

**South Carolina Water Resources Center
Annual Technical Report
FY 2014**

Introduction

The South Carolina Water Resources Center uses its operating funds to carry out its mission as a liaison between the US Geological Survey, the university community and the water resources constituencies of those institutions. This is accomplished by serving as a water resources information outlet through our web site, by serving as a research facilitator through our annual grants competition and by operating as a catalyst for research and educational projects and programs across South Carolina. The Water Center also serves as a conduit for information necessary in the resource management decision-making arena as well as the water policy arena of the state.

While continuing to be involved with numerous water issues across the state including membership on an ad hoc statewide committee identifying policy issues related to primary water concerns and analyzing population growth impacts on water resources, the Water Center is collaborating with multidisciplinary teams investigating natural system/social system interactions. The SCWRC also serves on the Savannah River Basin Advisory Council to assist SCDHEC and the SC Department of Natural Resources with management recommendations as well as serving on SCDNR's advisory group for the state water plan. The SCWRC has recently been funded to participate with the South Carolina Sea Grant Consortium in developing the first state of the knowledge report for storm-water pond management in coastal South Carolina. The SCWRC has also been asked by one of the states largest water utilities to be part of a master planning effort which will guide the growth of the Greenville, SC water system through the 21st century.

The SCWRC has reaffirmed relationships with key individuals from the South Carolina Department of Natural Resources, the South Carolina Department of Health and Environmental Control and South Carolina Sea Grant Consortium in order to advise these state agencies that have critical roles in managing the water resources of the state. As an outcome of those meetings, the SCWRC has continued work as a committee member on the Savannah River Basin Advisory Committee for SCDHEC. In addition, the SCWRC is an advisory member of Clemson University's Intelligent River program, a program funded through the National Science Foundation and Clemson University that is designing real time monitoring for South Carolina's rivers. The SCWRC also sits on the South Carolina Sea Grant Consortium's Program Advisory Board and is actively involved on a project with Sea Grant to investigate alternatives to beach renourishment for communities threatened by sea level rise.

In its relationship with the South Carolina Department of Natural Resources and the South Carolina Department of Health and Environmental Control, the SCWRC has collaborated on developing a framework for a new water plan for the state of South Carolina. Water supply plans vary in their content depending on need and governmental mandate. There are some basic elements that appear in all regional plans, including an assessment of existing supply, water demand forecasting based on population and economic sector projections with assumptions and scenarios, demand side control measures, and plan implementation, monitoring and evaluation. For the South Carolina water planning effort, SCDHEC and SCDNR will first provide a clear and concise mandate with specific objectives for regional and statewide water plans, facilitate a stakeholder driven process to derive water sustainability objectives, develop and execute a consistent and uniform approach for engaging stakeholders in developing regional water plans, utilize a systemic approach to integrate emerging water monitoring technologies for a cost effective program, carefully evaluate economic development opportunities by region, and foster a public private partnership for process management and funding.

Clemson University and the SCWRC will support SCDHEC and SCDNR in developing local, regional and statewide water plans. One of the most important tools for water resource managers, regulators and planners to effectively evaluate water resources is the surface water model. In South Carolina, surface water models have not yet been developed for most of the state. SC DNR, in cooperation with SC DHEC, has begun implementing the first "whole system," basin-wide surface water availability assessment with consultant,

CDM Smith. Each surface water model will be an individual basin assessment, though accounting for inter-basin transfers, withdrawals and discharges. This data collection, model development, calibration and stakeholder engagement process occur over the course of 2014 through 2016. Stakeholder engagement is critical to this process, as the models will be available for regulators, utilities and others, with training to be made available at the conclusion of this effort.

Clemson University seeks a role similar to that played by the University of Georgia in assisting the Georgia Department of Natural Resources in facilitating stakeholder driven regional planning to insure the water-planning mandate is followed and that consistent regional meetings are held that meet specified goals and objectives. Clemson University has the capability and capacity to support SCDHEC and SCDNR through this demanding process. Clemson University has demonstrated statewide leadership in addressing water resource issues through focused research and education programs, statewide Extension Service programs, development of an EPA-Designated Center for Watershed Excellence, and hosting the statewide biennial South Carolina Water Resources Conference to address water issues impacting multiple stakeholders.

Finally, The SCWRC has been an active participant in the South Carolina Water Conference Planning Committee. The previous South Carolina Water Conferences have been held in 2008, 2010 and 2012. The most recent conference was held in October of 2014 with the SCWRC being an active co-sponsor while leading and running the Water Policy and Planning track of papers and presentations. The Water Center is a sponsor, evaluates presentations, moderates all water policy tracks, and encourages graduate student presentations and research. Following the 2014 conference the director of the SCWRC was named chairman of the 2016 conference. Also in 2014, the conference published the first issue of the South Carolina Water Resources Journal based upon papers from the past conference. The SCWRC has been an active participant in getting the journal started and the director is one of five editors for the journal.

Research Program Introduction

The South Carolina Water Resources Center uses its operating funds to carry out its mission as a liaison between the US Geological Survey, the university community and the water resources constituencies of those institutions. This is accomplished by serving as a water resources information outlet through our web site, by serving as a research facilitator through our annual grants competition and by operating as a catalyst for research and educational projects and programs across South Carolina. The Water Center also serves as a conduit for information necessary in the resource management decision-making arena as well as the water policy arena of the state.

The SCWRC works with a broad constituency across South Carolina including memberships on numerous advisory boards and committees identifying policy issues related to primary water concerns and analyzing population growth impacts on water resources. The director of the SCWRC has testified on several occasions to state senate and house committees regarding water and natural resource issues. He also serves on the Savannah River Basin Advisory Council to assist SCDHEC and the SC Department of Natural Resources with management recommendations as well as serving on SCDNR's advisory group for the state water plan. The director of the SCWRC is a founder of and also holds a position on the editorial committee for the newly formed Journal of South Carolina Water Resources.

Over the past year the SCWRC has become a member of Clemson University's Water-Energy Consortium (WEC). The Water-Energy Consortium is a multidisciplinary group of CU faculty members, designated as WEC Fellows, who have assembled their knowledge and expertise to address an important global challenge: the Water-Energy Nexus. The nexus between water and energy encompasses energy aspects of water systems (energy footprint of water production), and water aspects of energy systems (water footprint of energy production). Besides the direct connection between water and energy, the WEC takes a broader perspective on sustainability, involving reduction of greenhouse gas (GHG) emissions and the environmental impact of both water and energy systems. While low unit costs are important, they are only part of the decision-landscape of sustainable water and energy systems. Added considerations are technology resilience within the context of climate change, and technology adaptation within the context of different climatic (temperate, arid, and tropical) regions.

The vision of the WEC is to promote global recognition of Clemson University as being at the forefront of research addressing the water-energy nexus. The mission of the WEC is to contribute research leading to technology innovations in water systems with a minimization of energy and carbon footprints as well as energy systems with a minimization of water and carbon footprints. Within the framework of the WEC, five strategic research themes have been identified: 1. Innovative, energy-efficient water/wastewater purification processes and systems 2. Improved water efficiency of energy resource development, and production processes and systems 3. Material science in water and energy processes and systems 4. Water and energy informatics, sensors, monitoring, and modeling 5. Water and energy management, policy, and economics

While the SCWRC will be involved to various degrees in all themes of the WEC, but has agreed to be a leader of theme number five. The WEC will seek funding from various agencies and foundations in order to accomplish its mission. The SCWRC and the WEC recently was invited by the National Science Foundation to submit a full proposal under the Partnerships for International Research and Education (PIRE) program. SCWRC and the Clemson WEC intend to partner with scientists at the University of Southern California as well as in South Korea, Singapore and Saudi Arabia to develop new membrane technologies for desalination processes as well as understand the policy processes either promoting or inhibiting use of desalination in multiple countries.

Research Program Introduction

The SCWRC has recently entered into an agreement with the Greenville Water System (GWS), one of the three largest water providers in South Carolina, to assist two consulting firms with producing a new master plan for the operation of GWS for the next fifty years. This plan will impact water use for the entire western half of South Carolina. In addition, the SCWRC has been contracted by the SCDNR and the SCDHEC to implement a stakeholder engagement process for the new water assessment and water plan for the state of South Carolina.

