddling the borders of Alabama, Georgia, and Florida (fig 6). The basin drains a considerable meridional extent from Helen, Georgia to Apalachicola, Florida, where it terminates into the estuaries of the Gulf of Mexico The various sources of data for the study are summarized in table 2.

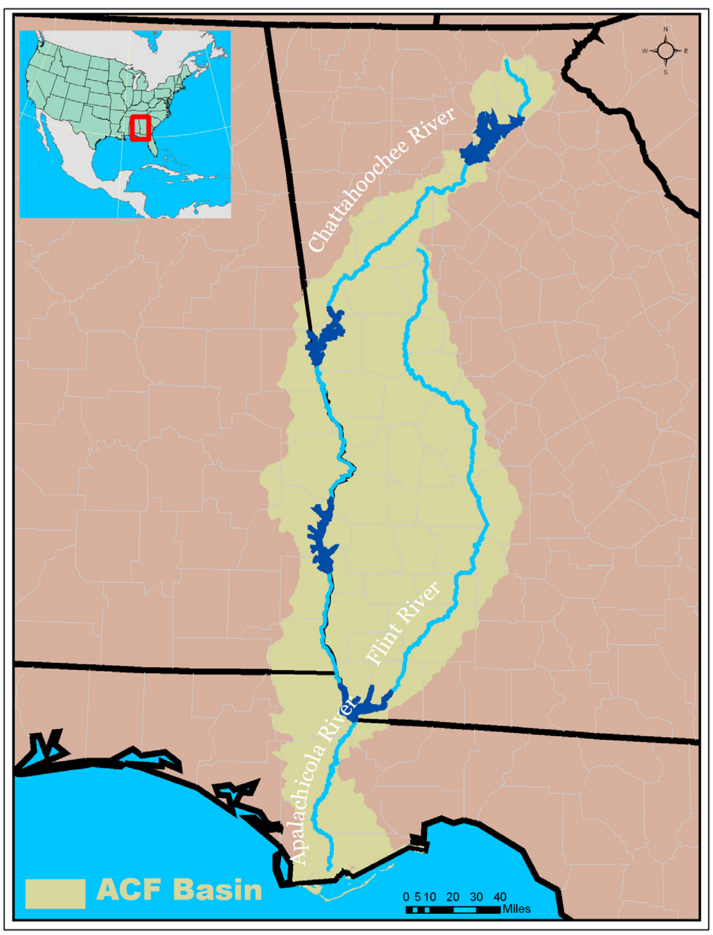


Figure 6. Outline of ACF drainage system.

Table 2. Summary of data sources.

Dataset	Parameter	Source
TD3200	rain gauge observations	National Climatic Data Center
NCEP/NCAR Reanalysis Project	model fitted upper air	NOAA Earth Systems Research Lab
USGS Hydrologic Boundaries	ACF Basin	National Atlas of the United States
PDSI	drought severity	NOAA Earth Systems Research Lab
SPI	meteorological drought	National Climatic Data Center
stream discharge	hydrologic drought	U.S. Geological Survey
hydrography	streams and waterbodies	National Atlas of the United States
political boundaries	towns and counties	ESRI
climate divisions	conventional districts	National Atlas of the United States
Digital Atlas of Georgia	physical geography	Georgia Geological Survey
GCM output	general circulation prediction	NOAA Geophysical Fluid Dynamics Lab

3.2 Rain Gauge Observations

The full time series of daily rain gauge observations were downloaded in delimited text format from the National Climatic Data Center's TD3200 data set (source: NNDC Climate Data Online web interface). The observations originate from the National Weather Service (NWS) cooperative network. The primary intent of this network in recent years has been to measure precipitation, and while mostly consisting of volunteers, it includes the principal NWS stations, the Department of the Interior, the Department of Transportation, and the Department of Defense stations. A useful station list and data dictionary for the TD3200 is available (National Climatic Data Center 2003). Geographic coordinates are converted from degree-minutes-seconds to decimal degrees and locations are assumed NAD83 datum for GIS use.

There are about 104 TD3200 stations available within the basin. The final rainfall extract is a selection of forty, uniformly dispersed localities, but there are actually forty-seven coop stations involved because occasionally a station is decommissioned (table 3). The National Climatic Data Center assigns S flags for measurements that are appended to subsequent days.

To ensure quality and preserve the highly empirical nature of the rain-gauge data, the rainfall data frequency is daily. For the 420,480 records in the database—covering forty localities over a

duration of 10,512 days—363,122 are absolutely empirical, and the rest are interpolations from nearby observations.

Rainfall data were extracted in comma delimited text files and stored in database. From here, they were queried and exported for cleaning in a spreadsheet program. Sometimes stations are decommissioned, and sometimes commissions overlap. This was handled in the database by querying only one station at a time for any time series. All S flags were coded to zero, missing months were inserted as placeholders, and the arrays were paneled. After this manual manipulation, the data were treated to a QC of six rainy episodes to ensure they still matched the original database.

Of the 420,480 rainfall observations in the duration, 57,358 (13.6%) were missing. The missing values were filled with an un-weighted average of the two nearest localities in opposition. Due to temporal clustering of incompleteness, some observations could not be filled in that way. Montezuma has a nearly complete record, and since it is near the center of the basin, that station was substituted for the remaining 11,118 values. Due to some incompleteness in even Montezuma's record, seven values remain, which were filled by nearby Americus's values.

Paneling allows each locality to be treated in a similar way. Every station had missing data, but, because the localities were paneled, every missing value was able to be filled with a spreadsheet formula: the only difference in the formula from panel to panel was that they used different sheets for the interpolation. Spreadsheet formulas were also used for the considerable averaging needed to derive a final, basin-wide value for each year, and again, the paneling allows the formulas to be very similar, differing primarily in the name of locality they are averaging.

Table 3. Characteristics of the 40 localities and associated weather stations. Plain identification number (ID); name, state, and county; NWS Cooperative Network identification number, alternate Cooperative Station if decommissioned; latitude (N); longitude (W); elevation (m); climate sub-region (North, Central, or South); % missing observations; average January—June rainfall (mm).

ID	LOCALITY	STATE	COUNTY	COOPID	COOPID	LAT (°)	LON (°)	ELEV	REGION	Missing	Rainfall
1	CLAYTON	AL	BARBOUR	11725		31.88	85.48	152	C	6.4	693
2	EUFAULA	AL	BARBOUR	12730	13761	32.00	85.08	66	C	4.5	699
3	HEADLAND	AL	HENRY	13761		31.35	85.33	113	S	4.5	718
4	LAFAYETTE	AL	CHAMBERS	14502		32.90	85.43	226	C	5.4	765
5	OPELIKA	AL	LEE	16129		32.67	85.45	195	C	18.3	745
6	SEALE	AL	RUSSELL	17328	17326	32.30	85.17	119	C	70.3	673
7	UNION SPRINGS	AL	BULLOCK	18438		32.02	85.75	134	C	2.9	728
8	CHIPLEY	FL	WASHINGTON	81544		30.78	85.48	40	S	1.8	729
9	FOUNTAIN	FL	BAY	83230		30.43	85.42	43	S	42.6	745
10	QUINCY	FL	GADSDEN	87424	87429	30.58	84.58	76	S	5.0	733
11	WEWAHITCHKA	FL	GULF	89566		30.12	85.20	13	S	16.0	744
12	ALBANY	GA	DOUGHERTY	90140		31.53	84.13	55	S	0.3	687
13	AMERICUS	GA	SUMTER	90253	97087	32.05	84.28	149	S	4.3	660
14	ATLANTA HARTSFIELD	GA	FULTON	90451		33.63	84.43	308	N	0.3	657
15	BAINBRIDGE	GA	DECATUR	90586	90581	30.80	84.65	58	S	6.9	694
16	BLAKELY	GA	EARLY	90979		31.37	84.95	82	S	22.9	716
17	BUENA VISTA	GA	MARION	91372		32.30	84.52	201	C	23.7	666
18	BUTLER	GA	TAYLOR	91425		32.55	84.23	191	C	9.0	641
19	CAIRO	GA	GRADY	91463		30.90	84.22	81	S	26.9	707
20	CAMILLA	GA	MITCHELL	91500		31.18	84.20	53	S	0.1	704
21	CARROLLTON	GA	CARROLL	91640		33.60	85.08	303	N	1.4	726
22	CLEVELAND	GA	WHITE	92006		34.58	83.77	485	N	0.9	848
23	COLUMBUS	GA	MUSCOGEE	92166		32.52	84.95	120	C	1.7	659
24	CORDELE	GA	CRISP	92266		31.98	83.78	94	S	2.3	608
25	CRISPCOUNTYDAM	GA	WORTH	92361		31.85	83.95	75	S	50.4	617
26	CUTHBERT	GA	RANDOLPH	92450		31.77	84.78	141	C	1.0	687
27	DAHLONEGA	GA	LUMPKIN	92475		34.53	84.00	384	N	12.9	839
28	DALLAS	GA	PAULDING	92485		33.98	84.75	335	N	1.4	723
29	DONALSONVILLE	GA	SEMINOLE	92736		31.02	84.88	41	S	36.2	687
30	FRANKLIN	GA	HEARD	93567		33.28	85.10	204	C	61.7	726
31	GAINESVILLE	GA	HALL	93621		34.30	83.87	357	N	0.7	737
32	GRIFFIN	GA	SPALDING	93271		33.27	84.28	282	C	5.5	689
33	HAMILTON	GA	HARRIS	94033	94028	32.75	84.93	201	C	46.8	669
34	MONTEZUMA	GA	MACON	95979		32.28	84.03	100	C	0.0	606
35	MORGAN	GA	CALHOUN	96043	96038	31.60	84.63	83	S	16.3	703
36	NEWNAN	GA	COWETA	96335		33.45	84.78	280	N	2.9	702
37	NORCROSS	GA	GWINNETT	96407		33.95	84.23	314	N	4.3	724
38	THOMASTON	GA	UPSON	98661		32.87	84.32	203	C	15.5	671
39	WOODBURY	GA	MERIWETHER	99506		32.98	84.60	241	C	1.1	684
40	WOODSTOCK	GA	CHEROKEE	99524		34.13	84.52	322	N	10.4	706

3.3 Upper Atmosphere Data

The renowned NCEP/NCAR Reanalysis Project (see Kalnay et al. 1996) provides the model fitted 700 mbar specific humidity q (the ratio of the mass of water vapor to the total mass of air in g/kg) and 700 mbar height (geopotential meters) (source: National Oceanic and Atmospheric Administration (NOAA), Earth System Research Laboratory, Physical Sciences Division Boulder, Colorado, USA, http://www.cdc.noaa.gov). Reanalysis data is publicly available in netCDF format. The geopotential meter is a vertical coordinate that represents the amount of work done to raise a parcel from sea level, and, under standard gravitational conditions, it is equivalent to the geometric meter (Huschke 1959, s.v. “geopotential meter”). The Reanalysis Project generates a global approximation of atmospheric parameters by mathematically fitting a surface over available empirical observations. Since they are much less empirical than rain gauge observations, there is little to be gained from daily data frequency, and monthly means were used. The Reanalysis Project classifies specific humidity, for example, as a class B variable, meaning the model has a very strong influence on the value, and there are fewer direct observations. The 700 mbar height is a class A variable, meaning the analysis is more strongly empirical. Both variables are held in a gridded dataset with 2.5º latitude by 2.5º longitude spatial resolution.

