Recent US Climate Change and Hydrology Literature Applicable to US Army Corps of Engineers Missions - Tennessee Region

**ABSTRACT**

To help the US Army Corps of Engineers (USACE) staff in meeting the requirements of the 2011 and 2014 policy statements on climate change adaptation by the Assistant Secretary of the Army for Civil Works, the USACE Climate Change Adaptation Plans, and agency policy and guidance, this report presents concise and broadly-accessible summaries of the current climate change science with specific attention to USACE missions and operations. This report, focused on the Tennessee Region, is part of a series of twenty-one (21) regional climate syntheses prepared by the USACE under the leadership of the Response to Climate Change Program at the scale of 2-digit Hydrologic Unit Code (HUC) Water Resources Regions, across the continental United States, Alaska, Hawaii, and Puerto Rico. Each of these regional reports summarize observed and projected climate and hydrological patterns cited in reputable peer-reviewed literature and authoritative national and regional reports, and characterize climate threats to USACE business lines.

**SUBJECT TERMS**

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**SECURITY CLASSIFICATION OF:**

- **REPORT:** U
- **ABSTRACT:** U
- **THIS PAGE:** U
- **LIMITATION OF ABSTRACT:** U
- **NUMBER OF PAGES:** 19a. NAME OF RESPONSIBLE PERSON (Include area code)
CLIMATE CHANGE AND HYDROLOGY LITERATURE SYNTHESIS FOR THE US ARMY CORPS OF ENGINEERS MISSIONS IN THE UNITED STATES

TENNESSEE REGION 06

January 20, 2015

CDM Smith
Contract # W912HQ-10-D-0004, Task Order 147

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Suggested Citation:

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1. Introduction

U.S. Army Corps of Engineers (USACE) staff are increasingly considering potential climate change impacts when undertaking long-term planning, setting priorities, and making decisions that affect resources, programs, policies, and operations, consistent with the 2011 and 2014 policy statements on climate change adaptation by the Assistant Secretary of the Army for Civil Works, the USACE Climate Change Adaptation Plans, and agency policy and guidance. USACE is undertaking its climate change preparedness and resilience planning and implementation in consultation with internal and external experts using the best available – and actionable – climate science and climate change information. This report represents one component of actionable science, in the form of concise and broadly-accessible summaries of the current science with specific attention to USACE missions and operations. This report is part of a series of twenty one (21) regional climate syntheses prepared by the USACE under the leadership of the Response to Climate Change Program at the scale of 2-digit Hydrologic Unit Codes (HUC) Water Resources Regions across the continental United States, Alaska, Hawaii, and Puerto Rico. The twenty one Water Resources Regions included in this series of reports is shown in Figure 1.1 along with USACE division boundaries. Each of these regional reports summarizes observed and projected climate and hydrological patterns cited in reputable peer-reviewed literature and authoritative national and regional reports, and characterizes climate threats to USACE business lines. They also provide context and linkage to other agency resources for climate resilience planning, such as sea level change calculation and coastal risk reduction resources, downscaled climate data for subregions, and watershed vulnerability assessment tools.

This report focuses on Water Resources Region 6, the Tennessee Region, the boundaries for which are shown in Figure 1.2. The entire Tennessee Region is within the USACE Nashville district territory.
Figure 1.1. 2-digit Hydrologic Unit Code Boundaries for the Continental United States, Alaska, Hawaii, and Puerto Rico.
Figure 1.2. Water Resources Region 6: Tennessee Region Boundary.
1.1. A Note on the Water Resources Region Scale

USACE and other resource management agencies require reliable, science-based methods for incorporating climate change information into the assessments that support water resources decisions and actions. Such planning assessments must quantify projections of future climate and hydrology. One common practice is to begin by developing relationships between the currently observed climate and the projected future possible climate over the assessment region.

However, the numerical models producing these multiple projections of future possible climate were not designed to support these assessments for local-to-regional scale operations. This means that intervening steps have to be taken to correct obvious biases in the models' outputs and to make the outputs relevant at the scales where hydrologic resource assessments can take place. The commonly used name for these post-processing steps is "downscaling" because one step is using one or another method to spatially (and temporally) disaggregate or interpolate (or other) the results produced at the numerical climate models' native scale to the scale of the water resources assessment. The current generation of climate models, which includes the models used to generate some of the inputs described in this work, have a native scale on the order of one to two hundred kilometers on each side of the grids used to simulate climate for Earth, substantially too coarse for the watershed assessments needed to inform resource assessment questions and decisions.

On the other hand, these questions and decisions should not be addressed with model inputs at scales so fine that they impart false precision to the assessment. False precision would appear by suggesting that the driving climate model information can usefully be downscaled, by any method, to individual river reaches and particular project locations, for example.

The approach at USACE is to consider the questions in need of climate change information at the geospatial scale where the driving climate models retain the climate change signal. At present, USACE judges that the regional, sub-continental climate signals projected by the driving climate models are coherent and useful at the scale of the 2-digit HUC (Water Resources Region), and that confidence in the driving climate model outputs declines below the level of a reasonable trade-off between precision and accuracy for areas smaller than the watershed scale of the 4-digit HUC (Water Resources Subregion). Hence, these summaries group information at the 2-digit HUC scale both to introduce relevant climate change literature and to support the vulnerability assessments USACE is conducting at the Water Resources Subregion scale. For Water Resources Region 6, both the 2-digit and 4-digit HUC boundaries are shown in Figure 1.2.

