USDA

United States
Department of
Agriculture
Forest Service

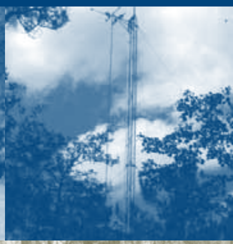
# Effects of Climate Variability on Forest Hydrology and Carbon Sequestration on the Santee Experimental Forest in Coastal South Carolina

**Southern
Research Station**
General Technical
Report SRS–172

**Zhaohua Dai, Carl C. Trettin, and Devendra M. Amatya**








## Authors:

**Zhaohua Dai**, Research Scientist, Earth System Research Center, Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, NH 03824;
**Carl C. Trettin,** Research Soil Scientist, and **Devendra M. Amatya**, Research Hydrologist, U.S. Department of Agriculture, Forest Service, Center for Forested Wetlands Research, Cordesville, SC 29434.

**Cover photographs** (left-to-right starting at the top):

Charles Harrison downloading data from the headquarters weather station on the Santee Experimental Forest (photo by Andrew Moreland); wet-dry deposition collector, headquarters weather station (photo by Julie Arnold); Pluvio rain gauge, headquarters weather station (photo by Charles Harrison); Santee Headquarters weather station (photo by Charles Harrison); above-canopy weather station, watershed WS-80 (photo by Charles Harrison); Santee Headquarters weather station circa 1960s (U.S. Forest Service); weir on watershed WS-79, circa 1960s (U.S. Forest Service); and V-notch weir on watershed WS-77 (U.S. Forest Service).

February 2013

Southern Research Station
200 W.T. Weaver Blvd.
Asheville, NC 28804

www.srs.fs.usda.gov

# Effects of Climate Variability on Forest Hydrology and Carbon Sequestration on the Santee Experimental Forest in Coastal South Carolina

**Z. Dai, C.C. Trettin, and D.M. Amatya**

# CONTENTS

# LIST OF FIGURES

# Effects of Climate Variability on Forest Hydrology and Carbon Sequestration on the Santee Experimental Forest in Coastal South Carolina

**Zhaohua Dai, Carl C. Trettin, and Devendra M. Amatya**

**Abstract**

Long-term weather and hydrology data from the Santee Experimental Forest were used to assess trends in air temperature, precipitation, and the water balance in gauged watersheds over a 63-year period. Since 1946, the mean annual air temperature has increased at a rate of 0.19 °C per decade, a rate higher than the global mean for the same period. Total annual precipitation has not changed significantly over the period of 1946–2008; however, large storm events (>50 mm precipitation) have increased 21 percent over the 63-year period. Annual stream discharge has varied from 5.5 percent of annual precipitation in dry years to 44.7 percent in wet years. In 1989, much of the forest was destroyed by Hurricane Hugo, a disturbance that, in turn, influenced streamflow. The water balance was estimated using the hydrologic model MIKE SHE; the long-term simulations showed that average annual flow was about 24 percent of annual precipitation and that mean annual evapotranspiration was approximately 76 percent over the 63-year period. The carbon balance on the 500-ha watershed was evaluated using Forest-DNDC. The model performance efficiency was 0.67 for soil $CO_2$ efflux, 0.70 for soil temperature, 0.40 for soil moisture, and 0.86 for wood biomass dynamics, demonstrating that this model was applicable for predicting carbon dynamics for this complex forest mosaic.

**Keywords:** Carbon cycling, climate change, Forest-DNDC, forest hydrology, long-term weather data, streamflow.

## INTRODUCTION

Climatic conditions influence hydrological processes and carbon (C) dynamics in forested ecosystems (Trettin and others 2006) because changes in temperature and precipitation can alter the hydrologic conditions that regulate the C balance in forest ecosystems. These changes are especially important in forested wetlands where hydrology is one of the most important elements influencing C accumulation and consumption (Pacific and others 2009, Pietsch and others 2003, Riveros-Iregui and McGlynn 2009, Trettin and Jurgensen 2003). While a sink for atmospheric C, forested wetlands also may be a significant source of terrestrial greenhouse gases, e.g., $CH_4$ and $CO_2$ (Trettin and others 2006). Understanding the effects of climate variability on forest hydrology and C balance of upland and forested wetlands is needed to assess their relative contributions of greenhouse gas to the atmosphere.