This past year the Water Center funded two research studies: 1) “Low impact development (LID) stormwater management techniques as a tool for mitigating climate change induced increases in rainfall intensity and frequency” with Nigel Kaye (Clemson University) as principal investigator and William Martin III (Clemson University) as co-principal investigator; and 2) “Monitoring of organic pollutants in the Savannah River, using a buoy-deployed data collection network” with Peter van den Hurk (Clemson University) as principal investigator and Cindy Lee (Clemson University) as co-principal investigator.

This coming year the Water Center intends to oversee the funding of two research studies: 1) “Effect of Climate and Land Use Change on Water Availability for the Savannah River Basin” with Ashok Mishra (Clemson University) as principal investigator; and 2) “A Preliminary Investigation into the Ecology, Hydrodynamics, and Limnological Parameters of Oxbow Lakes in the Middle and Lower Savannah River Basin” with John Haines (Clemson University) as principal investigator and Oscar Flight (Phinizy Center for Water Sciences) as co-principal investigator.

Monitoring of Organic Pollutants in the Savannah River, using a Buoy-Deployed Data Collection Network

Basic Information

Title:	Monitoring of Organic Pollutants in the Savannah River, using a Buoy-Deployed Data Collection Network
Project Number:	2014SC92B
Start Date:	3/1/2014
End Date:	2/28/2015
Funding Source:	104B
Congressional District:	SC-003
Research Category:	Water Quality
Focus Category:	Methods, Toxic Substances, Water Quality
Descriptors:	None
Principal Investigators:	Peter Van Den Hurk, Cindy M. Lee

Publication

1. Van den Hurk, P. & Lee, C. "Biomarkers as a tool for biomonitoring of water quality in the Savannah River", South Carolina Water Resources Center Conference-2014. Columbia, SC, October 15-16 (2014)

Peter van den Hurk, Cindy Lee

Graduate Program in Environmental Toxicology

Clemson University

Annual Report, May 2015

The Savannah River forms an essential natural resource to the counties and states bordering the river. But the many different services provided by the river require a balanced management of river flow and water quality. As one of the tools to aid management of the river, the Intelligent River project deploys a series of buoys throughout the length of the Savannah River. Each buoy has a water quality data collection unit, which is wirelessly connected to a central computer system. This will allow for real-time water quality data collection and monitoring, which will be a huge asset to water quality managers. Current technology allows only for monitoring of basic water quality parameters like temperature, conductivity, pH, dissolved oxygen etc. However, considering the urbanized and industrialized areas that border the Savannah River, there is constant concern about possible spills and unreported discharges of polluted effluents into the river. An array of sensors, connected to the data collectors on the Intelligent River buoys, which would detect these incidents, could provide very valuable additional information for water quality managers.

Unfortunately, small size, stand-alone detectors specifically for anthropogenic chemical pollutants are not available yet. The technology is rapidly developing, and small, portable units for detection of organic pollutants are becoming available. These units use a variety of techniques, mostly based on microfluidics systems, to separate and detect pollutants of interest. However, it is expected that the availability of stand-alone, remotely operated detectors that could be deployed from buoys will take another 5-10 years. Because three groups of environmental toxicants, the polynuclear aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs) and environmental estrogens are consistently showing up as problem pollutants in biomarker studies in the rivers of the Upstate of SC, and most recently also in the Savannah River, it appears that monitoring of these pollutants is of crucial importance for water quality managers in SC.

To obtain time integrated monitoring data of low concentration organic pollutants in the Savannah River, passive sampling devices (PSDs) were purchased and deployed at 5 locations in the watershed. Three of the locations are in the Savannah River downstream of the city of Augusta, and were selected because of potential pollutant sources immediately upstream of the location. At these locations the PSDs are deployed from a buoy, or are attached to a piling

in the main current of the river. The locations are close to a USGS stream gauge, which will allow integration of flow characteristics with the obtained pollutant concentration data. The other two PSDs are located in two of the main reservoir dams in the Savannah River: one in the Hartwell Dam, and one in the Strom Thurmond Dam. These locations were selected for specific reasons: the sampler in the Strom Thurmond dam will form a reliable reference site for the downstream river sites. The sampler in the Hartwell dam will give more information on the mobility of specific pollutants in the Savannah River (especially PCBs), and serves as an upstream monitoring location. The samplers are inside the dams and receive a constant flow of several gallons per minute of water that is normally released by the dams. Permits had to be obtained from the US-Corps of Engineers to place these PSDs inside the dams, which created the benefits of collaboration with the US-CoE, and constant supervision by their personnel.

The PSDs consist of a protective perforated container that holds two types of absorbing material: strips of low-density polyethylene (LDPE) and disks with membrane enclosed absorbing material (polar organic chemical integrative samplers, or POCIS). The absorbing materials are replaced every 4-6 weeks, and are extracted with solvents to collect the organic pollutants that are absorbed by the LDPE strips and POCIS disks. A spectrum of organic pollutants has been selected for further analysis, which can be arranged in three main groups: the polynuclear aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs) and pharmaceuticals and personal care products (PPCPs). Among the PAHs we are limiting the study to the 16 priority PAHs as recommended by US-EPA; for the PCBs we will focus on the most predominant isomers that were found in the commercial Arochlor mixtures; for the PPCPs a selection is made of estrogens, antibacterials, and some of the most common used therapeutic drugs. This broad spectrum of organic pollutants requires a suite of complex analytical methods because of the range of their chemical properties; PAHs will be analyzed by GC-FID, PCBs by GC ECD, and the PPCPs by UPLC ESI-MS/MS. We are in the process of finalizing these methods and started the initial sample analysis.

To help with field logistics, and additional water quality parameters, collaboration was established with the Phinizy Center for Water Sciences (Augusta, GA). The Phinizy Center has set up continuous river monitoring equipment which collects real-time data of temperature, specific conductance, pH, and dissolved oxygen levels at 15 minute intervals. Together with USGS flow data a complete picture will be created of overall water quality at the selected locations throughout the year.

In addition to chemical analysis of the PSD extracts, we plan on analyzing biological effects of the extracts as well. The zebrafish embryo developmental toxicity assay will be used for the biological effects monitoring of the site-specific chemical mixtures. For the assay, the zebrafish embryos are individually segregated in 96-well plates and exposed to a range of diluted 1:1

mixtures of the POCIS and LDPE extracts, as well as positive and vehicle controls. Observations will be made of each embryo at 24 hours and 5 days post-fertilization. Toxicity endpoints, which include mortality and 19 sublethal endpoints, will be noted and an index used to assign an overall toxicity to the extracts of each location and time point. Chemical analyses will be compared and correlated to the observed biological effects, including both overall toxicity and individual sublethal endpoints. Future directions will incorporate bioassays that address other sublethal endpoints including chemosensory toxicity and endocrine disruption, as well as toxicity identification evaluations to identify principal toxic components of the mixtures. This research will test and show that low concentration, complex mixtures of compounds are producing sublethal biological effects that correspond to the makeup of the mixture and its respective sources.