2. Observed Climate Trends

Observed climate trends within the Tennessee Region are presented in this section to generally characterize current, or past, climate in the study region. While the primary cause for global warming is attributed by the scientific community to human-induced increases in atmosphere levels of heat-trapping gases (Walsh et al., 2014), this section is not focused on attribution or cause (either natural or unnatural). Rather, it is specifically focused on the identification and detection of climate trends in the recent historical record. The interrelationships of Earth’s climate system are complex and influenced by multiple natural and unnatural (i.e., anthropogenic
greenhouse gas emissions) forcings. When additional detail is needed, the reader is referred to the specific references cited, including the third National Climate Assessment (NCA), which includes not only regional assessments, but also foundational resources related to climate science literacy.

The climate trends presented in this section are based on peer-reviewed literature on the subject of observed climate. To the extent possible, studies specific to the Tennessee Region or its sub-watersheds were relied upon. A focus is placed on identified primary variables including:

- mean temperature
- extreme temperatures
- average precipitation
- extreme precipitation events
- mean streamflow

In addition to primary variables, peer-reviewed literature addressing climate change within the geographic region of the Water Resources Region or inclusive of the Water Resources Region (fully or partially) revealed additional, secondary, climatic variables that have been studied such as the spring index (SI), drought indices, and soil moisture.

The results presented below indicate mild increasing trends in temperature and precipitation for parts of the Tennessee Region, particularly since the 1970s. However, clear consensus does not exist for either. Studies of regional streamflow reviewed here present no evidence of significant trends in flow over the past 50 to 60 years.

### 2.1. Temperature

A number of studies focusing on observed trends in historical temperatures were reviewed for this report. These include both national scale studies inclusive of results relevant to the Tennessee Region and regional studies focused more specifically and exclusively on the Tennessee Region. Results from both types of studies, relevant to the Tennessee Region, are discussed below.

At a national scale, a 2009 study by Wang et al. examined historical climate trends across the continental United States. Gridded (0.5 degrees x 0.5 degrees) mean monthly climate data for the period 1950 – 2000 were used. The focus of this work was on the link between observed seasonality and regionality of trends and sea surface temperature variability. The authors identified positive statistically significant trends in recent observed seasonal mean surface air temperature for most of the U.S. (Figure 2.1). For the Tennessee Region, seasonal differences are evident. A positive, but mild, warming trend is identified for most of the region in the winter (December – February) and spring (March – May), while a mild cooling trend is shown for the summer (June – August) and fall (September – November). The authors do not provide information on statistical significance of the presented observed trends. A later study by Westby et al. (2013), using data from the period 1949 – 2011, moderately contradicted these findings, presenting a general mild winter cooling trend for the entire region for this time period. Their cooling trend, however, was not statistically significant at a 95% confidence interval (C.I.). The third NCA report (Carter et al., 2014) presents historical annual average average temperatures for the southeast region. For the southeast study region, including the Tennessee Region, historical data...
generally shows mild warming of average annual temperatures in the early part of the 20th century, followed by a few decades of cooling, and now again showing indications of warming. However, the NCA report cites an overall lack of trend for the past century and a seasonal breakdown is not presented. Details on statistical significance are not provided.

Grundstein and Dowd (2011) investigated trends in one-day extreme maximum and minimum apparent temperatures across the continental U.S. The study was based on daily temperature data compiled by the National Climatic Data Center (NCDC) for 187 stations across the country for the period 1949 – 2010. For the Tennessee Region, they found a statistically significant (95% C.I.) increasing trend in the number of one-day extreme minimum temperatures for one of two stations in the region. No significant trend was found at the other station in the Tennessee Region. No significant trends were found in the number of one-day extreme maximum temperatures at either of the two stations in the Tennessee Region.

Schwartz et al. (2013) investigated changes in spring onset for the continental U.S. Their particular focus was on changes in the seasonality of plant growth as dictated by changing temperature regimes. The authors used historical data from over 22,000 stations across the United States, obtained from the NCDC with periods of record extending through 2010. Their findings indicate that for most of the Tennessee Region, spring onset is occurring more than four days later for the current period (2001 – 2010) compared to an earlier baseline reference decade.
(1951 – 1960) (Figure 2.2). In other words, an apparent small shift in seasons has been identified for most of the Tennessee Region, with spring warming occurring later than in the past.

**Figure 2.2.** Change in spring onset (first leaf date), in days for 2001 – 2010 compared to 1951 – 1960. The Tennessee Region is within the red oval (Schwartz et al., 2013).

Trends in overnight minimum temperatures (T\textsubscript{min}) and daily maximum (T\textsubscript{max}) temperatures for the southeast U.S., based on data from 1948 to 2010, were the subject of a study by Misra et al. (2012). Their study region includes a small number of stations at the southern and eastern edges of the Tennessee Region. Results of this study show increasing trends in both T\textsubscript{min} and T\textsubscript{max} for most of the sites in the region. The authors attribute at least a portion of these changes to the impacts of urbanization and irrigation. A single site, which appears to be just within the Tennessee Region southern boundary, exhibits decreasing trends in both metrics.

Laseter et al. (2012) present a continuous historical climate data set for the Coweeta Laboratory in North Carolina (the southeast edge of the Tennessee Region). This data shows significant warming since the late 1970s (Figure 2.3) in terms of annual average, maximum, and minimum air temperatures. They report that 1999 was the hottest year on record for their study site.

**Figure 2.3.** Annual maximum, average, and minimum historical air temperatures, 1940-2010, Coweeta Laboratory, North Carolina, 1940 – 2010. (Laseter et al., 2012).