The 700 mbar data was retrieved in netCDF format from the Reanalysis Project with freeware (Doty 1988) and stored on disc. Eight scripts were used to extract the data. A script is specific to a map point, and recalling that the mid-tropospheric data is monthly, a script extracts the first six months of the year and then averages them. Considering that it is easy to miss the geopotential level and longitude (west is negative), scripts are very helpful to ensure the correct

data was extracted. Each script reiterates the process fifty-eight times for 1950–2007. A spreadsheet program can be useful to create scripts because months are coded sequentially.

3.4 Drought Index Data

A drought index distills environmental data into one dimensionless number that evaluates drought severity. At least two indices are useful in the Southeast: the Palmer Drought Severity Index and Standardized Precipitation Index. The Palmer Drought Severity Index (PDSI) (Palmer 1965) is the most familiar of drought indices, and it was a turning point in the evolution of drought indices (Heim 2002). It is considered a meteorological drought index and is standardized for geographic location (Keyantash and Dracup 2002). Palmer's definition of drought is "prolonged and abnormal moisture deficiency". Guttman (1998) comments, ". . . it indicates the physical severity of drought on soil. It was intended to retrospectively look at wet and dry conditions from a water balance perspective." The PDSI tallies the moisture balance. It is a cumulative hydrologic summation: a hydrologic accounting system. The index tracks from the beginning of a weather "spell". The PDSI switches to a different algorithm when a spell reverses. Since a spell is difficult to resolve in real time, it is normal for PDSI to revise figures recursively. The Modified PDSI (MPDSI) addresses this backtracking problem (Heddinghaus and Sabol 1991), and the MPDSI is a truly operational, real-time index for water managers (Guttman n.d.).

The PDSI makes some assumptions about potential evapotranspiration. It considers temperature, latitude, and time of year but does not account for cloudiness, wind speed, relative humidity, vegetation, soil type, or moisture exhaustion (see Dai, Trenberth, and Qian 2004; Weber and Nkemdirim 1998; Guttman n.d.).

The Standardized Precipitation Index (SPI) was developed by T.B. McKee, N.J. Doesken, and J. Kleist (1993). It is a standardized, moving average of the precipitation anomaly for a discrete time step. It is a purely supply-sided index, meaning that it describes pure, meteorological drought. The SPI is used across North America and is currently favored in academic evaluations (Keyantash and Dracup 2002; Hayes et al. 1999; Guttman 1998).

Drought index data used in this study include the monthly Palmer Drought Severity Index (PDSI) and the Standardized Precipitation Index (SPI). The SPI is acquired in tab delimited text format in the twelve-month time-step from 1900–2007 for the climate divisions corresponding to Dahlonega and Milford (source: National Climatic Data Center web site keyword: North American Drought Monitor Standard Precipitation Index Data Files). The three-month time step for the climate division representing the central section of the basin is also acquired. All time steps are computed monthly for a monthly data frequency. The PDSI data is obtained in netCDF format for 1870–2003 for the two 2.5º latitude by 2.5º longitude grid cells corresponding to the northern and southern halves of the basin at a monthly data frequency (fig. 7) (source: NOAA, Earth System Research Laboratory, Physical Sciences Division Boulder, Colorado, USA, http://www.cdc.noaa.gov).

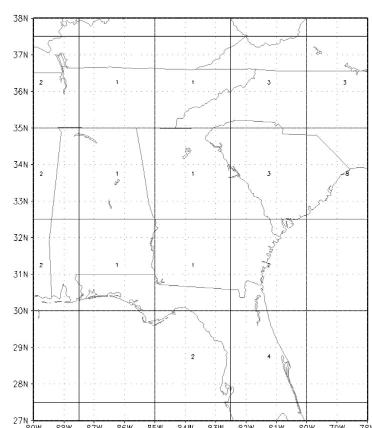


Figure 7. The Reanalysis Project 2.5º by 2.5º
grid cells that hold the PDSI data.

3.5 Stream Flow Data

Average stream flow data (ft^3/s) are retrieved from the U.S. Geological Survey (USGS) National Water Information System (source: http://waterdata.usgs.gov) at a monthly data frequency in text format for stations 02333500 and 02353500 for 1940–2006. These stream discharge observations are measured with stream gauges on the Chestatee River near Dahlonega and the Ichawaynochaway Creek at Milford. Both are free flowing at these points.

3.6 Ancillary Data

Other ancillary datasets include streams and water bodies (source: National Atlas of the United States 2005), political boundaries (source: ESRI), climate divisions (source: National Atlas of the United States 1991), and the Digital Atlas of Georgia (Alhadeff et al. n.d.). The ACF basin is delimited by USGS hydrologic unit boundaries (Watermolen 2005) and uniquely identified by huc4 code 313 (region 3, subregion 13).

3.7 Global Climate Model Output

GCM output is obtained from NOAA's CM2.1 coupled climate model under the "committed" scenario (source: U.S. Department of Commerce NOAA Geophysical Fluid Dynamics Laboratory in Princeton New Jersey; see Delworth et al. 2006). The data frequency is monthly and the spatial resolution is 2° latitude by 2.5°. Data is publicly available for download in netCDF format. The output is from the CM2.1U-H2_Stable-2000_S1 experiment, which stabilizes forcing agents such as CO_2 at year 2000 levels.

The CM2.1 model is chosen because it is held by the U.S. Department of Commerce, which is a highly credentialed source of meteorological expertise and data—housing the National

Oceanic and Atmospheric Administration and administering the National Weather Service. The CM2.1 was one of the leading models used in the Fourth Assessment Report of the IPCC. Additionally, it is provided free of charge online in a format convenient to the freeware provided by Brian Doty (1988). The "committed" scenario to 2000 level CO_2 concentration is used because the model might be more accurate if not complicated by the scenario of rising CO_2, which is a reasonable non-scenario considering the model is only used out to 2011: not enough time to incur considerable CO_2 increase.

3.8 Map Coordinate System

All geographic data is available in decimal degrees with a datum of NAD 83. For cartographic display of the Southeast, a map coordinate system based on the Albers equal-area projection with standard parallels at 29.5 degrees and 45.5 works well. Figure 8 uses a central meridian of 85° west longitude.

CHAPTER 4

METHODS

4.1 Overview

The methods for this study are based on measuring time-averaged atmospheric parameters at specific map points and relating the resulting variable to time-averaged and spatially smoothed regional rainfall. This is a variant on the compositing approach; it uses composite map points, not composite maps. The resulting continuous variables avert the inevitable loss of data from typing a continuous phenomenon into discrete, non-overlapping intervals. There is no classification or map compositing in this study.

This project was completed in four main legs. In the first, historical datasets of drought and rainfall were acquired and analyzed to develop a characterization of drought in the region. In the second, a dependent variable was compiled from nearly half a million daily rainfall observations from dispersed localities over the region to generate a fifty-eight-season, basin-wide time series. In the third, atmospheric predictor variables were compiled into eight time series representing eight map points around the basin. Finally, the dependent variable was fitted to the upper atmospheric predictor variables with a linear regression.

4.2 Characterization of Drought in the ACF Basin

Time series of PDSI, stream discharge, and SPI were plotted and compared. These time series are comparable because they are all from monthly data frequency. The purpose for this comparison was to explore the regionality and concurrency of drought types. Further goals were to characterize hydrologic drought as a summertime phenomenon, to assess the hazard of future

drought in the region, and to explore evidence for drought feedback mechanisms. The two PDSI time series, which are in netCDF format, were generated in the freeware from Doty (1988) and exported as graphics files. The time series were not superposed, but rather presented side-by-side because the freeware does not seem to have a provision for superposition. The stream discharge data and twelve-month SPI values were imported from text format to a spreadsheet program, columned with data labels, and charted with automated spreadsheet functions. Different time series for the north and the south were superposed to see if cycles are synchronous. The three-month SPI time series for the climate division representing the central section was queried for September for those years with the driest first six months of the year. The purpose for this was to see if the driest first six months of the year were followed by subsequent summertime rainfall deficiency, indicating a feedback. The stream discharge data and SPI series were compared with a two-tailed Pearson's product-moment correlation coefficient ($\alpha = 0.05$). The reason for doing that was to see if meteorological drought, which is what SPI represents, could be correlated with hydrologic drought, which is what stream discharge represents. The Pearson's product-moment test is warranted because the variables are normally distributed. It may seem obvious that rainfall and streamflow are related, but there might be a long lag time, making hydrologic drought an offset phenomenon rather than a salient summer event (see Allen 1995; Rose 1998).

4.3 Regionalization

The less a model has to generalize across disparate conditions, the better it should be able to fit a relationship. Consequently, across the meridionally extensive and heterogeneous ACF Basin, models should be specialized for climate sub-regions. This might create tighter and more accurate modeling.

To this end, a factor analysis was used to identify the unique factors contained within the 40 precipitation time series. A data matrix consisting of forty variables across fifty-eight seasons were loaded into an S-mode principal components analysis (PCA) to generate the factors, and the ones that had the highest eigenvalues were selected as principal components. Variables were grouped by which component they maximally loaded on. Variables represent localities, and since nearby stations tend to have similar rainfall behavior, i.e., congruent time series, they load on the same component and usually are spatially cohesive. These groupings of localities are zones of quasi-homogenous rainfall behavior; thus, they are called climate sub-regions.

Choices made during PCA can have a substantial effect on the outcome. The orthogonal rotation technique VARIMAX distributed the blend more evenly across the components. To impede mountain stations from being sharply cohesive, the correlation matrix ensures that stations with similar timings were grouped, not similar rainfall magnitude. An eigenvalue and scree-plot criterion were used to select the principal components that explain most of the variance in rainfall behavior. The maximum loadings rule was used with no alteration, meaning that a station was associated with the rotated component that it had the most loading with. The groups were then mapped to identify the climate sub-regions.

4.4 Trends in Precipitation

To explore trends in precipitation that might impart a certain backdrop or sense of urgency to drought prediction, precipitation time series for the overall basin and the three sub-regions were plotted. These time series were loaded into a spreadsheet program and columned for data labeling. The post 1980 time series were regressed on year (T) to look for a significant F statistic ($\alpha = 0.05$). Only post-1980 data was explored for trend because there was a change point just

prior to 1980, which is consistent with the reports of a global shift in climate during the 1970s (see Trenberth and Hurrell 1994).

4.5 Least Squares Regression

This work uses a stepwise, least-squares, multiple linear regression trained on fifty-eight seasons of observations to estimate a linear approximation of the true slope and y-intercept of the rainfall-to-atmosphere relationship in nature. A single, more-generalized, basin-wide model was generated as well as the three individual equations for each climate sub-region for a total of four different regression models. All models are static, meaning that lagged factors are not considered.