Low Impact Development (LID) Stormwater Management Techniques as a Tool for Mitigating Climate Change Induced Increases in Rainfall Intensity and Frequency

Basic Information

Title:	Low Impact Development (LID) Stormwater Management Techniques as a Tool for Mitigating Climate Change Induced Increases in Rainfall Intensity and Frequency
Project Number:	2014SC94B
Start Date:	3/1/2014
End Date:	2/28/2015
Funding Source:	104B
Congressional District:	SC-003
Research Category:	Climate and Hydrologic Processes
Focus Category:	Hydrology, Water Quantity, Climatological Processes
Descriptors:	None
Principal Investigators:	Nigel Kaye, William D MartinIII

Publications

1. Martin, W. D. & Kaye, N. B. "Taking hydrologic advantage of porous pavement systems through simplified models and design" World Environmental & Water Resources Congress, Austin, Texas, May 17-21 (2015)
2. Hutton, D. R., Kaye, N. B., & Martin, W. D. "Effectiveness of LID Technologies to mitigate the impact of climate change on stormwater design storms" Georgia Water Resources Conference, Athens, GA, April 28-29 (2015)
3. Hutton, D., Martin, W., & Kaye, N. B. "Analysis of the impact of climate change on stormwater design storms for the state of South Carolina" South Carolina Water Resources Center 2014 Conference, Columbia, SC, October 15-16 (2014)
4. Kaye, N. B. & Martin, W. "A proposal for standard reporting of extensive modular green roof hydraulic performance parameters" South Carolina Water Resources Center 2014 Conference, Columbia, SC, October 15-16 (2014)

Analysis of the Impact of Climate Change on Stormwater Design Storms for the State of South Carolina

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ABSTRACT. A warming climate leads to a moister atmosphere and more rapid hydrologic cycle. As such, many parts of the country are predicted to experience more total rainfall per year and more frequent extreme rainfall events. Most regions of the country have stormwater systems designed to a standard that matches outflow rates to pre-development values for specified return period storms. Increases in these return period storm depths, as predicted by many global climate models, will stress existing stormwater infrastructure. This paper examines how rainfall patterns will change over the remainder of the century across the state of South Carolina.

Rainfall simulations from 134 realizations of 21 global climate models were analyzed across the state of South Carolina through 2099. Results show that there will be increases in both annual total rainfall (ATR) and 24 hour design storm depth for a range of return period storms. Across South Carolina, ATR is predicted to increase by approximately 2.3-4.0 inches over the forecast period while the 100 year design storm depth is predicted to increase by 0.5-1.2 inches depending on location. However there are significant regional variations with the Savannah River Basin experiencing smaller increases in ATR compared to the rest of the state.

INTRODUCTION

Over the last century the average global temperature has risen 0.85 degrees Celsius (IPCC, 2014). Forecasting climate changes is important for preparing societies for possible impacts to food supply, water resources, infrastructure, ecosystems, and even human health. Temperature changes are only one aspect of the predicted changes the Earth will experience. Other changes include precipitation patterns and intensities, ice and snow cover, sea level, and ocean acidity. In 2001, the IPCC published strong conclusions in response to evidence of global climate change (IPCC, 2001). The 1990's were reported

to be the warmest decade, for the northern hemisphere, since adequate record keeping (IPCC, 2001). Trends in precipitation are increasing slightly, about 1% per ten years, and the number of severe precipitation events is also increasing (IPCC, 2001). The IPCC concluded that the warming that is being observed in the last century is not natural. Models that attempt to predict historical trends based on natural radiation perform less well compared to models that include increases in atmospheric greenhouse gas concentrations (IPCC, 2001).

The IPCC made its conclusions based upon a large variety of research and data. Specific to the United States, there has been trend analysis done for precipitation and temperature for major urban areas. Mishra and Lettenmaier (2011) found that there were significant increases in extreme precipitation events in 30% of urban areas from 1950-2009. Martinez et al. (2012) found increasing trends in temperature and decreasing trends for precipitation for the state of Florida for a similar time period.

In general, climate change models predict a warmer and moister atmosphere resulting in a more rapid hydrologic cycle and more extreme rainfall events. Stormwater systems, some of which are already overloaded, will be stressed even further with increased runoff. As a result water quality will decrease as sediment runoff and flooding will increase.

Current South Carolina stormwater regulations (DHEC, 2002), only regulate peak flows and not total runoff. As such, traditional stormwater designs have reduced infiltration and increased total runoff when compared to original site hydrology. Developing sites often requires significant downstream storm sewer infrastructure. With increased rainfall due to climate change, these design weaknesses will cause a disproportionate amount of the additional rainfall to directly become runoff. Responsible stormwater management is required to maintain the quality of surface water in a climate that will exhibit increased frequency and intensity of rainfall over time.

This paper presents the results of a detailed analysis of rainfall forecasts based on Global Climate Model (GCM) data archived through the Climate Model Inter-comparison Project – 5 (CMIP5). The data is analyzed to examine the change in annual total rainfall (ATR) and 2, 5, 10, 25, 50 and 100 year 24 hour storm depths between now and the end of the century (the storm depths selected are those used by various municipal and state agencies in their stormwater regulations).

Engineers and regulators will better understand the risk a changing climate will present to stormwater infrastructure as a result of this analysis. That is particularly true for state agencies with regulatory responsibilities for defining stormwater design events such as SC-DHEC and SC-DOT.

The remainder of the paper is structured as follows. The project description summarizes the main goals of the project and pertinent literature. The sources of data used and the analysis techniques are described in the methods section. The results section presents forecasts for the ATR and 2, 5, 10, 25, 50, and 100 year 24 hour storm depths for the entire state of South Carolina. Conclusions and suggestions for future work are presented in the discussion section.

PROJECT DESCRIPTION

As an increase of rainfall intensity and frequency is expected, the responsibility of designing stormwater systems to be effective for their entire design life lies with the designing engineer. However, in order to effectively plan for future rainfall patterns, data on expected changes is required. GCM's typically produce low spatial resolution data that must be statistically downscaled for the purposes of local hydrologic trend analysis. There are a number of approaches to downscaling including Bias Corrected Constructed Analogs (BCCA) and Bias Correction and Spatial Disaggregation (BCSD) (Ahmed et al. 2013). The choice of downscaling technique depends on the application. Downscaling GCMs using Bias Corrected Constructed Analogs (BCCA) provides a higher temporal and spatial resolution (Barsugli, et al, 2009, Maurer & Hidalgo, 2008) and improved estimates of precipitation compared to other downscaling methods (Brown & Wilby, 2012). Using multiple GCMs removes the bias that a certain model may have and improves the estimation of variability that is typically under estimated by using a single downscaled data set (Brekke, et al., 2008). This study uses projected rainfall data from 134 realizations of GCMs with daily temporal resolution and 1/8° degree spatial resolution to explore long term trends in rainfall in South Carolina. These data sets include GCM model runs for all four Representative Concentration Pathways

(RCPs). That is, they include model runs for a range of different long term atmospheric CO₂ concentration levels. The choice of appropriate RCP would require a prediction of future public policy which is beyond the scope of this paper. As such, all four data sets were lumped together. The results, therefore, represent an average set of predictions of future rainfall patterns. This approach may under estimate the potential changes in rainfall patterns if global CO₂ emissions are not curbed.

METHODS

Downscaled GCM data was analyzed for each of the locations of NOAA precipitation measuring stations, **Error! Reference source not found.**, so that the projected rainfall data could be directly compared to historical data and posted 24 hour storm depths. Historical rainfall data is available for all of the stations through the National Climatic Data Center (NCDC) run by NOAA. While breaks in the data (no data recorded) exist in the data sets they only exist for relatively short periods and are not accounted for in the analysis. The average data set for the historical data from 1950-1999 contained 41.6 years of data. The list of stations was edited to remove duplicate stations (occurring for stations that measured both hourly and daily values), stations located outside the projection grid (occurring for some coastal stations), or stations with region information not specified by NOAA (Bonnin, et al., 2006). BCCA downscaled CMIP5 daily hydrologic projections were downloaded for each station from an online archive (U.S. Department of Interior, 2014). The projections used 21 climate models with various combinations of four representative concentration pathways (RCPs) and different realizations creating a total of 134 different daily rainfall projections for a period of record (POR) from 2015-2099.

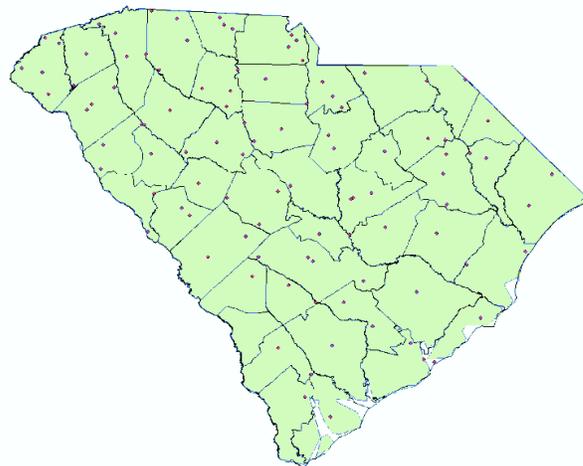


Figure 1 NOAA weather station locations in South Carolina for which observed data was collected and downscaled GCM data was analyzed.