*Key point: Limited evidence points toward a possible warming trend in the region, particularly since the 1970s. Literature consensus, however, is low.*
2.2. Precipitation

Palecki et al. (2005) examined historical precipitation data from across the continental United States. They quantified trends in precipitation for the period 1972 to 2002 using NCDC 15-minute rainfall data. For the Tennessee Region, a statistically significant decrease (90% C.I.) in summer mean storm intensity (total precipitation divided by storm duration) was identified for the region that includes the Tennessee Region. No statistically significant trends were found for total storm precipitation, storm duration, or 15-minute maximum intensity for any seasons in the Tennessee Region.

Multiple authors have identified significant increasing trends in total annual precipitation in recent historical records for the study region. Grundstein (2009) identified statistically significant (95% C.I.) increasing trends in soil moisture for two climate division stations in Tennessee (Figure 2.4) based on annual data from 1895 to 2006. Soil moisture is a function of both supply (precipitation) and demand (evapo-transpiration [ET]), and therefore is an effective proxy for both precipitation and ET. A statistically significant trend in annual precipitation, for the same time period, was quantified for one of the stations. Note that there are a total of four climate division stations in Tennessee. For two of the stations, no significant trend in soil moisture was identified and no significant trend in precipitation was identified for three of the stations.

**Figure 2.4.** Statistically significant linear trends in (a) soil moisture index (unitless) and (b) annual precipitation (cm) for the continental U.S., 1895 – 2006. The Tennessee Region is within the red oval (Grundstein, 2009).

As described in Section 2.1, a similar study by Wang et al. (2009) also focused on historical climate trends across the continental U.S. using gridded climate data and a shorter period of record (1950 – 2000). The authors identified generally positive significant trends in annual precipitation for most of the U.S. For the Tennessee Region, the authors identified a mild decreasing trend in winter precipitation and mild increasing trends in precipitation for the other
seasons (Figure 2.1). The authors do not provide information on statistical significance of the presented observed trends.

A 2011 study by McRoberts and Nielsen-Gammon used a new continuous and homogenous data set to perform precipitation trend analyses for sub-basins across the United States. The extended data period used for the analysis was 1895 – 2009. Linear positive trends in annual precipitation were identified for most of the U.S. (Figure 2.5). For the Tennessee Region, results indicate mild (2 – 15% per century) increasing trends in annual precipitation. The authors do not provide information on statistical significance of the presented observed trends.

![Figure 2.5. Linear trends in annual precipitation, 1895 – 2009, percent change per century. The Tennessee Region is within the red oval (McRoberts and Nielsen-Gammon, 2011).]

Changes in extreme precipitation events observed in recent historical data have been the focus of a number of studies. Studies of extreme events have focused on intensity, frequency, and/or duration of such events. Wang and Zhang (2008) used recent historical data and downscaled Global Climate Models (GCMs) to investigate changes in extreme precipitation across North America. They focused specifically on the changes in the frequency of the 20-year maximum daily precipitation event. The authors looked at both historical trends in observed data and trends in future projections. Statistically significant increases in the frequency of the 20-year storm event were quantified across the southern and central U.S., in both the recent historical data and the long term future projections (described below). For the Tennessee Region, there do not appear to be any significant changes in the recurrence of this storm for the period 1977 – 1999 compared to the period 1949 – 1976. A portion of the region shows a small increase (0 – 25%) while a different portion shows a small decrease (0 – 25%) in frequency of occurrence.

Pryor et al. (2009) performed statistical analyses on 20th century rainfall data to investigate for trends across a range of precipitation metrics. They used data from 643 stations scattered across the continental U.S. For the Tennessee Region, the analysis showed generally increasing, and statistically significant, trends in total annual precipitation, extreme high precipitation events (90th percentile daily), and the number of precipitation days per year (Figure 2.6 a, b, and d). These trends were determined to be significant at the 90% confidence interval. Results are mixed for precipitation intensity (Figure 2.6 c), with some locations exhibiting an increasing trend and others a decreasing trend. The authors note that the trends identified are not necessarily linear, with an apparent increase in the rate of change in the latter part of the century for most of the trends.
Figure 2.6. Historical precipitation trends (20th century). a.) annual totals, b.) 90th percentile daily, c.) precipitation intensity (annual total/number of precipitation days), and d.) number of precipitation days per year. Note that blue dots indicate positive trend, red circles indicate negative trend, and symbol sizes are scaled to 3% change per decade. The Water Resources Region 6 is generally within the red oval (Pryor et al., 2009).

Brommer et al. (2007) investigated changes in long duration precipitation events over the past century. This study found no significant changes for the Tennessee Region during the 20th century, despite such changes quantified for many other areas in the U.S. Villarini et al. (2013) identified statistically significant (p ≤ 0.05) increasing trends in the frequency of occurrence of heavy rainfall in a region inclusive of the Tennessee Region for multiple climate stations with at least 50 years of historical record. While significant trends were identified for a number of stations in the region, an even greater number of stations in the Tennessee Region exhibited no significant trends.
A number of recent studies have focused more specifically on the southeast region of the U.S., including the Tennessee Region. As above, regional investigations have targeted trends, or changes, in annual precipitation and the occurrence of extreme events. The work of Small et al. (2006) included analysis of the Tennessee Region specifically. These authors investigated for significant trends in various precipitation and flow metrics based on USGS Hydroclimatologic Data Network (HCDN) climate data from 1948 to 1997. Statistically significant (95% C.I.) increasing trends were identified for the region in fall precipitation for three locations in the region (Figure 2.7). One of the stations in the Tennessee Region did not exhibit a statistically significant trend in fall precipitation. None of the stations showed significant trends for annual precipitation (panel b).

Figure 2.7. Historical trends in precipitation (P) and streamflow (Q), 1948 – 1997. The Tennessee Region is within the red oval (Small et al., 2006).