4.5.1 Dependent Variable

The dependent "predicted" variable (y) is an average of paneled (longitudinal) localities, each with its own fifty-eight-year time series. The time series are not continuous; they are six-month aggregates: January thru June. There are actually four independent variables corresponding to the four regression models. One is a basin-wide average for each season. The other are sub-regional averages. Each season is a case: the spatially averaged, six-month precipitation. There are fifty-eight cases of y: one for each year of the epoch, which is 1950-2007. Since each case is a mean of forty members, y has a sample size of forty.

The rationale for using the basin-wide, six-month, January–June approach is that droughts of all types are regionally concurrent and synchronous in the basin and that socioeconomic drought is a summertime phenomenon because that is the time when stream flows are at their nadir and human demand is highest. Moreover, the aforementioned feedback mechanisms with dry, hot

soil might also play a role with the relationship between 1 July deficit and the successive deficiency later into the summer. Water resource managers need an outlook of the rainfall deficiency over the six-months prior to summer to prepare for the kind of drought impact that the Georgia Drought Management Plan and the Flint River Drought Prediction Act are designed to mitigate. Also, rainfall deficit is conveniently reported by the local media as rainfall deficit for the year. For these reasons, the January–June six-month rainfall deficiency is used as a proxy for summer drought in the basin.

4.5.2 Predictor Variables

The eight independent “predictor” variables (x_1, x_2, x_3… x_8) are standardized, six-month-averaged 700 mbar geopotential height Z and 700 mbar specific humidity q taken from eight map-point locations. The eight locations generate eight variables (four points for Z and four points are dedicated to q) with fifty-eight cases (seasons) each. All independent variables were standardized with respect to their mean and standard deviation (i.e. z-scores) because higher latitude points, with their higher variance, could have a disproportionate influence on the regression.

With strong spatial autocorrelation in the atmosphere, the eight map points need to be separated by some distance to be independent and suitable for statistical analysis, yet the measurement scale needs to be smaller than the geographic scale, which in this case is the synoptic scale: 1000—6000 km. In response to this need, and considering that points closest to home should be the most important (Klein and Bloom 1987), this study strikes a measurement compromise with an interval of 1000—1400 km centered directly over the region (fig. 8). These points should be dense enough to capture the synoptic scale, the scale that inertial and frictional

terms are an order of magnitude smaller than the Coriolis and pressure forces (Carlson 1991, 1,6,16, 33), yet far enough apart to be independent. If they are not independent, the corruption will show up as multicollinearity in the regression statistics. The points are placed equidistant to not interject any preconceived notion.

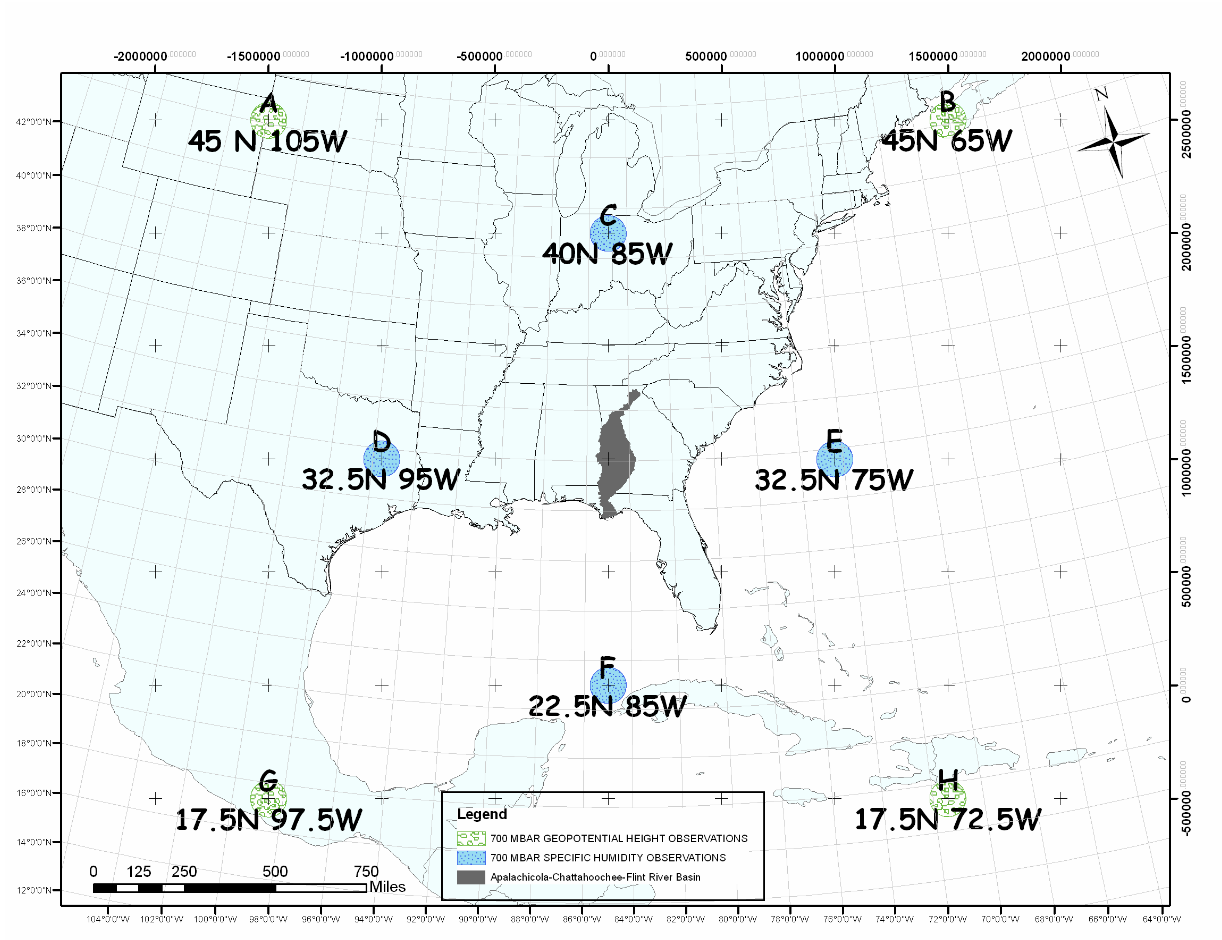


Figure 8. The location of the eight sampling points (decimal degrees) for upper atmospheric data. Tic marks for map coordinate system are in meters.

Both geopotential height and specific humidity were compiled at the 700 mbar level as others (q.v. Klein and Bloom 1987) have done. Also, general circulation models are better at predicting mid-tropospheric processes (Yarnal et al. 2001). While geopotential height is an obvious parameter for circulation, the four most inward points, C, D, E, and F, capture only specific

humidity because of the importance of water vapor transport in precipitation processes (Trenberth et al. 2003). Yarnal et al. (2001, 1933) comment, ". . . it is useful to include a predictor of atmospheric moisture because changes in the hydrologic cycle are likely to be the underlying cause of future changes in precipitation." Cavazos and Hewitson (2005) reported that mid-tropospheric geopotential heights and mid-tropospheric humidity were the two most relevant controls of daily precipitation at 15 different locations across diverse climate regimes. Crane and Hewitson (1998) found that including specific humidity improved correlations. Hanssen-Bauer et al. (2003) thought they could have modeled warm-season rainfall better with the inclusion of humidity as a predictor and expected that accelerations in the hydrologic cycle with climate change would make humidity an important factor.

4.5.3 Suitability of Data for Least Squares Regression

The fifty-eight cases of $x_{1\text{-}8}$ and y were screened for suitability for linear regression. Scatter plots were used to screen for any large gaps in values across their ranges. Outliers were reported and possibly dropped because they can have an anomalous influence on the regression line; although, since the models cannot be used outside the range of y, marginal outliers in y might be allowed. The independent variables were inspected for any salient curvilinear relationship to y because, implicit to all linear regression is the existence of some true linear relationship in nature. A non-linear relationship—an exponential one for example—could be treated by substituting the log of y. Some researchers (e.g. Crane and Hewitson 1998) address this problem with artificial neural nets (ANN) as a kind of non-linear multiple regression.

As for time trends, linear trends in y should be sought and reported because there might be a better way to compute R-squared (see Woolridge 2000, 339). Otherwise, it is not a violation for

any input variable to have a time trend, but if both *y* and x are trending, it might be because there is some more comprehensive factor affecting both. The null hypothesis that *y* has no time trend is tested by comparing the *t* statistic of the slope coefficient of a regression of *y* on year (T) to the critical value of ±2.00 needed for a two-tailed test with N-1=57 degrees of freedom at $\alpha = 0.05$. The test is two-tailed because the trend could be negative or positive.

y is screened for a standard normal distribution and the results are reported with Skewness and Kurtosis index. A skewed distribution of *y* is commonly addressed with a ladder-of-powers transformation, though the transformation is not straightforward to undo.

A primary assumption of many statistical techniques is that the data are independent, and data become independent by originating from dispersed measurements. Clustering can make observations redundant and biased towards some background condition. This study uses the systematic sampling technique, so the points are expected to be dispersed. Recalling that even a geometrically random distribution could be clustered, the null hypothesis that the nearest neighbor index ≤ 1 is tested by comparing the Z statistic of a nearest neighbor analysis to the critical value of 1.65 needed for a one-tailed test at $\alpha = 0.05$. The alternative hypothesis is that the points are more dispersed than random (1 < nearest neighbor index ≤ 2.15).

4.5.4 Performing the Regresssion

The dependent and independent variables were loaded into a competitive statistical software package and entered into a multiple linear regression. The stepwise option was used, meaning that the software includes variables with a significant slope ($\alpha = 0.05$) but might drop them later if their slopes became insignificant ($\alpha = 0.10$). These are the default tolerances for this software. The software provides the coefficients and y-intercepts and reports the *t*-statistics for the

coefficients along with the F-statistic for the entire model and its *R*-squared. The beta coefficients are also provided by the software. The error terms are provided and the option to save them was chosen. It is recommended to chose the descriptive statistics option to confirm that all fifty-eight cases are always picked up in the analysis.