A precipitation frequency analysis had already been performed on the historical data by NOAA and was the computational method behind the Precipitation Frequency Data Server (PFDS), which gives the storm depths for different return periods and durations. The NOAA Atlas 14, Volume 2 is based on data from 13 states and covers precipitation frequency estimates for event durations of 5 minutes through 60 days at recurrence intervals of 1-year through 1,000 years. The method is based on converting annual maximum data to partial duration data series and then further “personalizing” by location through regionalization. The analysis herein focused on 24 hour storm depths due to their role in stormwater design regulations.

After importing the data for each station, the maximum daily values were converted to 24-hour maximum values using

$$P_{24max} = P_{max} * t_{24} \dots \dots \dots (1)$$

where $t_{24}=1.13$ is the ratio between average daily maxima and average 24-hour maxima. This ratio is empirically derived from 86 stations that had 15 years of concurrent data. Comparing the conversion factors to past NOAA volumes and other studies finds that the conversion value is comparable if not the same. The 24 hour annual maximum depth data set was then converted to partial duration data series using

$$P_{AAmax} = P_{24max} * \frac{T_{AMS}}{T_{PDS}} \dots \dots \dots (2)$$

The parameter $\frac{T_{AMS}}{T_{PDS}}$ is equal to 1.58 and represents the frequency ratio between an annual maximum series and a partial duration series. This ratio allows for multiple large storms in a single year be considered in the final value such as occurred in Clemson, SC in 2013. The partial duration series was averaged and converted into a set of 24 hour storm depths of specified return period using

$$P_{n_yr} = \bar{P}_{AAmax} * RGF_n \dots \dots \dots (3)$$

where n is the return period in years. The Regional Growth Factor (RGF) for each return period depends on the location of the rain gauge and is given in the NOAA Atlas. Distribution of the regions for the RGF can be seen in **Error! Reference source not found.** For example, since the station in Clemson, SC (Station ID 38-1770) is assigned to NOAA Region 12, its RGFs for the 2, 5, 10, 25, 50, and 100 year storms are 0.907, 1.196,

1.429, 1.801, 2.148, and 2.272 respectively (Bonin, et al., 2006). Using the same frequency analysis technique employed by NOAA allows for direct comparison of the GCM precipitation

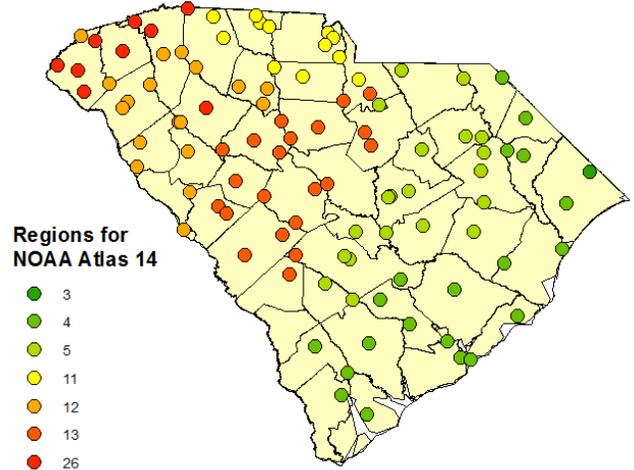


Figure 2 Regions for Stations in SC from NOAA Atlas 14.

frequency values to the precipitation frequency values reported by NOAA based on historical rainfall data.

RESULTS

Results are presented for changes in Annual Total Rainfall (ATR) and for the 24 hour storm depth for 2, 5, 10, 25, 50, and 100 year return period storms. Because much of the data presented is location specific, Clemson, SC was chosen as a case study and is represented in many of the figures herein to illustrate a typical location. There are also figures that summarize this data for the entire state of South Carolina.

Changes in annual total rainfall

For each NOAA precipitation gauge location the daily time series of historical rainfall data and each downscaled GCM data set was converted into an ATR time series. A plot of the 134 ATR time series from 2015-2099 along with the historical recorded data from 1948-2011 for Clemson, SC are shown in **Error! Reference source not found.** The data shows significant year to year variation in the historical recorded data and a similar level of variation across the different GCM data sets presented. There is also a steady increase in the GCM predicted ATR over time. This is seen more clearly in Figure 4 which shows the mean and standard deviation of the historical data along with the yearly mean and standard deviation from the 134 GCM data sets. Note that there is a slight jump in average ATR from the historical mean to the start of the GCM time series. However, this discontinuity is well within the

range of variability observed in both the historical and GCM projected data.

The downscaled GCM data shows a clear increase in the ATR over time. However, a histogram of the ATR from 2089-2099 for each of the 134 GCMs shows only a

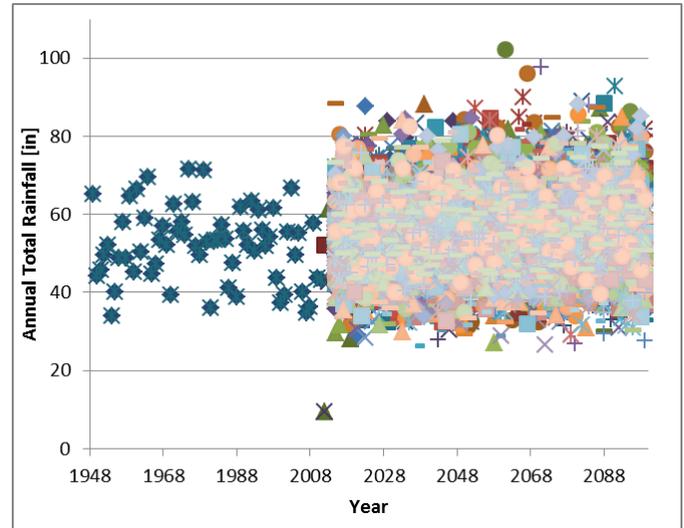


Figure 3 NOAA observed historical annual total rainfall (1948-2011) and predicted annual total rainfall (2015-2099) from 134 different realizations of GCMs for Clemson, SC.

slight increase in mean ATR compared to historical records (see Figure 5). To verify that the increase is statistically significant a T-test was performed to compare the historical data with the GCM data for the last eleven years of the century (2089-2099). The T-test showed that the difference in the means was statistically significant with a 97.5% confidence interval.

The data and analysis above was for a single location, Clemson, SC. Similar analysis was conducted for each of the precipitation gauge locations throughout the state. All locations showed an increase in ATR between 2015 and the end of the century. However, the net increase in ATR historical mean and standard deviation in ATR was compared to the mean and standard deviation of the ATR for 2015 based on all 134 GCM realizations. These data

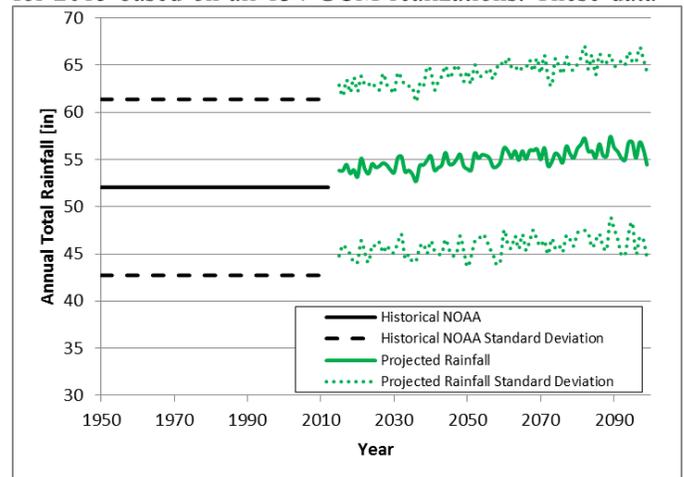


Figure 4 Averaged ATR for Clemson, SC based on NOAA observed data (1950-2011) and projected rainfall for 2015-2099 based on 134 realizations of GCMs.