In North Carolina (the southeast edge of the Tennessee Region, Coweeta Laboratory), changes in precipitation variability have been observed (Laseter et al., 2012) (Figure 2.8). These changes include wetter wet years and dryer dry years compared to the middle of the 20th century. As an example, the wettest year on record occurred in 2009 at Coweeta, and only two years earlier (2007) the driest year on record was observed. This pattern of change is supported by the National Climate Assessment (Carter, 2014), which states that, “summers have been either increasingly dry or extremely wet” in the southeast region. This assessment is based on analysis of data dating back to the turn of the 20th century.
Figure 2.8. Total annual precipitation at Coweeta Laboratory (North Carolina). Lines show modeled 10th and 90th quantiles as a function of time, 1940 – 2010. (Laseter et al., 2012)

Trends in the frequency and severity of droughts in the Southeast U.S. were the subject of studies by Chen et al. (2012) and Cook et al. (2014). In the first study, historical data (1895 – 2007) for the southern USA, including the Tennessee Region, were used to identify trends in drought, as defined by the standard precipitation index (SPI). The SPI is a metric of precipitation only and neglects the impacts of ET on droughts (Chen et al., 2012). The authors were not able to identify significant trends in either the frequency or intensity of droughts in the study region. The second set of authors used tree ring data to assess the frequency and severity of droughts over the past millennium (1000 – 2005), across the U.S. For the southeast region, which includes the Tennessee Region, the authors identified a statistically significant (90% C.I.) decline in drought frequency (droughts per century) over the past 1,000 years and a general increase in soil moisture, as defined by the Palmer Drought Severity Index (PDSI), over the same period (Figure 2.9).
2.3. Hydrology

Studies of trends and non-stationarity in streamflow data collected over the past century have been performed throughout the continental U.S., some of which are inclusive of the Tennessee Region. In 2013, Xu et al. investigated trends in streamflow for multiple stations in the Tennessee Region. This study used the Model Parameter Estimation Experiment (MOPEX) data set for the period 1950 – 2000. None of the stations in the Tennessee Region show significant (at 95% C.I.) trends in streamflow in either direction. These findings are supported by Kalra et al. (2008), who found no significant (95% C.I.) trends in either direction, for a number of stream gages distributed throughout the Tennessee Region. Data (1952 – 2001) were aggregated by USGS HUC for this study. Further support is provided by Small et al. (2006) who also found no significant (95% C.I.) trends in Tennessee Region stream gages, using HCDC data for the period 1948 – 1997.

Key point: No significant trends have been identified in the region’s streamflow data for the latter half of the 20th century.

2.4. Summary of Observed Climate Findings

Evidence has been presented in the recent literature of mild increases in annual temperature in the Tennessee Region over the past century, particularly since the 1970s. Consensus, and the number of available region-specific studies, is low, however.

Annual precipitation totals have become more variable in recent years compared to earlier in the 20th century. Evidence has also been presented, but with limited consensus, of mildly increasing trends in the magnitude of annual and seasonal precipitation for parts of the study region. No such trend, however, has been observed in streamflow data for the region. Results presented here...
suggest that increasing temperatures may play a role in moderating the impacts of increasing precipitation on streamflows in the region.

3. Projected Climate Trends

While historical data is essential to understanding current and future climate, non-stationarity in the data (i.e., a changing climate) dictates the use of supplemental information in long-term planning studies. In other words, the past may no longer be a good predictor of the future (Milly et al., 2008). Consequently, the scientific and engineering communities are actively using computer models of the Earth’s atmosphere and associated thermodynamics to project future climate trends for use in water resources planning efforts. Although significant uncertainties are inherent in these model projections, the models, termed global climate models (GCMs), are widely accepted as representing the best available science on the subject, and have proven highly useful in planning as a supplement to historical data. A wealth of literature now exists on the use of GCMs across the globe.

This section summarizes projected climate trends, as projected by GCMs, within the Tennessee Region identified in a review of recent peer-reviewed literature. The information presented should be considered an overview, and similar to Section 2 on observed climate trends, does not focus on attribution or causation of the projected climate trends or the casual relationships between climate variables. These relationships are complex and influenced by multiple natural and unnatural (i.e., anthropogenic greenhouse gas emissions) forcings that influence the Earth’s climate system. Typical of projected climate studies, often specific (and sometimes multiple) greenhouse gas emission scenarios (or representative concentration pathways) are modeled by a single GCM (or ensemble of GCMs). The spectrum of scenarios offer a wide range of “climate futures” so each study’s assumed emission scenario(s) are noted. When additional detail is needed, the reader is referenced to the specific references cited, including the third NCA which includes not only regional assessments, but also foundational resources related to climate science literacy, GCMs, and emission scenarios.

The USACE vulnerability assessments (https://corpsclimate.us/rccvar.cfm) rely on downscaled climate projection data and hydrologic simulations produced by USACE in conjunction with Lawrence Livermore National Laboratory, Bureau of Reclamation, U.S. Geological Survey, Climate Central, Scripps Oceanographic Institute and Santa Clara University, and others. The data are housed in the publicly accessible Downscaled Climate and Hydrology Projections website archive, hosted by Lawrence Livermore National Laboratory, which is meant to provide access to climate and hydrologic projections at spatial and temporal scales relevant to watershed or basin-scale water resources management decisions. These data, and the vulnerability assessments for which they provide a foundation, serve as supplements to the information about projected climate conditions provided in this report.