4.5.5 Compliance to Mathematical Assumptions

All multiple, linear equations—especially those based on time series—are subject to mathematical assumptions: mostly manifested in the error term (u). The error term must (a) have a standard, normal distribution, (b) have a mean of zero, (c) not have variance related to the independent variables, (d) not be correlated with the independent variables, and (e) not have serial autocorrelation. If condition (a) is violated, the model is asymmetrical in how it handles high and low values. If condition (b) is violated, the model is said to be biased. If condition (c) is violated, the model is said to be heteoroskedastic. Heteoroskedasticity invalidates the significance of the t score of the slope coefficients and the F statistics that rate the model. Evidence of heteroskedasticity suggests that heteroskedasticity-robust t and F statistics will be needed in future work. If condition (d) is fulfilled, the model is said to be exogenous, which makes the model easier to test for serial autocorrelation. If condition (e) is violated, the model is said to have serial autocorrelation, which is a serious condition. Time series typically suffer from serial autocorrelation (Kleinbaum et at. 1998, 43). The presence of serial autocorrelation in u invalidates the t score of the slope coefficients

The models were tested for compliance to the mathematical assumptions. The error term (u) was inspected for normal distribution (a) and a mean of zero (b) and reported with Skewness and Kurtosis by using descriptive statistics in the software package. The null hypothesis that the

model is homoskedastistic (c) is tested with the significance of the F statistic from regressing u^2 on the independent variables ($\alpha = 0.05$) according to (Woolridge 2000, 257). This regression was an enter regression, meaning all the independent variables were forced with the enter technique. The null hypothesis that u has no contemporaneous correlation to the independent variables (d) is tested by entering all nine variables into two-tailed Pearson's correlation coefficient ($\alpha = 0.05$). The test is two-tailed because some correlations are positive, some negative. The Pearson's product-moment test is warranted because all variables approximate a normal distribution. The null hypothesis that there is no serial autocorrelation (e) in u is tested with the significance of the F statistic from regressing u on $u_{T\text{-}1}$ ($\alpha = 0.05$). To accommodate this, the error term was copied and pasted into a second column but off set forward by one year. This provides the previous year's error term in the same row. Then, u was regressed on lagged u ($u_{T\text{-}1}$). This test is merited because the model has been shown above to be contemporaneously exogenous (Woolridge 2000, 320, 381).

4.5.6 Model Characteristics

In the interest of the most parsimonious model, the null hypothesis that the slope coefficient for any variable is zero in the real world (i.e., the variable is irrelevant in nature) is tested with the t statistic at $\alpha = 0.05$. The test is two-tailed because the coefficient need only be non-zero. This is done by inspecting the significance of the coefficients from the regression statistics. It is assumed these significances are reported by the software as two-tailed. A failure to reject the null means the predictor is dropped. This is mostly an academic exercise; with the stepwise option, it is unlikely that any insignificant variables would remain, though presumably, with the default setting, any coefficient with a significance < 0.10 could remain. The amount of variance in y

explained by the models is reported with a coefficient of determination *R*-squared sometimes called "goodness of fit". Finally, an overall "trial by fire" for the regression model is that it predicts the dependent variable better than the mean of the dependent variable. The null hypothesis that it cannot do this is tested by comparing the significance of the F statistic for the entire model to the $\alpha = 0.05$ significance level. This means *P*-value of F statistic should be less than 0.05.

4.5.7 Model Validation

A model that complies well with the mathematical assumptions of multiple linear regression could be acceptable for inference yet still not be accurate enough for the rigors of scientific research. Since all measurements are used to train this model, a subset approach to validation is not available. A leave-one-out-cross-validation approach is taken to recursively generate predictions that can be compared to observed values. This means that fifty-eight quasi-modes of the original model were generated, and this was reiterated for the northern model, the central model, and the southern model. None of the fifty-eight versions will resemble the inducted model because they are all trained on N-1 cases, the left out season being rotated out through the iterations. The fifty-eight equations are then used to predict the season that each was not trained on. This series of predictions is then compared to the independent data. Validation statistics used to assess the model as "accurate" or "inaccurate" include (a) the percent error (PE), which should be less than 10%, (b) the mean bias error (MBE), which should be zero, and (c) the index of agreement (D), which should be 0.9 or greater.

4.5.8 Multicollinearity

Multicollinearity is a common problem with multiple linear regression in geography because social and climate variables are always linked to some degree. It artificially makes the F statistic look better than it really is (as can small sample size). As long as the independent variables are not perfectly correlated, however, the situation is not a violation of any assumption of ordinary least-squares regression. A strong correlation does suggest, however, that not all the variables are freestanding factors in their own right (see Woolridge 2000, 196). There might be less factors than variables.

Multicollinearity was handled by inspecting multicollinearity statistics reported by the software. The stepwise option should drop highly correlated predictor variables, but the multicollinearity of the ones that remain can still be inspected. If any remaining variables are found to have a variance inflation factor (VIF) > 10, one will be dropped. If two variables seem moderately collinear, but within tolerance, they will be combined, but if the combination is deleterious to the model, this would indicate the model is requesting both sets of information, and they would be retained separately.

4.6 Extrapolation of Trends in Predictor Variables

In light of Ross and Elliot (2001) indicating a statistically significant increase in surface–500 mbar precipitable water in the eastern United States, a second set of predictors was compiled by extrapolating trends from the historical measurements. Since Trenberth and Hurrell (1994) noted a pronounced shift in North Pacific atmospheric and oceanic trends starting in about 1976, and since the empirical time series did indeed have change points just prior to 1980, the trends from 1980 were the trends used in the extrapolations. The slope and y-intercept of a time series was

determined by regressing the variable on year (T) where $T \geq 1980$. If the F statistic was not significant ($\alpha = 0.10$), then the variable was considered to have no trend, and the mean was used. When there was a trend, the resulting regression equation was used to compute what the value would be for a future year.

4.7 Invoking the Models for Future Seasons

There are many GCMs to choose from (see Randall et al. 2007, 596). There are half a dozen from the Geophysical Fluid Dynamic Laboratory alone. This study downscales the CM2.1 model (assuming year 2000 CO_2 concentration) from the Geophysical Fluid Dynamics Laboratory. Other sources of GCMs include the Earth System Grid (ESG). Both these sources are available for public download. Randell et al. (2007), exhaustively provide their account of GCMs. They conclude that, in general, global climate models are an important and credible tool. GCMs are more reliable at general scales (thus downscaling) and suffer from uncertainly in the role of clouds in climate change, but they show an ability to successfully simulate current and past climates. Monsoons, storm tracks, and hemispheric oscillations have all been successfully simulated. Future researchers are encouraged to use the specification provided in this work on other GCMs.

GCM output was extracted with freeware from Doty (1988). Eight scripts were used: specific to a map point. The 700 geopotential level was set with the script, and recall that longitude is negative in the western hemisphere. The script then extracts the first six months of the year and averages them. It is useful to have a script reset all settings at the end to ensure the new script inherits a fresh environment.

The downscaled rainfall forecast is generated with spreadsheet formulas. All four regression equation are formulated into a spreadsheet program. Additionally, a tool to pre-standardize incoming values to 1950–2007 means is programmed in. The input data need only be entered into the correct, prearranged spreadsheet cells, and the four equation clusters look to those cells and display the rainfall output. Two identical arrays are needed: one for GCM driven data and one for empirically driven data. Finally, a fifth output variable is derived as a weighted blend of the three regional outputs. The blend is (a) 9/40 for the north, (b) 16/40 for the central, and (c) 15/40 for the south.

CHAPTER 5

RESULTS

5.1 Regionalization

The S-mode PCA decomposition results in the selection of three principal components that explain 81.8 percent of the variance in the rainfall localities. The fourth largest component contributed less than one eigenvalue. Nine contiguous localities in the northern basin load up maximally on one component, 16 central stations loaded on another, and the 15 southern stations loaded maximally on the other (fig. 9).

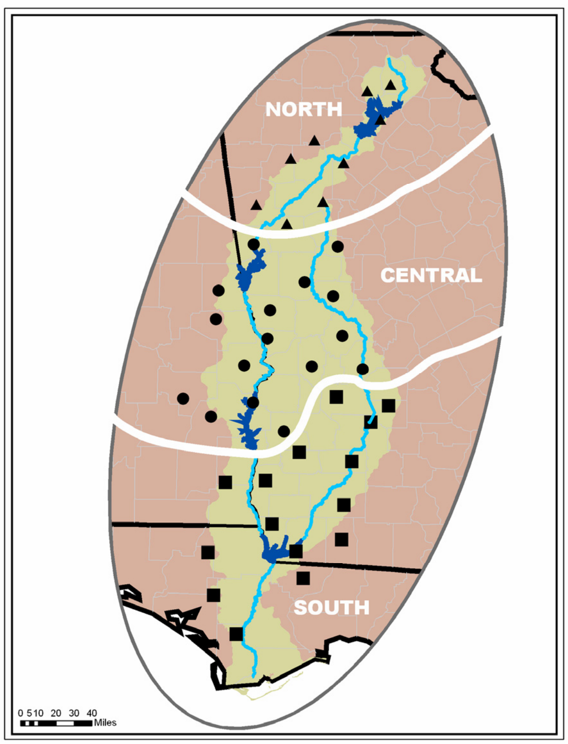


Figure 9. Results from the S-mode PCA decomposition of 40 time series.

5.2 Trends in Precipitation

The rainfall time series for the different sub-regions are presented in figure 10. None of the time series had a significant trend from 1980 or even 1990. This is due to the high variance. Interestingly, even with very high variance, the three sub-regions are remarkably in phase in recent years.

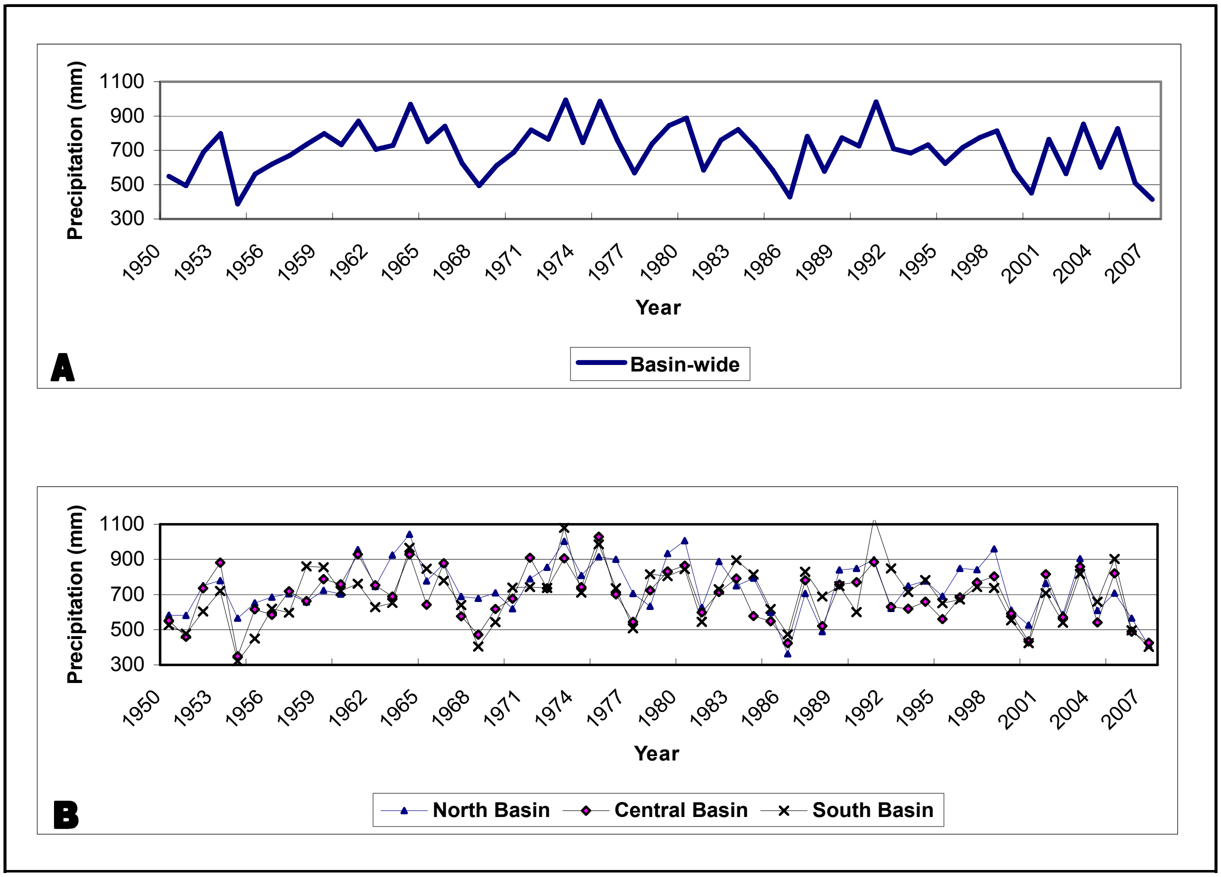


Figure 10. Time series of semiannual precipitation for the entire basin (A), and the PCA decomposed sub-regions (B).