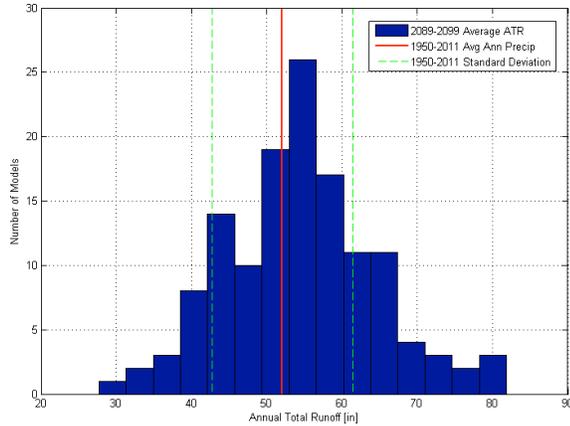


Figure 5: Histogram of the average ATR for Clemson, SC from 2089 to 2099 based on 134 downscaled realizations of GCM data sets. The vertical line represents the current average ATR.

varied across the state. There was also an offset between the predicted 2015 mean ATR based on 134 GCM data sets and the historical record. At each gauge location the are plotted in **Error! Reference source not found.** and **Error! Reference source not found.** shows a scatter plot of historical mean ATR versus 2015 GCM mean ATR. The offset between the historical mean and the 2015 mean varies by location though the 2015 GCM mean ATR is almost always larger than the historical mean ATR. This would be expected for a climate with increasing mean ATR as the historical record would average over a non-stationary data set and would, therefore underestimate the current mean ATR. **Error! Reference source not found.** shows the standard deviation in the historical ATR versus the 2015 GCM ATR standard deviation. Again the difference varies with location though in this case the standard deviation is not consistently higher or lower for the GCM data. The historical data shows a greater range of standard deviations compared to the GCM data, though this is likely due to the smaller number of data

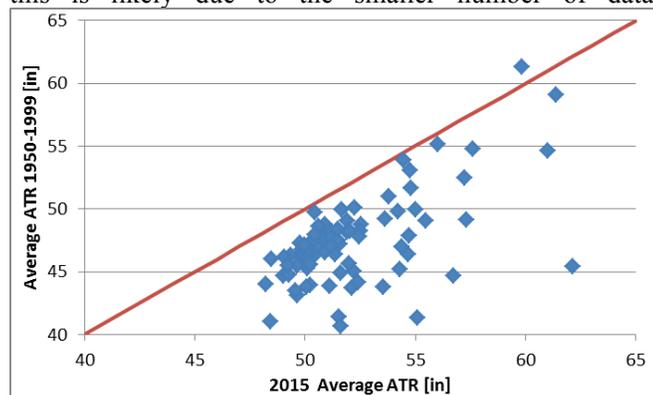


Figure 6. Scatter plot of 2015 GCM mean ATR versus historical average ATR for 1950-1999 with the red line

showing exact agreement. Each data point represents a station.

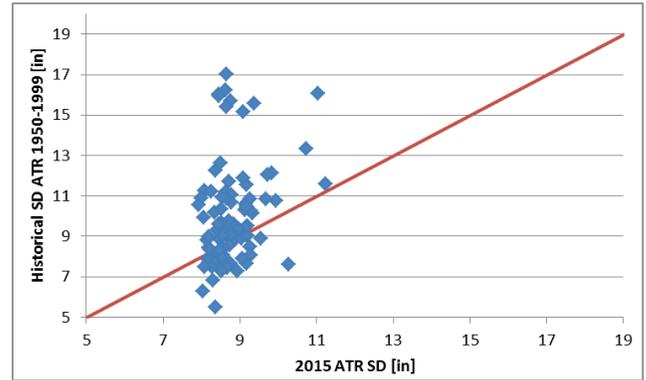


Figure 7. Scatter plot of 2015 GCM SD of ATR versus historical average ATR with the red line showing exact agreement. Each data point represents a station.

points in the historical data sets used in this analysis (average 41 years of data, 14 year standard deviation) compared to the 134 data points for the 2015 GCM ATR standard deviation.

Given the variation in both mean offset and predicted standard deviation it might be somewhat misleading to simply present the difference between the historical mean and the mean averaged over the later years of the century. Instead, we present data for the projected change in ATR based on a linear curve fit through the mean ATR for the GCM data from 2015-2099. Straight lines were fitted through the mean GCM ATR for each location. The slope of this line (with units of in/year) was then multiplied by 84 years (the GCM POR) to give a projected change in ATR over the remainder of the century. The data from each station was then entered into ArcGIS by ESRI where the geographic data information was interpolated using a tensioned spline method to create contour surfaces. A tension spline interpolation results on a surface that is less smooth but more closely constrained by the inputted data. This contour plot is presented in **Error! Reference source not found.**

Error! Reference source not found. shows significant variation in ATR change from 2.3 in for certain parts of the Savannah River basin to over 3.8 in in the coastal region, especially Charleston and Horry County. Much of the upstate and the length of the Savannah River Basin are all predicted to see lower levels of ATR increase compared to the rest of the state. The exception to this is the northern section of the border between Greenville and Spartanburg counties which will see ATR increases of around 4 in.

Changes in 24 hour design storm depths

Stormwater design in South Carolina is generally based on the 2, 10, and 100 year return period storms

(DHEC 2002). Therefore, it is important to see how these design storm depths change over time, especially in comparison to the current NOAA return period data. In a changing climate the idea of a return period storm is not

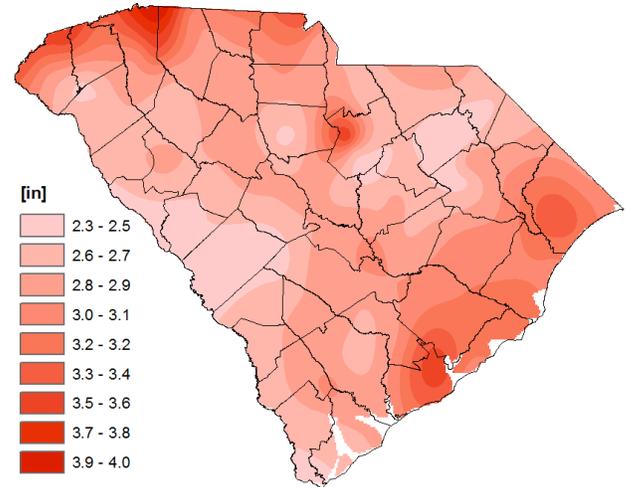


Figure 8 GCM simulations of change in average ATR (inches) over the forecast period (2015-2099) using the ATR trendline slope.

clearly defined. However, given 134 annual time series per year it is possible to get reasonable estimates of 2, 5, 10, 25, 50, and 100 year return period 24 hour storm depths for each year in the GCM POR and analyze how they change over time. A sample plot of the variation in storm depth for Clemson, SC is shown in Figure 9 along with the current NOAA values for the same return periods.