Results of this review indicate a strong consensus in the scientific literature that air temperatures and extreme precipitation events will increase over the next century in the Tennessee Region. There is much less consensus on the future trending, or lack thereof, in precipitation and streamflow in the region.
3.1. Temperature

GCMs have been used extensively to project future climate conditions across the country. At a national scale, model projections generally show a significant warming trend throughout the 21st century, with a high level of consensus across models and modeling assumptions. There is much less consensus on future patterns of precipitation. Results of studies inclusive of the Tennessee Region typically fall in line with both of these generalizations.

Maximum air temperature projections were investigated by Liu et al. (2013) using a single GCM and assuming an A2 greenhouse gas emissions scenario (worst case) in a national analysis. The results of their study, specific to the Tennessee Region, show a projected increase in winter and spring maximum air temperature of about 2 °C for a 2055 planning horizon compared to a baseline period of 1971 – 2000 (Figure 3.1). The results of the study project increases in maximum air temperature from 2.5 to 4 °C for summer and fall temperatures.

![Figure 3.1. Projected changes in seasonal maximum air temperature, °C, 2041 – 2070 vs. 1971 – 2000. The Tennessee Region is within the red oval (Liu et al., 2013).](image)

Similar results are presented by Scherer and Diffenbaugh (2014). These authors apply a multi-member ensemble GCM, assuming an A1B (middle of the road) emissions scenario, to the continental U.S. For the southeast region of the country, including the Tennessee Region, model projections indicate steadily increasing air temperatures throughout the 21st century for both summer and winter seasons (Figure 3.2). By 2090, projections show an increase of 3.9 °C in the summer and 3.2 °C in the winter, compared to a 1980 – 2009 baseline period. These results agree well with those described previously for Liu et al. (2013).
Also at a regional scale, Dale et al. (2010) present GCM projections for Tennessee, included in Water Resources Region 6. This study focuses on the 2030 and 2080 planning horizons using three GCMs and assuming a single greenhouse gas emissions scenario (A1B, middle of the road). Results (Table 3.1) show significant projected increases in mean monthly temperatures, compared to a recent historical baseline. Reasonable consensus exists across the three models. The largest temperature increases are projected for the summer and fall months (1 – 2°C increase in 2030; 2 – 6°C increase in 2080).

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Table 3.1. Mean climate projections for Tennessee; 3 GCMs, 2 planning horizons, changes relative to mean current conditions, 1980 – 1997. (Dale et al., 2010).

Elguindi and Grundstein (2013) present results of regional climate modeling of the U.S. focused on the Thornthwaite climate type – a measure of the combination of relative temperature and precipitation projections. For the Tennessee Region, results show a shift from primarily warm wet climate type in the latter decades of the 20th century to a much larger proportion of warm moist climate type areas with some areas remaining warm wet by the period 2041 – 2070 (Figure 3.3).
Projections of changes in temperature extremes have been the subject of many recent studies. A 2006 study by Tebaldi et al. applied nine GCMs at a global scale focused on extreme precipitation and temperature projections. Model projections of climate at the end of the century (2080 – 2099) were compared to historical data for the period 1980 – 1999. For the general region of the southeastern U.S., specifically around the Tennessee Region, the authors identified small to little increases, or potential slight decreases in the projected extreme temperature range (annual high minus annual low temperature), a moderate increase in a heat wave duration index (increase of 3 to 4 days per year that temperatures continuously exceeds the historical norm by at least 5 ºC), and a moderate increase in the number of warm nights (6 to 7% increase in the percentage of times in the year when minimum temperature is above the 90th percentile of the climatological distribution for the given calendar year), compared to the baseline period.

Similar results are presented by Kunkel et al. (2010). In this study, two different downscaled GCMs were applied to the continental U.S., assuming high greenhouse gas emissions scenarios (A2 and A1F), with a focus on summer heat wave occurrence and intensity. For the Tennessee Region, projections indicate a 4.5 to 5.5 ºC increase in three-day heat wave temperatures and a 50 to 65 day increase in the annual number of heat wave days for a 2090 planning horizon compared to a recent historical baseline.

Gao et al. (2012) focus on future extreme climate events in the eastern U.S., as forecast by GCMs. They applied a single GCM downscaled to a high resolution grid (4 km x 4 km) that included the entire Tennessee Region. The analysis compared present (2001 – 2004) conditions to future projected conditions (2057 – 2059). A single representative concentration pathway was simulated, representative of intensive future fossil fuel use and high greenhouse gas emissions.
Results (Figure 3.4) show projected increases in heat wave intensity, duration, and frequency for the study region. Extreme heat wave temperatures are projected to increase by up to 5 °C in the Tennessee Region, and the frequency of heat waves is projected to increase by 0 – 4 events per year, with some areas showing trends of decreasing heat wave frequency, compared to the baseline period (2001 – 2004) within the region. There were no clear trends with respect to the projected duration of heat wave events in the Tennessee Region.

![Figure 3.4. GCM Projections of heat wave patterns in eastern USA (intensity, duration, frequency) for a 2058 planning horizon (compared to 2002 baseline); first column = baseline, second column = future, third column = difference between the two. The Water Resources Region 6 is generally within the black ovals (Gao et al., 2012).](image)

The third NCA (Carter et al., 2014) generally supports the findings presented above. Climate model projections for the southeast region of the U.S., inclusive of the Tennessee Region, presented in this report indicate a sharp, and statistically significant, increase in both annual average temperature and the number of extreme heat days over the next century (Figure 3.5). Additionally, projections are presented showing a decrease in the number of nights below freezing (Figure 3.6).
a) Annual average temperature

![Graph showing annual average temperature projections for Higher Emissions (A2), Lower Emissions (B1), and Observed, with a sharp increasing trend from 1900 to 2100.]