5.3 Least Squares Regression

5.3.1 Suitability of data for Regression

The data is suitable for linear regression. There are no missing cases (seasons) in any variable. There is a fairly-continuous spread across the range of each variable. As for outliers, the "A" series of 700 mbar *Z* exhibits a pair of suppressed cases in the mid 1970s (three standard deviations), and the "H" series has less-severe suppressions in the 1950s, however, since they occur in consecutive years, these are accepted as naturally occuring. None of the *q* series have outliers. Scatter plots do not reveal any salient curvilinear relationships with *y*. The observed *t* statistic for a regression of *y* on T is -0.283, which does not fall outside the range of critical values; thus, we conclude there is no time trend in *y,* and this is true of the sub-regional rainfall time series also. Probably owing to the fact each case has a sample size of forty, *y* meets the assumption of normality. The distribution is only slightly negatively skewed (Skewnwess = -0.134) and slightly flatted (Kurtosis = -0.255). A transformation of *y* is not needed (see Kleinbaum et al. 1998, 46, 219). The Z statistic of the nearest neighbor analysis of the N=40 localities is 2.03. Since this exceeds the critical value of 1.65, the null hypothesis is rejected, and we conclude the points are more dispersed than random. The most proximate members are 22 km apart.

5.3.2 Compliance with Mathematical Assumptions

The error term for the regional model and the three sub-regions has a mean of zero, indicating that the models are not biased in their ability to fit a line to the data. The residuals for all four models are negatively skewed and flattened. The sub-regional models are less skewed.

The negative skewing is due to over-predictions in the mid-dry years that are not balanced by equivalent under-predictions in the moist years. There is no obvious reason for why the residuals should be negatively skewed; basin-wide rainfall is normally distributed, and wet and dry years are of about equal magnitude, The problem is not necessarily limited to the very driest seasons; in fact, the very dry seasons of 1954, 1986, and 2007 were handled better, and the very dry season of 2000 was handled much better. It is the mid-dry seasons that are the problem. A scatter plot of *u* on *y* for the regional model illustrates the trouble fitting moderately dry years (fig 11).

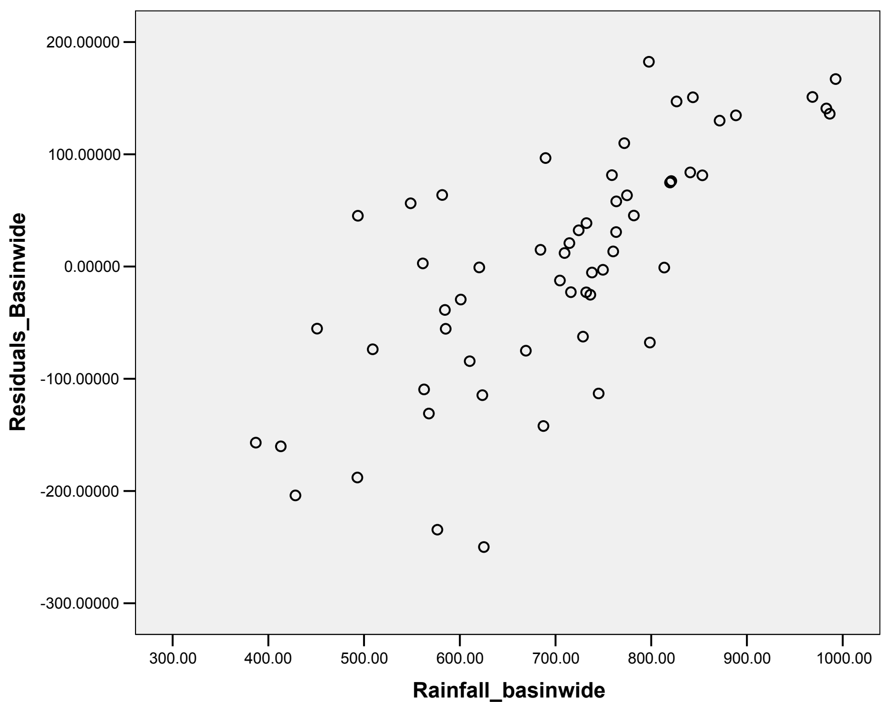


Figure 11. Residuals from the model plotted against observed rainfall (mm). A negative value is an overestimate. Mean rainfall is 703 mm.

The null hypothesis of homoscedasticity is not rejected for any model, and we conclude that there is no evidence of heteroskedasticity. The variance of the residuals is not dependent upon

the independent variables. Future researchers may not need to worry about heteroskedasticity-robust *t* and F statistics in future work, and it is not needed here.

Since none of the observed Pearson's correlation coefficients comparing u to the independent variables were significant for any of the models, the null hypothesis of an exogenous model is not rejected, and we conclude there is no evidence of a non-compliance to contemporaneously exogenous. It does not look like rainfall residuals tend to be correlated to predictor variables. Had the models not been exogenous, a more complex test for serial autocorrelation would be needed.

The test for serial autocorrelation is simply the observed F statistic for a regression of u on $u_{T-1.}$ This statistic was not significant for any of the models. The null hypothesis of zero serial autocorrelation is not rejected, and we conclude there is no temporal autocorrelation in the error term. This is important; serial autocorrelation adds considerable complication to linear regression. The six-month separation between cases likely helped, possibly because the first of the year is a kind of hydrologic reset, whereas the ground is nearly always moist due to heavy rains and cool temperatures, and the circulation has no way to remember past rainfall yields. It may be that the tendency to forget past rainfall is a global atmospheric proclivity, yet future researchers might consider putting a six-month interlude between observations in the ACF Basin. Results of the tests for mathematical assumptions are summarized in table 4.

Table. 4 Assessment for compliance to the mathematical assumptions of least squares regression.

	Mμ	Skμ	Kμ	Hsk	Exnous	SerAuto
Basin	0	-0.414	-0.374	0.787	0.116	0.264
North	0	-0.202	-0.496	0.284	0.201	0.678
Central	0	-0.048	-0.554	0.819	0.058	0.616
South	0	-0.238	-0.378	0.338	0.079	0.700

Mμ = mean of residuals.
Skμ = Skew of residuals.
Kμ = Kurtosis of residuals.
Hsk = the significance of the F statistic of the test of the null hypothesis that the model is homoskedastic.
Exnous = the most significant Pearson's Product-moment correlation of the residuals to independent variables.
SerAuto = the significance of the F statistic of the test of the null hypothesis that there is no serial autocorrelation.

5.3.3 Model Characteristics

The four models were quite different (table 5). The regressions dropped various predictors for insignificant coefficients, and none of them used the same set of predictors. What the models did have in common was a poor *R*-squared, which was the problem that the sub-regional models were designed to solve. None of the models could explain half the variance in the rainfall data they trained on. The models all had a significant F statistic: meaning that they were better than using the mean of the dependent variable. Again, this would be expected with a stepwise regression, or there would be no output at all.

Table 5. Characteristics of the linear regression models.

	Az	Bz	Cq	Dq	Eq	Fq	Gz	Hz	y-intercept	R-squared
Basin	N/A	N/A	N/A	-35.584	55.938	N/A	-79.112	98.740	702.756	0.461
North	-73.85	N/A	N/A	N/A	N/A	N/A	N/A	51.576	739.945	0.269
Central	-43.14	N/A	N/A	N/A	N/A	N/A	-58.977	99.654	687.567	0.311
South	N/A	N/A	N/A	N/A	50.385	N/A	-109.133	147.039	696.606	0.465

Az = coefficient for 700 mbar geopotential height at 45N 105W
Bz = coefficient for 700 mbar geopotential height at 45N 65W
Cq = coefficient for 700 mbar specific humidity at 40N 85W
Dq = coefficient for 700 mbar specific humidity at 32.5N 95W
Eq = coefficient for 700 mbar specific humidity at 32.5N 75W
Fq = coefficient for 700 mbar specific humidity at 22.5N 85W
Gz = coefficient for 700 mbar geopotential height at 17.5N 97.5W
Hz = coefficient for 700 mbar geopotential height at 17.5N 72.5W

5.3.4 Model Validation

The models are fundamentally sound, but their cross-validation is lackluster, and an attempt to improve accuracy by breaking the domain down into specialized sub-regions seems ineffective (table 6). While the predictions are symmetrical—meaning that over-predictions and under-predictions are of equal magnitude—they are somewhat erroneous. The proportion of systematic error (PSE), for example, would be expected to be closer to 0.10, and percent error (PE) should be less than 10%. The index of agreement (D) should be closer to 0.9. The model does not seem to follow the variations in observed rainfall very closely, being off by 115–134 mm on average. The indications are that the models need more information, the nature of which is difficult to speculate. Many climate downscaling projects use surface data, but GCMs are known to predict mid-troposphere patterns better.