As with the ATR, the 24 storm depths are also seen to increase over time for each return period. However, there is also a difference between the historical record and the 2015 GCM projection for the each return period storm. In this case, the 2015 GCM data is lower than the NOAA value for the 2 year storm and higher than the NOAA

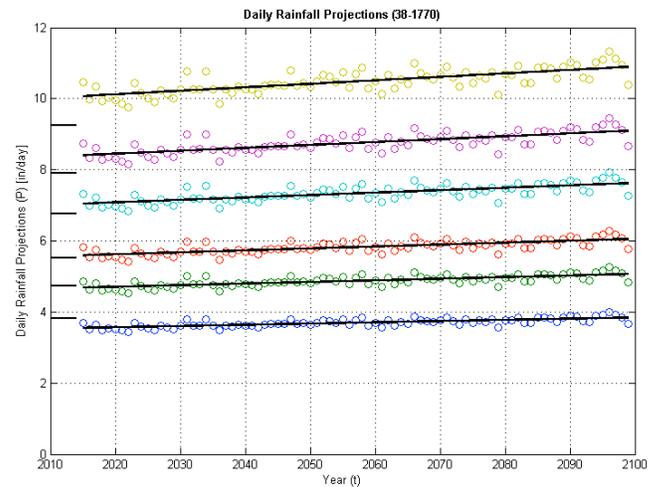


Figure 9 Forecast of storm depths versus year based on 134 downscaled GCM data sets. 100, 50, 25, 10, 5, and 2 year storm depth are shown from top in descending order. The horizontal lines on the y-axis show the current NOAA value for the respective storm depth. The solid lines through the data are linear best fits to the data.

value for the 100 year storm. In general the 2015 GCM projections for the 100 year storm were higher than current NOAA values though not always. Figure 10 shows a histogram of this difference for the 101 precipitation gauges analyzed as part of this study. The vast majority of locations have a difference of less than 1 in though some exhibit differences of up to 4 in. Twenty stations had 2015 GCM 100 year 24 hour storm depths lower than the current NOAA data. Regardless of the offset between 2015 GCM predictions and current NOAA data there is a clear upward trend in all six return period storm depths. Therefore, as with the ATR data, the projected change in depth is reported. Lines were fitted through the yearly return period depths for each return period and each precipitation gauge. The slope of these lines was then used to calculate the projected increase in storm depth by the end of the century across the state.

As with the mean ATR, there is significant uncertainty in the calculated values of 24 hour storm depth for a given return period. As such, NOAA reports the calculated depth and the depths at the extremes of the 90% confidence interval. For each rain gauge location, the projected year at which the GCM calculated storm depth exceeded the upper range of the 90% confidence interval for the historical data was calculated. Histograms of this year for each of the calculated return period storms are shown in Figure 11.

The data shows that there is a larger change in the longer return period storms. For example, most locations will not see the 2-year storm depth exceed the current NOAA 90% confidence interval value until well into the next century whereas most locations will have 100-year storm depths that exceed the current 90% confidence interval in the next few years. The year in which the

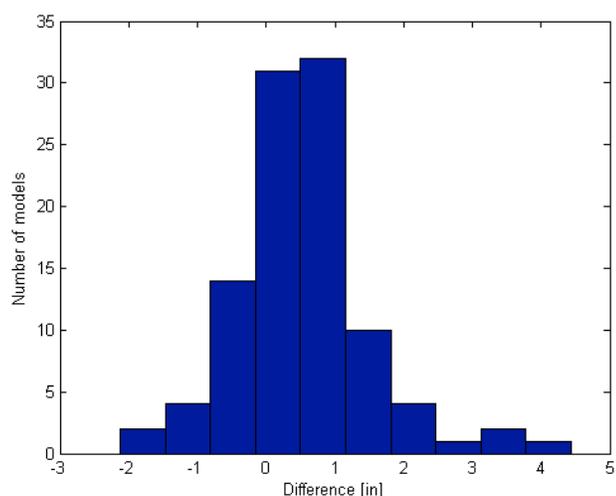


Figure 10. Histogram of the difference between the linear trend line value for the 2015 GCM 100 year storm depth and the current 100 year storm depth reported by NOAA for all 101 stations analyzed.

GCM trendline exceeds the current 90% confidence interval is sometimes greatly outside the simulation period of record and should, therefore, not be taken as predictive. However, the data clearly shows that longer return period storms will exceed the current 90% confidence interval sooner than smaller storms.

The linear fits for each location and each return period were used to create contour plots of the total change in depth predicted over the GCM POR. The slope of each line was multiplied by 84 (the number of years in the POR) to calculate a change in depth. This approach is the same as that used for calculating changes in mean ATR over the GCM POR and ignores any offset between the 2015 GCM data and historical data. This offset is discussed below. A contour plot of the projected depth change for each return period storm is shown in Figure 12. The GCM data projects that the 100 year storm depth will increase by between 0.5 in and 1.2 in over the next 84 years whereas the 2-year storm depths only increase by between 0.2 and 0.5 in. As with the ATR data there is significant variation across the state with the largest increases in similar regions to those that were predicated to have the largest increase in ATR.

One possible explanation for the 2015 GCM 100 year storm depth being different, and typically deeper, from the current NOAA data is that the climate has already been changing over time. If this is the case, and the extreme event depths have been increasing over time, then there should be a correlation between the GCM 2015 to NOAA difference and the projected change in 100 year storm depth as plotted in Figure 12. **Error! Reference source not found.** shows a contour plot of the GCM 2015 to NOAA difference for the entire state. Visual comparison between Figure 12 and **Error! Reference source not found.** indicates that the regions of higher storm depth growth (darker regions of Figure 12) correspond to regions of greater initial difference in depth (darker regions of **Error! Reference source not found.**). Further evidence of this relationship is shown in Figure 14 which shows scatter plots of the initial difference versus projected change for each of the return periods considered. Again, a clear correlation is observed between the offset and the projected rate of increase in storm depth.

DISCUSSION

A detailed analysis of the projected change in rainfall patterns in South Carolina has been conducted using BCCA downscaled GCM data from CMIP5. The GCM data show that average total annual rainfall will increase across the state over the remainder of the century. However, the increase is not uniform across the state

with coastal regions predicted to have greater increases than most of the state. The Savannah River Basin is

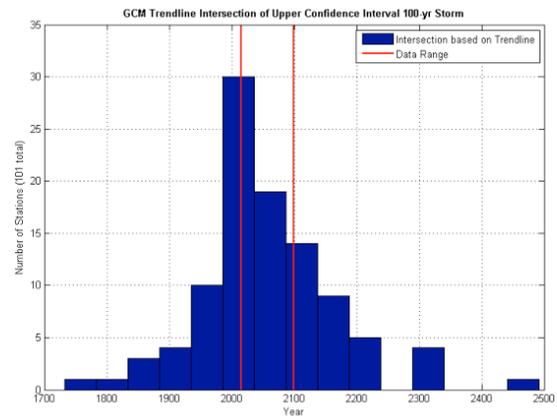
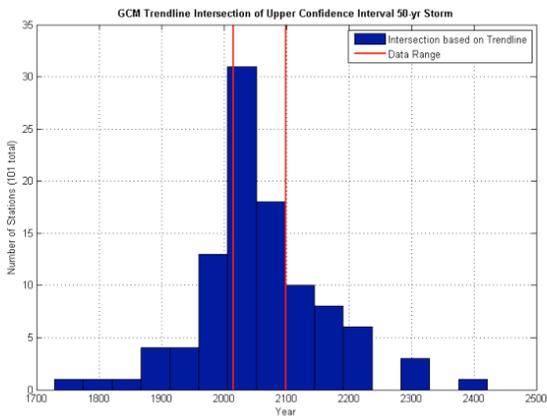
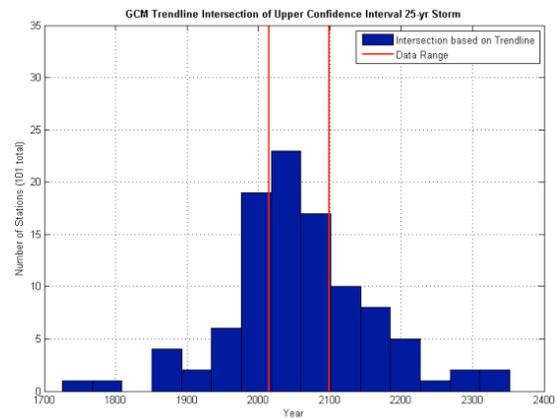
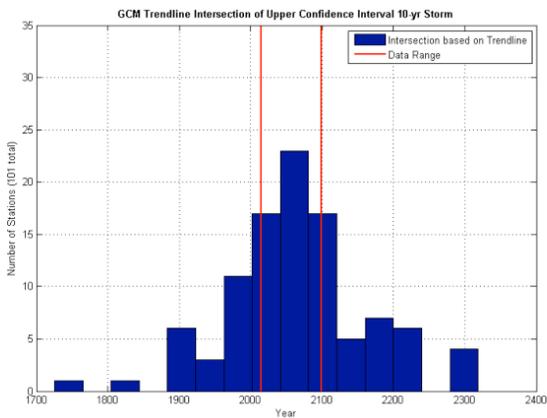
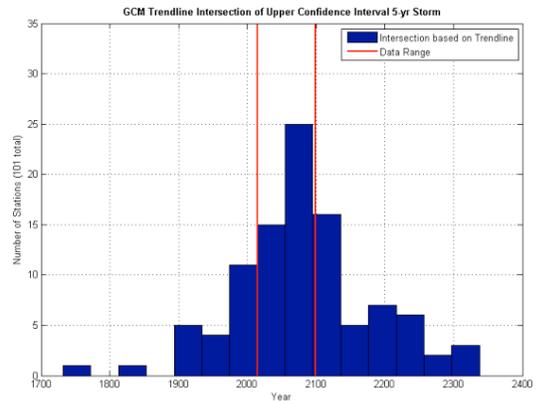
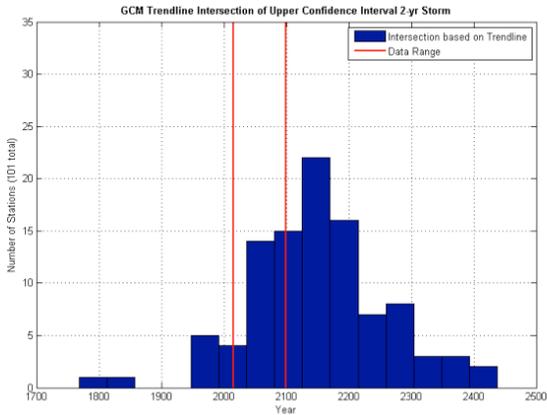