**Figure 3.5.** GCM projections of temperature change in the southeast USA. The Water Resources Region 6 region is within the black oval (Carter et al., 2014).

b) Extreme heat days

![Graph showing projected difference in number of days over 95°F from historical climate with change in number of days, and maps depicting historical climate (1971-2000) and projection (2041-2070).]

**Figure 3.6.** GCM projections of change in overnight minimum temperatures in the southeast USA. The Tennessee Region is within the black oval (Carter et al., 2014).

*Key point: Strong consensus exists in the literature that projected temperatures in the study region show a sharp increasing trend over the next century.*

### 3.2. Precipitation

In line with projections for the rest of the country, projections of future changes in precipitation in the Tennessee Region are variable and generally lacking in consensus among studies or across models. From a global analysis using three GCM projections, Hagemann et al. (2013) projects a decrease in annual precipitation of approximately 100 mm per year for the Tennessee Region (**Figure 3.7**).
The Liu et al. study (2013) of the U.S., described above, quantified significant increases in winter and spring precipitation associated with a 2041-2070 planning horizon, relative to a recent historical baseline (1971-2000, centered around 1985), for the southeastern U.S., including the Tennessee Region (Figure 3.8). Smaller increases, or even slight decreases, are projected for summer and fall seasons in the Tennessee Region.

In a regional study, three sets of GCM projections presented by Dale et al. (2010), display a low level of consensus in their future precipitation forecasts for Tennessee, with no clear trends projected (Table 3.1). Their results show three distinct possible futures for their study area and
selected planning horizons: a wet scenario with increases in monthly precipitation up to 1 mm/month; a middle scenario with some months predicted to be slightly wetter and others slightly dryer; and a dry scenario with projected decreases in precipitation across most months up to 1 mm/month.

Future projections of extreme events, including storm events and droughts, are the subject of studies by Tebaldi et al. (2006), Wang and Zhang (2008), Gao et al. (2012), and Wang et al. (2013). The first authors, as part of a global study, compared an ensemble of GCM projections for the southeast U.S. and a 2080 – 2099 planning horizon with historical baseline data (1980 – 1999). They report slight decreases or no change in the number of high (> 10 mm) precipitation days for the region, and increases in the number of storm events greater than the 95th percentile of the historical record and increases the daily precipitation intensity index (annual total precipitation divided by number of wet days). In other words, the projections forecast increases in the intensity of storm events by the end of the 21st century for the general study region with spatial variability in the future frequency of such events. In addition to the historical data trend analyses by Wang and Zhang (2008) described above, these authors also used downscaled GCMs to look at potential future changes in precipitation events across North America. The GCMs were forced with the Intergovernmental Panel on Climate Change (IPCC) high emissions scenario (A2) to quantify a significant increase (c. 30 to 50%) in the recurrence of the current 20-year 24-hour storm event for their future planning horizon (2050 – 2099) in the Tennessee Region (Figure 3.9).

Figure 3.9. Projected risk of current 20-year 24-hour precipitation event occurring in 2070 compared to historical (1974). A value of 2 indicates this storm will be twice as likely in the future compared to the past. Black dots show the locations of stations. The Water Resources Region 6 is generally within the red oval (Wang and Zhang, 2008).
The GCM applied in the Gao et al. (2012) study for the eastern U.S. generally projects increases in extreme precipitation events throughout the eastern U.S. Within the Tennessee Region, increases were projected in the magnitude of annual total precipitation (up to 200 mm yr$^{-1}$), daily extreme precipitation events within the 95th percentile (up to 20 mm day$^{-1}$), and frequency of storm events (increases of up to up to 5 days yr$^{-1}$), for the 2057 – 2059 planning horizon compared to current conditions (2001 – 2004) (Figure 3.10).

**Figure 3.10.** GCM projections of future precipitation patterns in eastern USA (annual extreme totals, daily extremes, frequency of events) for a 2057 - 2059 planning horizon (compared to 2001 - 2004 baseline); first column = baseline, second column = future, third column = difference between the two. The Tennessee Region is within the red oval (Gao et al., 2012).

Key point: Strong consensus exists in the literature that the intensity and frequency of extreme storm events will increase in the future for the Tennessee Region. Low consensus exists with respect to projected changes in total annual precipitation for the region.

### 3.3. Hydrology

A number of global and national scale studies have attempted to project future changes in hydrology, relying primarily on a combination of GCMs and macro-scale hydrologic models. These studies include projections of potential hydrologic changes in the southeastern United States. Thomson et al. (2005) applied two GCMs, across a range of varying input assumptions, in
combination with the macro-scale Hydrologic Unit Model to quantify potential changes in water yield (considered to be a surrogate for streamflow) across the United States. Results are presented for both continuous spatial profiles across the country (Figure 3.11) and for individual USGS 2-digit HUCs. For the Tennessee Region, and most of the United States, contradictory results are generated by the two GCMs. For the same set of input assumptions, one model predicts significant decreases in water yield, the other projects significant increases in water yield.

![Figure 3.11. Projected change in water yield (from historical baseline), under various climate change scenarios based on 2 GCM projections. The Tennessee Region is within the red oval (Thomson et al., 2005).](image)

The results presented by Thomson et al. (2005), described above, highlight the significant uncertainties associated with global climate modeling, particularly with respect to hydrologic parameters. Additional uncertainty is generated when these climate models are combined with hydrologic models that carry their own uncertainty. This comparison and quantification of uncertainty is the subject of a 2013 study by Hagemann et al. In this study, the authors apply three GCMs, across two emission scenarios to seed eight different hydrologic models for projecting precipitation, ET, and runoff on a global scale. Their findings, in agreement with CDM Smith (2012), indicate that the uncertainty associated with macro-scale hydrologic modeling is as great, or greater, than that associated with the selection of climate models. Study projections from Hagemann et al. (2013), for the Tennessee Water Resources Region show an overall decrease in runoff by approximately 160 mm per year for their future planning horizon (2071 – 2100) compared to the recent historical baseline (1971 – 2000) (Figure 3.12), assuming an A2 emissions scenario. The largest changes in seasonal runoff are expected to occur in winter and spring (Figure 3.13).
Figure 3.12. Ensemble mean runoff projections (mm/year) for A2 greenhouse gas emissions scenario, changes in annual runoff, 2085 vs. 1985. The Tennessee Region is within the red oval (Hagemann et al., 2013).