Table 6. Cross validation statistics for all models.

	n	MBE	RMSE	D	PSE	PE
Basin	58	1.51	115.10	0.74	0.53	16.40
North	58	1.30	132.85	0.58	0.71	18.00
Central	58	-0.03	134.17	0.63	0.69	19.50
South	58	0.57	132.28	0.75	0.53	19.00

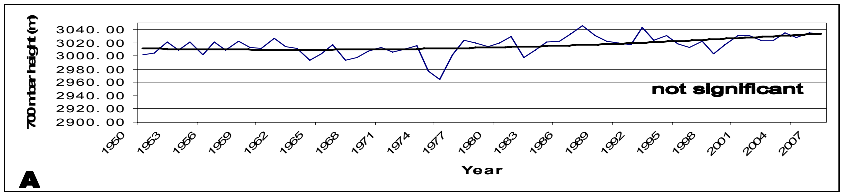
n = number of cases
MBE = mean bias error (mm)
RMSE = root mean square error (mm)
D = coefficient of agreement
PSE = proportion of systemic error
PE = percent error (%)

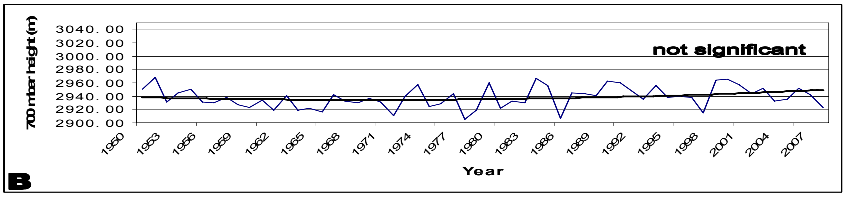
5.3.5 Multicollinearity

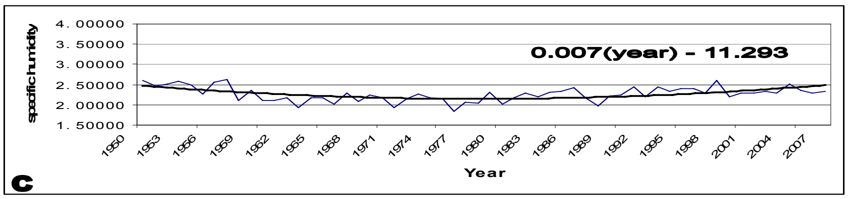
No variable in any model was dropped for multicollinearity, however, multicollinearity statistics for the models that used data point G and H indicate that the two series might be partially overlapping functions of the same factor. Since the variance inflation factors for these variables was less than 10 (around 2), and since an attempt to combine them degrades the *R*-squared considerably, they are retained.

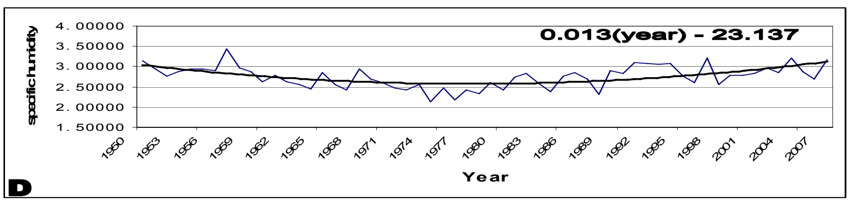
5.4 Extrapolation of Trends in Predictor Variables

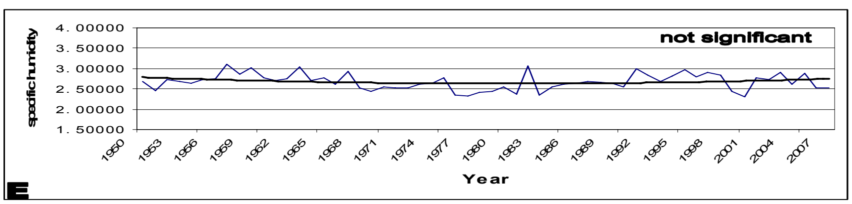
The time series with the associated slopes and y-intercepts of the mid-tropospheric data are presented in figure 12. Several time series did not have significant trends, but D and G did (C was not used by any regression equation). A qualitative inspection of data point A evokes a trend, but it is not statistically significant due to the high variance. Note, for the aforementioned reasons, all slope and y-intercepts are calculated from 1980.

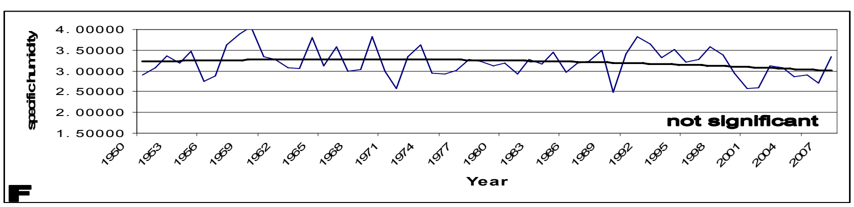

700 mbar height (m)
not significant
Year
A

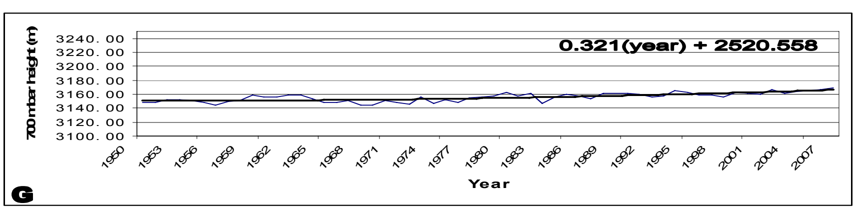

700 mbar height (m)
not significant
Year
B


specific humidity
0.007(year) - 11.293
Year
C


specific humidity
0.013(year) - 23.137
Year
D


specific humidity
not significant
Year
E


specific humidity
not significant
Year
F


700 mbar height (m)
0.321(year) + 2520.558
Year
G

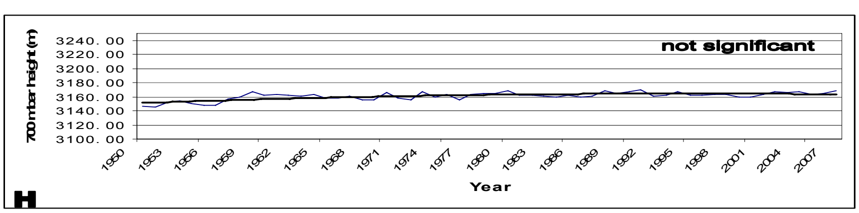

700 mbar height (m)
not significant
Year
H

Figure 12. Time series of 700 mbar geopotential height in meters (ABGH) and specific humidity in g/kg (CDEF). Slope and y-intercept since 1980 is provided where a significant trend exists.

5.5 Invoking the Model

The regression models are invoked with both GCM input and extrapolations of empirical data for years 2008–2011. The results are presented in table 7. This table presents a considerable amount of information, but one of the easiest points to realize is that empirical trends are for increasing drought, especially in the south. GCM driven predictions do not necessarily depict this trend. The reason that GCM driven forecasts depart from empirically driven forecasts is that GCMs do not predict trends in the atmosphere; they predict processes.

Table 7. Invoking the models. Empirically extrapolated 700 mbar specific humidity (q) geopotential height (Z) for 2008–2011, the GCM model output, the corresponding l July rainfall, the 1950–2007 average (AVE), and standard deviation (SDEV).

	D	E	A	G	H	ACF	$sub_{(N)}$	$sub_{(C)}$	$sub_{(S)}$	weighted
	q		Z							
					Empirically Driven					
2008	2.960	2.677	3015.99	3165.13	3160.91	557.28	739.91	599.74	534.13	606.67
2009	2.980	2.677	3015.99	3165.45	3160.91	550.64	739.91	596.74	528.57	603.39
2010	2.993	2.677	3015.99	3165.77	3160.91	544.91	739.91	593.74	523.02	600.11
2011	3.006	2.677	3015.99	3166.09	3160.91	539.18	739.91	590.74	517.47	596.83
					GCM Driven					
2008	3.170	2.281	3002.69	3149.84	3154.13	492.01	745.78	663.18	522.54	629.02
2009	2.839	2.669	3016.51	3146.79	3152.08	647.40	656.74	614.57	620.73	626.37
2010	2.885	2.462	3023.93	3148.69	3151.25	544.60	611.41	560.07	513.60	554.19
2011	2.810	2.756	3009.20	3147.98	3151.20	645.41	685.92	609.64	599.31	622.93
AVG	2.749	2.677	3015.99	3155.77	3160.91	702.81	739.99	687.63	696.69	702.81
SDEV	0.271	0.198	14.51	6.29	5.66	143.82	148.25	151.26	167.82	

q = 700 mbar specific humidity (g/kg).
Z = 700 mbar geopotential height (m).
ACF = precipitation output (mm) for the basin-wide model.
$sub_{(N)}$ = precipitation output (mm) for the north sub-regional model.
$sub_{(C)}$ = precipitation output (mm) for the central sub-regional model.
$sub_{(S)}$ = precipitation output (mm) for the southern sub-regional model.
weighted = a weighted average of the three sub-regional models (mm).
D, E, A, G, H are map points.

CHAPTER 6

DISCUSSION AND CONCLUSION

6.1 Accuracy

The validation of the regression models in this study all show lackluster accuracy with Percent Errors in the 15–20% range. The literature indicates that spatial averaging and temporal smoothing are important factors in the research design, as well as staying within the middle latitudes and within the cool season, and this project has those characteristics. Moreover, there is a special effort to fit models to specialized climate regions so as not to overburden them with a broad range of conditions. Nevertheless, the results of the validation indicate that something is missing from the models, and it is difficult to speculate on what that might be. It is noteworthy that several downscaling studies cited in this research use surface data, and surface data was not used in this study, but other literature indicates that GCMs are better at predicting mid-tropospheric processes; thus, there seems to be precedent for not using surface data.

6.2 Inference

Though the models developed in this project may not be accurate enough to be used under the rigors of scientific research for prediction, they do comply well with the mathematical assumptions of multiple linear regression, and therefore can be used for inference. The most salient inference to be taken from these models is that low-latitude data points seem to be a dominant influence. Only one data point at higher latitudes was ingested. Two high latitude points (B and C) were not used at all. The basin-wide model, which used the most data points, used none of the higher latitude points. Only the north basin and central basin models used the

lone higher latitude point. Klein and Bloom (1987), specifying 700 mbar height to spatially-averaged precipitation in the U.S., also noted the importance of low-latitude points (20º–25º N). If the variables were unstandardized, the more northern ones would have likely been ingested because they have higher variance.

Geopotential height at low-latitude appears to drive rainfall in the ACF basin. The inference from the coefficients is that, of the two low-latitude geopotential height points, the southeastern one needs to be high and the southwestern one needs to be low to encourage precipitation. This may evoke a return flow process from the Gulf of Mexico (Kara, Elsner and Ruscher 1998), but the reader is cautioned that moisture flow from the Gulf of Mexico also depends on ocean temperature, the depth of transport, time spent over the water, soil moisture at coastal locations, and may not necessarily result in increased precipitation; therefore, a process is not necessarily implied from the relationship.

Specific humidity is not regarded by the models to be as important as geopotential height; the coefficients were smaller and two specific humidity points (E and F) were completely disregarded by all the models. Having made that point, the coefficients still evoke a process, and again, this process involves return flow from the Gulf of Mexico. This time, however, it seems to be that the situation of a lack of moisture to the west of the ACF Basin favors rainfall. Could it be that, in wet years, moisture is flowing directly over the ACF Basin instead of being shunted to the west?

One might protest that coefficients cannot be compared in such a way—that only the beta coefficients can be directly compared across variables in different units. Recall, however, that the predictors are all standardized; thus, comparison is merited. A cursory inspection of the beta coefficients did show the same pattern.