Figure 11. Histograms of the year in which the 24 hours storm depth will exceed the current NOAA 90% confidence interval upper limit using the GCM trendline equation. Reading from top and left to right, 2, 5, 10, 25, 50, and 100 year return period storms. The vertical red lines represent the GCM simulation POR.

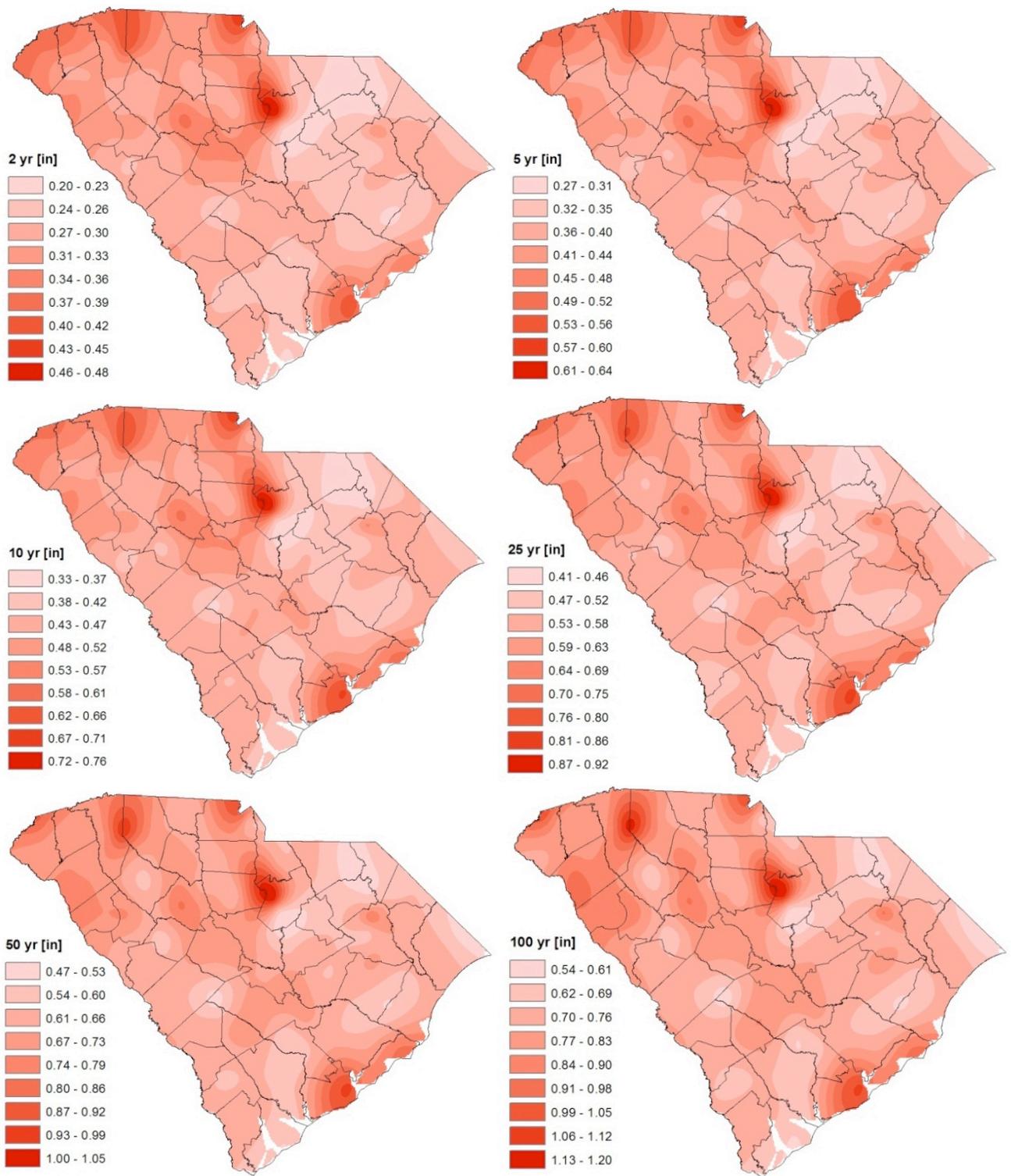


Figure 12 Contour plot of the GCM prediction of the change in 24 hour design storm depth (inches) over the forecast period. Reading from top and left to right, 2, 5, 10, 25, 50, and 100 year return period storms.

predicted to have below average growth in average annual total rainfall compared to the rest of the state. While the trend toward increasing ATR is clear in the data, the increase is quite small compared to typical year to year variability (see Figure 5).

The analysis also shows that the 2, 5, 10, 25, 50, and 100 year 24 hour design storm depths will all increase across the state over the remainder of the century. For example, the 100-year design storm depth is projected to increase between 0.5 and 1.2 inches across the state by 2099. In fact the GCM projections for 100 year return period 24 hour storm depths for most of the state will exceed the current NOAA 90% confidence interval in the next few years. However, the 2-year 24 hour storm depth will not exceed the NOAA 90% confidence interval until well into the next century for most locations in the state.

For both the ATR and the 24 hour storm depths there was an offset between the projected 2015 values and the historical data. In almost all cases the 2015 GCM ATR was greater than the historical mean though well within historical levels of variability. The offsets between the current NOAA 24 hour storm depth data and the projected 2015 GCM values were quite varied. A substantial number of the offsets were negative indicating that the GCM storm depths were below the historical calculated values. However, the increase in storm depth over time was clear for every return period throughout the state. Further, the offset between the GCM and historical data was shown to be correlated to the local rate of change in the projected storm depths (see Figure 14). In general, the longer the return period of the storm, the greater the rate of increase in storm depth and the sooner the storm depth is predicted to exceed the current NOAA 90% confidence interval upper value.

The projected increases in both average annual total rainfall and design storm depths have the potential to stress existing stormwater infrastructure. The increases may also require regulatory agencies to re-visit their published design storm depths. One possible approach to mitigating the impact of these changes is to require new developments, as well as re-developments and retro-fits, to more closely replicate the predevelopment site hydrology. This could be done through the use of low impact development (LID) best management practices (BMP) to encourage infiltration and on-site runoff management. Such an approach has the potential to make new development more resilient to the projected changes in rainfall patterns.