Figure 3.13. Ensemble seasonal (a. winter b. spring c. summer d. fall) mean runoff projections (mm/season) for A2 greenhouse gas emissions scenario, changes in seasonal runoff, 2071 – 2100 vs 1971 – 2000. The Tennessee Region is within the red oval (Hagemann et al., 2013).

One method for addressing uncertainty in climate change projections is to use probabilistic modeling approaches (CDM, 2011). Such studies are described by Wu et al. (2014), where a full suite of CMIP3 GCM projections were used, in combination with a lumped rainfall-runoff
model, within a probabilistic framework to project future changes in streamflow for a watershed in North Carolina (Coweeta Laboratory). They compared future (2070 – 2099) projections with historical (1961 – 1990) data. Probabilistic results (Figure 3.14) suggest a likely increase in winter streamflow (up to c. 30%) across a range of assumed greenhouse gas emission scenarios. Results are mixed for the other seasons. Summer flows are projected to likely decrease under the A2 (worst case) scenario but likely increase (slightly) under the B1 (best case) scenario. Spring flows appear just as likely to be lower as higher for the A2 and A1B scenarios but more likely to be higher under the B1 scenario.

![Figure 3.14](A2_scenario.png)  
**Figure 3.14.** Projected changes in streamflow, Coweeta Laboratory (North Carolina): 2070 – 2099 vs. 1961 – 1990. Winter = thick black line, spring = thin black line, summer = dotted line, fall = dashed line. (Wu et al., 2014).
Lastly, the National Climate Assessment (Carter et al., 2014) presents projections of a mild decrease in water availability for the southeast region of the country through the next century, in agreement with only some of the study results presented above.

Key point: Variability exists with projected streamflow changes in the Tennessee Region.

3.4. Summary of Future Climate Projection Findings

There is strong consensus in the literature that air temperatures will increase in the study region, and throughout the country, over the next century. The studies reviewed here generally agree on an increase in mean annual air temperature of approximately 2 to 6 °C by the latter half of the 21st century for the Tennessee Region. The largest increases are projected for the summer months. Reasonable consensus is also seen in the literature with respect to projected increases in extreme temperature events, including more frequent, longer, and more intense summer heat waves in the long-term future compared to the recent past.

Projections of precipitation in the study region are less certain than those associated with air temperature. Results of the studies reviewed here are roughly evenly split with respect to projected increases versus decreases in future annual precipitation. This is not unexpected as, according to the recently released NCA (Carter et al., 2014); the southeast region of the country (inclusive of the Tennessee Region) appears to be located in a “transition zone” between the projected wetter conditions to the north and dryer conditions to the west. There is, however, moderate consensus among the reviewed studies that future storm events in the region will be more intense and more frequent compared to the recent past.

Similarly, clear consensus is lacking in the hydrologic projection literature. Projections generated by coupling GCMs with macro-scale hydrologic models in some cases indicate a reduction in future streamflows but in other cases indicate a potential increase in streamflows in the study region. Some studies exhibit variability in the results based on the GCM or emissions scenario evaluated, while other studies project variable streamflow impacts by season.

A number of studies reviewed here employed probabilistic modeling methods to capture and quantify some of this projection uncertainty, resulting from both climate and runoff modeling steps. These methods frame output in the form of probability distributions that can viewed as characterizations of likelihood of occurrence (risk) or levels of consensus among modeling scenarios.

The trends and literary consensus of observed and projected primary variables noted above are summarized for reference and comparison in Figure 3.15.
4. **Business Line Vulnerabilities**

The Tennessee Region encompasses a limited area in southern Tennessee, northern Alabama and northern Georgia, and western North Carolina. USACE recognizes the potential impacts of future climate considering the exposure and dependency of many of its projects on the natural environment. To assess the potential vulnerabilities that climate change may pose on USACE’s missions, a set of primary USACE business lines were identified. They include:

- Navigation
- Flood Risk Management
- Water Supply
- Ecosystem Restoration
- Hydropower
- Recreation
- Emergency Management

**Figure 3.15.** Summary matrix of observed and projected climate trends and literary consensus.
The navigation mission in the USACE Tennessee Region is focused on maintaining locks and inland riverways. By the end of the 21st century, the frequency and intensity of large storm events and associated flooding are also expected to increase. In addition, the Tennessee Region may experience increases in ambient air temperature and a broader range of extremes in water availability throughout the year, which has implications for water levels and thus the ability for vessels to navigate these inland rivers.

USACE implements flood risk management projects in the region to limit flooding. Higher peak rainfalls and increased precipitation event frequency are predicted for the region. An increase in peak rainfall would cause increased runoff and may cause flash floods if the storms are intense. Flood risk management projects may be very important for reducing the residual flooding impacts due to extreme storm events, which are predicted to be more frequent and intense.

USACE also maintains and operates several fresh water supplies to maintain water quality in the region. The contrast between increasing mean air temperatures along with increased frequency and magnitude of heat waves, versus the increase, storm intensity and frequency will make managing competing water needs a challenge, especially when water demand is high and water supply is low.