6.3 The Predictions

An overarching and gripping conclusion to be drawn from table 7 is that no model at any time, using any data, forecasts above normal precipitation: except for in the north in 2008. All other times and data result in below-average precipitation. If these four consecutive seasons of below-normal rainfall come to pass on the heels of the second driest year in history (2007), it will be an unusual and costly episode in the climate history of the Southeast. Enduring, unrelenting drought is not the norm (see figure 3), yet these models seem to depict a status quo of drought over the entire period. The empirically driven forecasts, since they are starting from dry conditions and trending downward, forecast a steady deterioration in conditions as the years progress. No (used) atmospheric variable is significantly trending in a direction that would favor precipitation, and two of them are trending in a direction that disfavors precipitation. The GCM driven forecasts, however, are based on atmospheric processes that jump from year to year, so one might expect at least one wet year to be juxtaposed among the dry years. A dendrochronology study by Stahle and Cleaveland (1992) suggested that decade-long regimes in spring rainfall are possible in the Southeast; perhaps we are entering one.

There is opportunity, at the late writings of this work, for a pseudo-validation of the 2008 forecasts. The forecast can be summarized as such: normal to above normal rainfall in the north, below normal rainfall in the central, and much below normal rainfall in the south. The overall models depict overall drought for the basin. At the time of this writing, (mid June) the basin is experiencing overall drought, especially in the south, where Apalachicola is experiencing a 135 mm deficit for the year. Even rainfall in the north is not achieving normal yields. The Gwinnett Daily Post reported on 12 June 2008 that the Chattahoochee River upstream of Lake Lanier at Cornelia, Georgia was flowing at 28 percent its normal discharge.

The 2009 forecasts are for continued below normal rainfall, however, unlike the other three years that strike the southern basin particularly hard, in 2009 the drought conditions shift more into the central section. Though the ACF river system is managed as one body of water, most of Georgia's agriculture is in the south. Consequently, a meteorological drought in the central sections might incur less social cost.

The hydrological outlook is grim for 2010. That year is predicted to see drought, especially in the south. All the different approaches show this to be the case. There is a chance the north might escape this drought, but if the south sees severe drying, the issue of water release from Lake Sidney Lanier will become contentious again.

In 2011 the outcomes begin to diverge. Of course, by this time, empirical trends in the atmosphere predict worsening drought: especially in the south. This is due to the fact that circulation parameters at map points D and G, which are influential points, are trending in favor of drought and, by this time, overwhelm the output. The GCMs, however, reverse the empirical trends and relax these predictors; thus, the GCM forecasts are for improved yet still sub-optimal conditions in all sections.

6.4 Summary of Findings

The major points and findings of this study are:

(1) There is increasing risk of basin-wide, meteorological, hydrological, and socioeconomic drought in the region.

(2) All three types of drought are concurrent and regionally synchronous, and hydrologic and socioeconomic drought are a summertime phenomenon.

(3) There have been climate downscalings elsewhere, and there have been drought predictions in the ACF Basin, but there have been no predictions from climate downscaling for the ACF Basin.

(4) Future researchers should give attention to improved accuracy.

(5) The medium-dry years seem most difficult to predict.

(6) Future researchers can expect that their models will be mathematically sound.

(7) The six-month interlude between cases might help.

(8) Mid-tropospheric, geopotential heights at lower latitudes are important.

(9) Higher pressure to the southeast and lower pressure to the southwest favor rainfall.

(10) Drier air to the west and moist air to the east favor rainfall.

(11) Several atmospheric variables are trending in favor of drought; none are trending in favor of precipitation.

(12) The basin seems to have three climate regions.

(13) The prediction is for prevailing drought conditions throughout the 2008–2011 period, especially in the south, with particularly strong drought in 2010.

6.5 Avenues for Future Research

We need more assimilation between public policy and climate science. One avenue towards this goal is to provide a more practical interpretation of climate data for decision makers. As one example, Steinemann (2003) has added a probabilistic approach to drought forecasting by transforming the categories of the two popular drought indexes (SPI and PDSI) into probabilistic brackets. (An interval of SPI in the high range of magnitude represents less shift in the probability of occurrence). Decision makers need to know the actual probability that an event

will occur. This will help them develop actionable thresholds. Key events that managers might be concerned with are depleted flow in the Flint River and pool levels on Lake Sidney Lanier. To meet those managerial needs, scientists should develop standardized, accessible, trustworthy, and practical statistics to compliment raw scientific data.

Georgia, like other states such as South Carolina (Carbone and Dow 2005), has been slow to reconcile climate science with water management policy. To improve progress, the challenge for climatologists now is to make policymakers aware of their new tools, to make the tools relevant and tailored to user needs, and to provide a convincing case for reliability. “Pulling the trigger” on drought mitigation protocols is naturally an uncomfortable commitment for a politician because it can affect his/her prospects of re-election. Agricultural decisions are particularly irreversible. Perhaps an isolated bad call might have the benefit of unveiling true economic consequences so that planners can hedge the risk, but repeated misuse or misunderstanding will diminish the credibility of climate science. If we cannot cushion political risk, the best climate data in the world might go completely unused.

REFERENCE LIST

Adams, Jennifer, Dottie Crews, and Ronald Cummings. 2004. The sale and leasing of water rights in western states: an update to mid-2003. Geogia Water Planning & Policy Center. Retrieved August 12, 2006 from http://www.h2opolicycenter.org.

Alhadeff, Jack S., Jonathan W. Musser, Alan C. Sandercock, and Thomas R. Dyar. n.d. *Digital environmental atlas of Georgia.* Atlanta, GA: Georgia Geological Survey. version 2.0.

Alexandrov, Vesselin A., and Gerrit Hoogenboom. 2001. Climate variation and crop production in Georgia, USA, during the twentieth century. *Climate Research* 17:33–43.

Allen, David J. 1995. Channels and flow. Chapter 1 of *Stream Ecology: Structure and function of running waters*. Dordrecht, The Netherlands: Kluwer Academic Publishers.

Barber, Nancy L., and Timothy C. Stamey. 2000. Droughts in Georgia. Reston, Virginia: U.S. Geological Survey. Open-File Report OFR 00-380.

Cancelliere, A., G. Di Mauro, B. Bonaccorso, and G. Rossi. 2007. Drought forecasting using the Standardized Precipitation Index. *Water Resource Manager* 21:801–819.

Carlson T.N. 1991.Vorticity and vertical motion. Chapter 2 of *Mid-latitude weather systems*. London: HarperCollins*Academic.*

Carbone, Gregory, J., and Kristin Dow. 2005. Water Resource Management and Drought Forecasts in South Carolina. *Journal of the American Water Resources Association* 41, no. 1:145–155.

Cavazos, Tereza and Bruce. C. Hewitson. 2005. Performance of the NCEP-NCAR reanalysis variables in statistical downscaling of daily precipitation. *Climate Research* 28, no. 2:95–107.

Chakravorty, Ujjayant and Donna K. Fisher. 2005. Water management in a river basin with downstream externalities. Geogia Water Planning & Policy Center. Retrieved August 12, 2006 from http://www.h2opolicycenter.org.

Conway D., R. L. Wilby, and P. D. Jones. 1996. Precipitation and air flow indices over the British Isles. *Climate Research* 7, no. 2:169–183.

Couch, Carol A. 1993. Environmental setting of the Apalachicola-Chattahoochee-Flint river basin. In *Proceedings of the 1993 Georgia Water Resources conference, held April 20 and 21, 1993 at the University of Georgia*, edited by Kathryn J. Hatcher. Athens, Georgia: University of Georgia.

Crane, Robert G., and Bruce C. Hewitson. 1998. Doubled CO_2 precipitation changes for the Susquehanna Basin: Downscaling from the GENESIS general circulation model. *International Journal of Climatology* 18:65–76.

Crews, Dottie and Kristina Dowling. The Flint River basin's changing faces: Water management challenges for Georgia. 2002. Geogia Water Planning & Policy Center. Retrieved August 12, 2006 from http://www.h2opolicycenter.org.

Cummings, Ronald G., Nancy A. Norton, and Virgil J. Norton. 2001. Enhancing in-stream flows in the Flint River basin: Does Georgia have sufficient policy tools? 2001. Geogia Water Planning & Policy Center. Retrieved August 12, 2006 from http://www.h2opolicycenter.org.

Curtis, Scott. 2006. Developing a climatology of the South's 'other' storm season. *Southeastern Geographer* 46, no. 2:231–244.

Dai, Aiguo, Kevin E. Trenberth, and Taotao Qian. 2004. A global dataset of Palmer Drought Severity Index for 1870-2002: Relationship with soil moisture and effects of surface warming. *Journal of Hydrometeorology* 5:1117–1130.

Delworth, Thomas L., et al. 2006. GFDL's CM2 global coupled models. Part 1: formation and simulation characteristics. *Journal of Climate* 19:643–674.

Diem, Jeremy E. 2006. Synoptic-scale controls of summer precipitation in the southeastern United States. *Journal of Climate* 19, no. 4:613–621.

Doty, Brian. 1988. *Grid Analysis and Display System (GRADS)* provided free from and the Institute of Global Environment and Society (IGES).

Edgens, Jefferson G. 2001. Thirst for growth. *Forum for Applied Research and Public Policy* 16, no. 1:14–18.

Fennessy, M. J., and J. Shukla. 1999. Imapact of initial soil wetness on seasonal atmospheric prediction. *Journal of Climate* 12, no. 11:3167–3181.

Field, C. B., L. D. Mortsch,, M. Brklacich, D. L. Forbes, P. Kovacs, J. A. Patz, S. W. Running and M. J. Scott. 2007. in North America Chapter 14 of: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 617–652.

Frick, Elizabeth A., Daniel J. Hippe, Gary R. Buell, Carol A. Couch, Evelyn H. Hopkins, David J. Wangsness, and Jerry W. Garrett. n.d. Water quality in the Apalachicola-Chattahoochee-Flint river basin, Georgia, Alabama, and Florida, 1992-95. Reston, Virginia: U.S. Geological Survey. Circular 1164.

Georgakakos, Aris, and Huaming Yao. 2003. Climate variability and change assessments for the ACF and ACT river basins. In *Proceedings of the 2003 Georgia Water Resources conference, held April 13-24, 2003 at the University of Georgia*, edited by Kathryn J. Hatcher. Athens, Georgia: University of Georgia.

Goodrich, Gregory B., and Andrew W. Ellis. 2006. Climatological drought in Arizona: An analysis of indicators for guiding the Governor's drought task force. *The Professional Geographer* 58, no. 4:460–469.

Guttman, Nathaniel B. 1998. Comparing the Palmer Drought Index and the Standardized Precipitation Index. *Journal of the American Water Resources Association* 34, no. 1:113–121.

Guttman, Nathaniel B. n.d. Determination of drought frequencies for the National Drought Atlas. National Climatic Data Center, Asheville, NC. Retrieved November 2005 from ftp://ftp.ncdc.noaa.gov/pub/data/drought/archive/drtindex.dat.

Hanssen-Bauer I., E. J. Förland, J. E. Haugen, and O. E. Tveito. 2003. Temperature and precipitation scenarios for Norway: Comparison of results from dynamical and empirical downscaling. *Climate Research* 25, no. 1:15–27.