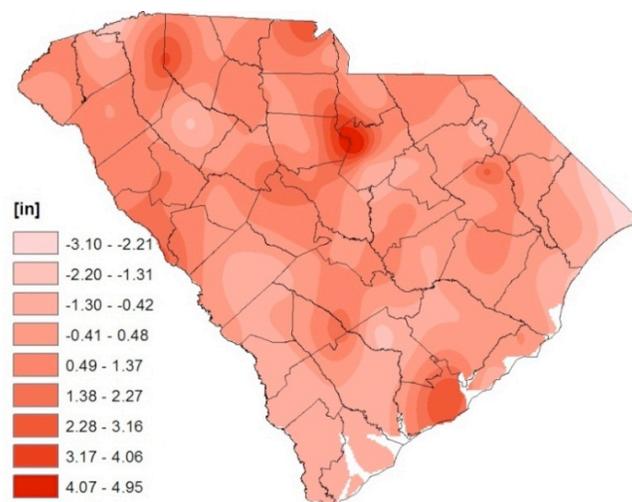


Figure 13 Contour plot of the offset between the 2015 GCM 100 year storm and the current NOAA data.

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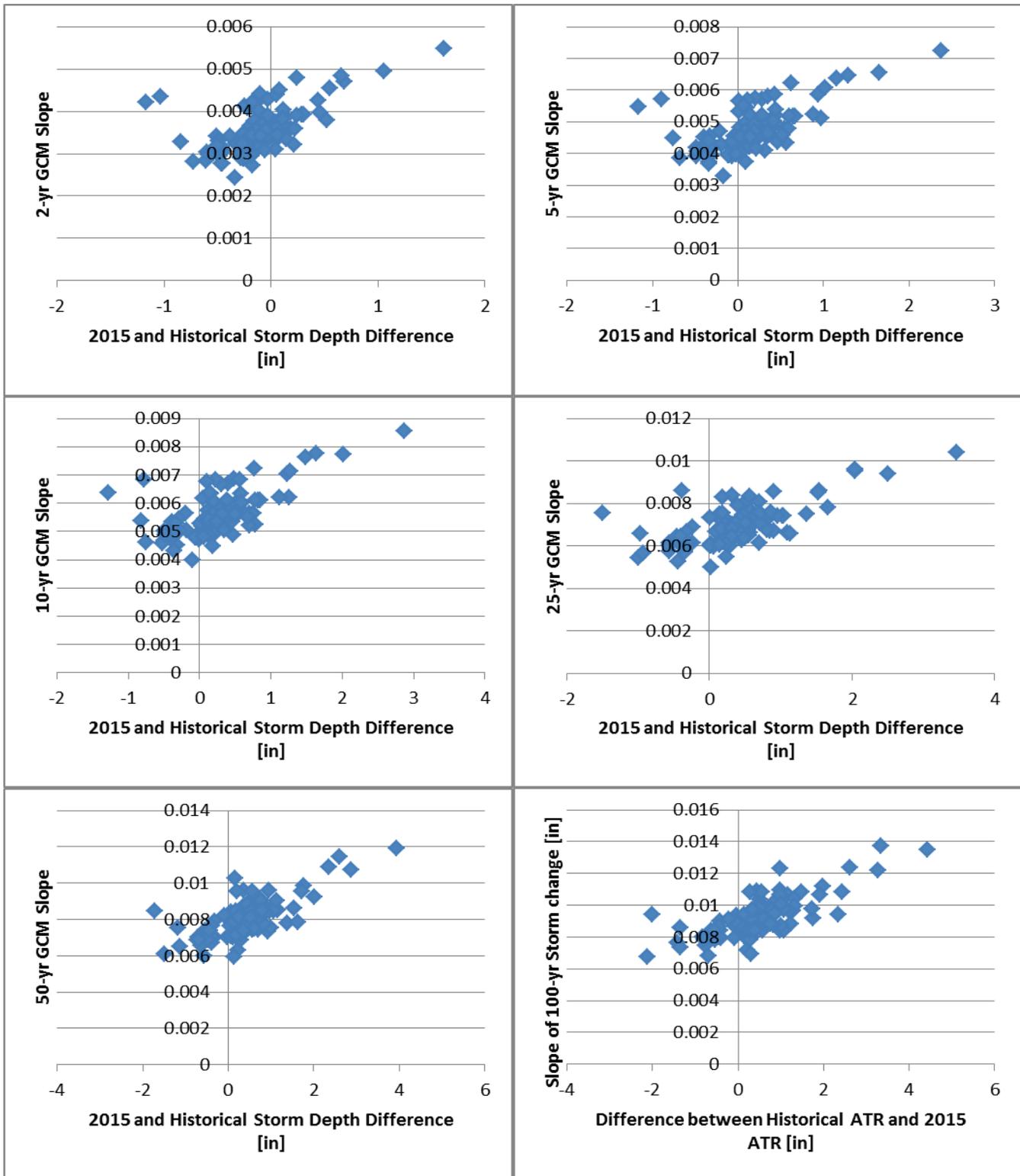


Figure 14 Scatter plot of the offset between the 2015 GCM 24 hour storm depth and the current NOAA data versus the projected growth in storm depth over the next 84 years. Reading from top and left to right, 2, 5, 10, 25, 50, and 100 year return period storm.

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Information Transfer Program Introduction

None.

USGS Summer Intern Program

None.

Student Support					
Category	Section 104 Base Grant	Section 104 NCGP Award	NIWR-USGS Internship	Supplemental Awards	Total
Undergraduate	1	0	0	0	1
Masters	3	0	0	0	3
Ph.D.	0	0	0	0	0
Post-Doc.	0	0	0	0	0
Total	4	0	0	0	4

Notable Awards and Achievements

Secured funding for writing the policy and management chapter for the South Carolina Storm-water Pond State of the Knowledge Report

Secured funding to conduct stakeholder engagement meetings for the SCDNR sponsored South Carolina River Basin Water Assessment

Secured funding for a partnership to develop a master plan to the year 2100 for the Greenville, SC Water System

Successfully conducted SCWRC statewide research solicitation under the guidelines of USGS.

Served on Planning Committee of the S.C. Water Resources Conference

Elected chairman of the S.C. Water Resources Conference

Served on editorial committee for the Journal of South Carolina Water Resources

Co-sponsored second workshop with SC Rural Water Association, American Rivers and SCDHEC on water auditing for municipal water systems.

Continued work with partners to do remote sensing research for habitat preservation in Brazil.

Lakelands Regional Workforce Alliance Mapping Research Project Overview Produced workforce mapping efforts and conducted a preliminary demographic analysis for the Alliance.

Worked with Clemson University Environmental Engineering and Earth Sciences to co-host global climate change lectures.

Worked with Clemson University Political Science to co-host their Globalization Lecture Series.

Continued work to build a partnership for a public/private national technology research center to be housed at Clemson University.

Served on the Savannah River Basin Advisory Council.

Served on the Carolinas Integrated Sciences & Assessments Advisory Board

Served on the SC Sea Grant Consortium Coastal Communities Advisory Board

Served on SCDNR State Water Plan Advisory Committee

Served on the SC Sea Grant Consortium Program Advisory Board

South Carolina Water Resources Center at Clemson University

<http://sti.clemson.edu/centers-mainmenu-26/water-resources-center> Jeffery S. Allen, Ph.D., Director
jeff@sti.clemson.edu

Mission: The SCWRC serves as a liaison between the US Geological Survey, the university community and the water resources constituencies across South Carolina. The Water Center acts as a conduit for information necessary in the resource management decision-making arena as well as the water policy arena of the state.

Highlighted Project: Creating a Stakeholder Engagement Framework and Process for the South Carolina State Water Plan PI: Jeffery Allen, Lori Dickes, Donna London and Katie Giacalone—Clemson University The Clemson University Stakeholder Engagement Team (SET) will facilitate the stakeholder engagement framework for South Carolina's eight major river basins using different tools, methods and strategies to maximize input and decrease barriers to participation. The SET effort will strive to encourage a high level of participation, inventory and document stakeholder feedback and implement a multi-basin strategy in a cost effective manner.