USACE implements ecosystem restoration projects in the Tennessee Region. Increased ambient air temperatures – including increasing high and low temperatures, will result in increased water temperatures. This may lead to water quality concerns, particularly for the dissolved oxygen levels, which are an important water quality parameter for aquatic life. Increased air temperatures are associated with the growth of nuisance algal blooms and influence wildlife and supporting food supplies.

Increased storm intensities may pose complications to planning for ecosystem needs and lead to variation in flows. This may be particularly true during dry years, when water demands for conflicting uses may outweigh water supply. During wet years, flooding may raise particular ecological concerns and may threaten ecosystems.

USACE owns and operates several hydropower plants in the Tennessee Region. By the end of the 21st century, large storm events are expected to increase in the region, which may be beneficial for hydropower plants in the region, as flooding and increased river flows may lead to increased power generation. However, in extreme cases excess flooding may present some operational issues at these projects. Conversely, there may also be times during any given year where flows and reservoir levels are reduced due to high temperatures and drought conditions, which reduce the amount of power that may be generated by the hydropower plants.

Recreational facilities in the Tennessee Region offer several benefits to visitors as well as positive economic impacts. Increases in air temperature along extended heat waves in the summer months and the increased frequency of extreme storm events have the potential to decrease the number of visitors to USACE’s recreational facilities. Periods of extreme high heat poses human health concerns and higher water temperatures can result in algal blooms and other water quality issues which may cause health risks for those involved in aquatic activities.
Increased extreme storm events may make recreational activity difficult, dangerous, or impossible.

USACE has extraordinary capabilities to respond to natural disasters and other emergency situations throughout the country, and it is a top priority. There are designated emergency managers and assigned staff in each region and subregion that are able to quickly mobilize. Extreme storm events are capable of creating emergency situations in which USACE would be needed to provide assistance in the Tennessee Region. These types of storms are capable of intense precipitation, winds, and storm surge in coastal areas. Since these may occur more frequently, USACE can expect an increased need for their assistance in disaster response and recovery.

USACE’s regulatory mission has a serious commitment to protecting aquatic resources while allowing reasonable development. The climate projections may have indirect implications for permitting in the region, and may result from modifications in federal laws and guidance. This may spur stricter regulation or increase the permitting breadth and depth. While most of the permitting processes may not change, the volume and frequency of the permitting requirements may increase – thus increasing the permitting costs for projects.

In addition, USACE provides engineering, construction, real estate, environmental management, disaster response, and other support or consulting services for the Army, Air Force, other assigned U.S. Government agencies, and foreign governments. Environmental management services include rehabilitation of active and inactive military bases, formerly used defense sites, or areas that house excess munitions. Expected changes in climate may necessitate adjustments in rehabilitation approaches, engineering design parameters, and potential types of military construction/infrastructure projects that USACE may be asked to support.

USACE projects are varied, complex, and at times, encompass multiple business lines. The relationships among these business lines, with respect to impacts from climate change, are complicated with cascading effects. The interrelationships between business lines must be recognized as an essential component of future planning efforts when considering the best methods or strategies to adapt. Figure 4.1 summarizes the projected climate trends and impacts on each of the USACE business lines.
<table>
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<tr>
<th>CLIMATE VARIABLE</th>
<th>VULNERABILITY</th>
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| Increased Ambient Temperatures | Increased ambient air temperatures throughout the century, and over the next century are expected to create the following vulnerabilities on the business lines in the region:  
• Loss of vegetation from increased periods of drought and reduced streamflows may have impacts on vegetation within the region, which is important for sediment stabilization in the watershed. Loss of non-drought resistant vegetation may result in an increase in sediment loading, potentially causing geomorphic changes in the tributaries to the river system.  
• Decrease in flows may result from periods of drought and reduced streamflow has implications for maintain water levels in the rivers.  
• Flora and fauna that are not drought resistant can also be impacted by longer drought conditions, which may reduce opportunities for recreational wildlife viewing.  

| Increased Maximum Temperatures | Air temperatures are expected to increase, including maximum high and low temperatures in each season. This is expected to create the following vulnerabilities on business lines in the region:  
• Increased water temperatures leading to water quality concerns, particularly for the dissolved oxygen (DO) levels, growth of nuisance algal blooms and influence wildlife and supporting food supplies.  
• Increased evapotranspiration.  
• Human health risk increases from extended heat waves, impacting recreational visitors and increasing the need for emergency management.  

| Increased Storm Intensity and Frequency | Extreme storm events may become more intense and frequent over the coming century which are expected to influence the following vulnerabilities on business lines in the region:  
• Increased flows and runoff, which may carry pollutants to receiving water bodies, decreasing water quality.  
• Increased erosion with subsequent changes in sediment accumulation rates and creating water quality concerns.  
• Change in engineering design standards to accommodate new extreme storms magnitudes.  
• Increased groundwater recharge rates, as residence times are shortened within areas where evapotranspiration takes place during high intensity events.  
• Increased flooding, which may have negative consequences for all infrastructure, habitats, and people in the area.  

| Streamflow Variability | The changes in streamflow may be positive or negative, depending on local conditions.  


*NOTE: The Regulatory and Military Program business lines may be impacted by all climate variables.*

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**Figure 4.1.** Summary of projected climate trends and impacts on USACE business lines.
## Appendix A: References Climate/Hydrology Summary Table

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Appendix B: Reference List


CDM Smith, (2012) Incorporating Climate Change into Water Supply Planning and Yield Studies: A Demonstration and Comparison of Practical Methods