Hardin, Marie. 2002. Murky waters. *Georgia Trend: Norcross*, 1 July, 69. Database on-line. Available from Proquest, 133761071.

Harman, Jay R. 1991. *Synoptic climatology of the westerlies: Processes and patterns*. Washington D.C.: Association of American Geographers.

Harnack, Robert P., and John R. Lanzante. 1985. Specification of United States seasonal precipitation. *Monthly Weather Review* 113:319–325.

Hayes, Michael, J., Mark D. Svoboda, Donald A. Wilhite, and Olga V. Vanyarkho. 1999. Monitoring the 1996 drought using the Standardized Precipitation Index. *Bulletin of the American Meteorological Society* 80, no. 3:429–438.

Heddinghaus, Thomas R., and Paul Sabol. 1991. A review of the Palmer Drought Severity Index: Where do we go from here? In *Proceedings of the seventh conference on applied climatology held in Salt Lake City, Utah 10-13 September 1991*, edited by American Meteorological Society. Boston, Massachusetts.

Heim, Richard R. Jr. 2002. A review of twentieth-century drought indices used in the United States. *Bulletin of the American Meteorological Society* 83, no. 8:1149–1165.

Henderson, Keith G., and Peter J. Robinson. 1994. Relationships between the Pacific/North American teleconnection patterns and precipitation events in the southeastern USA. *International Journal of Climatology* 14:307–323.

Henderson, Keith G., and Anthony J. Vega. 1996. Regional precipitation variability in the southern United States. *Physical Geography* 17, no. 2: 93–112.

Hewitson, B. C. and R. G. Crane. 1996. Climate downscaling: Techniques and applications. *Climate Research* 7, no. 2:85–95.

Huschke, Ralph A., ed. 1959. *Glossary of Meteorology*. Boston: American Meterological Society.

Jacobs, Katharine, Gregg M. Garfin, and Barbara J. Morehouse. 2005. Climate science and drought planning: The Arizona experience. *Journal of the American Water Resources Association* 41, no. 2:437–445.

Kalnay, E., et al. 1996. The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society* 77, no. 3:437–471.

Kara, Birol A., James B. Elsner, and Paul H. Ruscher. 1998. Numerical models of boundary layer processes over and around the Gulf of Mexico during a return flow event. *Weather and Forecasting* 13, no. 4:921-933.

Keables, Michael J. 1988. Spatial associations of midtroposperic circulation and upper Mississippi River basin hydrology. *Annals of the Association of American Geographers* 78, no. 1:74–92.

Keyantash, John, and John A. Dracup. 2002. The quantification of drought: An evaluation of drought indices. *Bulletin of the American Meteorological Society* 83, no. 8:1167–1180.

Klein, William, H. 1983. Objective specification of monthly mean surface temperature from mean 700 mb heights in winter. *Monthly Weather Review* 111:674–691.

Klein, William H., and Hal J. Bloom. 1987. Specification of monthly precipitation over the United States from the surrounding 700 mb height field. *Monthly Weather Review* 115:2118–2132.

Kleinbaum G. David, Lawrence L. Kupper, Keith E. Muller, and Azhar Nizam. 3d ed. 1998. *Applied regression analysis and other multivariable methods*. Pacific Grove, CA: Duxbury Press.

Knight, Troy. 2004. Reconstruction of Flint River streamflow using tree rings. Geogia Water Planning & Policy Center. Retrieved August 12, 2006 from http://www.h2opolicycenter.org.

Kundell, James E., Terry A. DeMeo, and Margaret Myszewski. 2000(?). Developing a comprehensive state water management plan. Research Atlanta, Inc., Georgia State University Andrew Young School of Policy Studies.

Landers, Mark N., and Jaime A. Painter. 2007. How much water is in the Apalachicola, Chattahoochee, and Flint rivers, and how much is used? Reston, Virginia: U.S. Geological Survey. Fact Sheet FS 2007–3034.

Lettenmaier, Dennis P., Andrew W. Wood, Richard N. Palmer, Eric F. Wood, and Eugene Z. Stakhiv. 1999. Water resource implications of global warming: A U.S. regional perspective. *Climatic Change* 43:537–579.

Lipford, Jody W., 2004. Averting water disputes: A Southeastern case study. *Perc Policy Series* no. PS-30. Retrieved August 2007 from http://www.perc.org/.

Lohani, V. K., and G. V. Loganathan. 1997. An early warning system for drought management using the Palmer Drought Index. *Journal of the American Water Resources Association* 33, no. 6:1375–1386.

Martin, Rebecca, S. 2008. Executive Director, Development Authority of Bainbridge and Decatur County and formerly of Tri-River Waterway Association. Interview by telephone 7 July 2008.

McDowell, Rob, Bill Frechette, Kevin Farrell, David Hawkins, Mark Masters, and Alice Miller-Keyes, Georgia Department of Natural Resources, Environmental Protection Division. 2006. Flint River Basin regional water development and conservation plan. Retrieved August 25, 2006 from http://www.gadnr.org/frbp/index.html.

Meehl, G. A., T. F. Stocker, W. D. Collins, P. Friedlingstein, A. T. Gaye, J. M. Gregory, A. Kitoh, R. Knutti, J.M. Murphy, A. Noda, S. C. B. Raper, I. G. Watterson, A. J. Weaver, and Z.-C. Zhao. 2007. in Chapter 10 Global Climate Projections of: *Climate Change 2007:The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Melton, Harold, and Todd Silliman. 2005. Reflections on the ACF and ACT basin compacts. In *Proceedings of the 2005 Georgia Water Resources conference, held April 25-27, 2005 at the University of Georgia*, edited by Kathryn J. Hatcher. Athens, Georgia: University of Georgia.

Metropolitan North Georgia Water Planning District. 2003a. *Water supply and water conservation management plan.*

Metropolitan North Georgia Water Planning District. 2003b. *Watershed management plan.*

McKee, T. B., N.J. Doesken, and J. Kleist. 1993. The relationship of drought frequency and duration to time scales. In *Proceedings of the eighth conference on applied climatology held in Anaheim, California*, edited by American Meteorological Society. Boston, Massachusetts.

National Climatic Data Center. 2003. *Data documentation for data set DSI – 3200.* Ashville, N.C.: National Climatic Data Center.

National Atlas of the United States. 1991. *Climate divisions.* Reston, Virginia: U.S. Geological Survey version 1.1 (see water.usgs.gov/GIS).

National Atlas of the United States. 2005. *Streams and waterbodies of the United States*. Reston, Virginia: National Atlas of the United States.

Nicholls, Neville, Michael J. Coughlan, and Karl Monnik. 2005. Chapter 2 of *Drought and water crisis*. Edited by Donald A. Wilhite. Boca Raton FL: Taylor & Francis Group.

Palmer, Wayne. C. 1965. Meteorological drought. Reasearch Paper 45, U.S. Department of Commerce, 58pp.

Randall, D.A., R.A. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, A. Pitman, J. Shukla, J. Srinivasan, R.J. Stouffer, A. Sumi, and K.E. Taylor. 2007. in Chapter 8 Climate Models and Their Evaluation of: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Redmond, Kelly T. 2002. The depiction of drought. *Bulletin of the American Meteorological Society* 83, no. 8:1143–1165.

Rind, D.1982. The influence of ground moisture conditions in North America on summer climate as modeled in the GISS GCM. *Monthly Weather Review* 110:1487–1493.

Rose, Seth. 1998. A statistical method for evaluating the effects of antecedent rainfall upon runoff: applications to the coastal plain of Georgia. *Journal of Hydrology* 211: 168–177.

Ross, Rebecca J., and William P. Elliot. 2001. Radiosonde-based northern hemisphere tropospheric water vapor trends. *Journal of Climate* 14:1602–1612.

Ruhl, J. B. 2005. Water wars eastern style: Divvying up the Apalachicola-Chattahoochee-Flint river basin. *Journal of Contemporary Water Research and Education* 131:47–54.

Stahle, David W., and Malcolm K. Cleaveland. 1992. Reconstruction and analysis of spring rainfall over the southeastern U.S. for the past 1000 years. *Bulletin of the American Meteorological Society* 73, no. 12:1947–1961.

Steinemann, Anne C. 2003. Drought indicators and triggers: A stochastic Approach. *Journal of the American Water Resources Association* 39, no. 5:1217–123.

Steinemann, Anne C. 2006. Using climate forecasts for drought management. *Journal of Applied Meteorology and Climatology* 45:1353–1361.

Trenberth, Kevin E., Aiguo Dai, Roy R. Rasmussen, and David Parsons. 2003. The changing character of precipitation. *Bulletin of the American Meteorological Society* 84, no. 9:1205–1217.

Trenberth, Kevin, E., and James W. Hurrell. 1994. Decadal atmosphere-ocean variations in the Pacific. *Climate Dynamics* 9, no.6:303–319.

Trewartha, Glenn T., and Lyle H. Horn. 1980. *An introduction to climate*. 5th ed. New York: McGraw-Hill Book Company.

Turner, Monica G., Dirginia H. Dale, and Robert H. Garner. 1989. Predicting across scales. *Landscape Ecology* 3, nos. 3/4:245–252.

U.S. Army Corps of Engineers Mobile District Water Management Section - ACF historic project data. n.d. Retrieved August 2007 from http://water.sam.usace.army.mil/acfframe.htm.

Vickers, Amy. 2005. Chapter 7 of *Drought and water crisis*. Edited by Donald A. Wilhite. Boca Raton FL: Taylor & Francis Group.

Watermolen, John. 2005. *1:2,000,000-scale hydrologic unit boundaries.* Reston, Virginia: National Atlas of the United States. version 2.4.

Weber, Lena, and Lawrence Nkemdirim. 1998. Palmer's drought indices revisited. *Geografiska Annaler Series A: Physical Geography* 80, no. 2:153–173.

Western Governors' Association. 2004. *Creating a drought early warning system for the 21st century*. Denver: The National Integrated Drought Information Center. Retrieved August 04, 2007 from http:// www.westgov.org.

Wilhite, Donald A. 1997. Responding to drought: Common threads from the past, visions for the future. *Journal of the American Water Resources Association*. 33, no. 5:951–959.

Wilhite, Donald A., and Margie Buchanan-Smith. 2005. Chapter 2 of *Drought and water crisis.* Boca Raton, FL: Taylor and Francis.

Wilhite, Donald, Mark D. Svoboda, and Michael J. Hayes. 2007. Understanding the complex impacts of drought.: A key to enhancing drought mitigation preparedness. *Water Resources Management* 21:763–774.

Woolridge, Jeffrey, M. 2000. *Introductory Econometrics*. South-Weston College Publishing.

Yarnal, Brent. 1993. *Synoptic climatology in environmental analysis*. London: Belhaven Press.

Yarnal, Brent, Andrew C. Comrie, Brent Frakes, and David Brown. 2001. Developments and prospects in synoptic climatology. *International Journal of Climatology* 21: 1923–1950.