The forest landscape of the lower coastal plain along the Atlantic Ocean is typified by a mosaic of upland and wetland ecosystems. Streamflow and depth to water table within that landscape is heavily dependent on precipitation and evapotranspiration (Amatya and others 1996, 2006a; Brooks 2009; La Torre Torres and others 2011; Sun and others 2006). In first-order forested watersheds on the coastal plain, the water table level can decrease substantially when precipitation decreases and temperature increases (Amatya and others 1996, Dai and others 2010a, Lu and others 2009); in such watersheds, the annual evapotranspiration (ET) is approximately equal to potential evapotranspiration (PET) (Amatya and Trettin 2007a; Amatya and others 1996, 2006b). The decrease in the water table level of wetlands can lead to an increase in soil $CO_2$ release when the typically anaerobic soil environment is converted to aerobic conditions (Dai and others 2011a, Fissore and others 2008, Pietsch and others 2003, Smith and others 2008). It is not uncommon for first-, second-, and third-order watersheds within the lower coastal plain to have no streamflow in normal dry periods (Amatya and Radecki-Pawlik 2007, Amatya and others 2009, Dai and others 2010b). However, large storms along the coast can also cause flooding problems (Amatya and others 2006b, Callahan and others 2004, Frey and others 2010, La Torre Torres and others 2011, Miwa and others 2003, Young and Klawitter 1968). These relationships suggest that changes in temperature and precipitation may influence the hydrology of these forested watersheds on the coastal plain, particularly with respect to streamflow and water table dynamics (Amatya and others 2006a, Brooks 2009, Hartig and others 1997, Lu and others 2009, Scavia and others 2002).

Watersheds on Santee Experimental Forest, comprising wetlands and uplands, are typical of the southeastern Atlantic Coastal Plain. The Santee Experimental Forest was created in 1937 to study pine and hardwood silviculture, and the effects of forest management on forest hydrology (Amatya and Trettin 2007b). Water quality, quantity, runoff dynamics, and the impact of storms on downstream flooding have been studied since the 1960s, with results showing that streamflow is closely linked to precipitation and evapotranspiration (Amatya and Radecki-Pawlik 2007; Amatya and others 2006a, 2006b; Harder 2004; Harder and others 2007; La Torre Torre and others 2011; Sun and others 2000; Young 1966; Young and Klaiwitter 1968; Young and others 1972). Yet the studies also suggest uncertainty in the relationship, e.g., the ratio of annual streamflow to annual precipitation has varied between 7 and 43 percent between 1965 and 2007 (Dai and others 2011b, Harder and others 2007, Young 1966). Hydrological simulations show that the ratio could increase 2.4 percent with an increase in 1 percent of annual precipitation (Dai and others 2010a). The water table in this region is also influenced by precipitation (Amatya and others 2003, Dai and others 2010a, Harder 2004), nonlinearly increasing with an increase in precipitation (Dai and others 2011a) and streamflow (Harder and others 2007). Water table conditions on the coastal plain can be influenced by changing temperature, decreasing about 1.9 cm per °C temperature increase (Dai and others 2010a). The impacts of prescribed fires on streamflow and water quality and quantity have been studied since the 1970s, with results showing that the impact of prescribed fires on water quality are insignificant when only a portion of the watershed is burned but that prescribed fire could cause an increase in streamflow (Richter and others 1983a, 1983b).

Recently, Trettin and others (2009) reported changes in hydrological functions and pathways with respect to land use change from agriculture to forest using LIDAR and historical land use data. That work demonstrated the importance of understanding the environmental history of an area and the associated long-term effects of land use change on watershed hydrology. Tropical storms are another factor that can shape forest hydrology and the functional linkages with ecosystem processes. The long-term climate and hydrological data collected on the Santee Experimental Forest has shown that the destruction of forest by Hurricane Hugo in 1989 influenced the hydrology on the Santee Experimental Forest for years afterwards (Amatya and others 2006b, Dai and others 2011b, Wilson and others 2006).

Long-term environmental monitoring facilities, such as the Santee Experimental Forest, provide a basis to assess the interactions between ecosystem process and controlling factors such precipitation. They also provide a basis for assessing long-term trends in weather variables and in providing valuable data for the development and application of simulation tools that are needed to assess forest hydrology and the linkages between the C cycle and variations in climatic conditions (Amoah and others 2012; Dai and others 2010a, 2010b; Harder and others 2006, 2007; Lu and others 2006). Recently, the biogeochemical model Forest-DNDC (Li and others 2000) was calibrated and validated with data from the Santee Experimental Forest. Data on climate, hydrology, and carbon in biomass and soils was used to assess C sequestration and greenhouse gas emissions from watersheds consisting of a mosaic of upland and wetland forest types (Dai and others 2011a). The purpose of this study was to employ long-term climatic and hydrological observations on the Santee Experimental Forest to (1) evaluate trends in temperature and precipitation, (2) assess the long-term effects of potential climate variability on forest hydrology on the second-order watershed (WS79) using the hydrology model MIKE SHE (DHI 2005) and the Thornthwaite water balance approach (Flerchinger and Cooley 2000, Ward 1972), and (3) estimate the impact of climate variability on carbon sequestration to the forest ecosystems and greenhouse gas ($CH_4$ and $CO_2$) emissions from soils using the biogeochemical model Forest-DNDC (Li and others 2000, Stang and others 2000). The long-term data, including climatic observations (1946–2008), hydrological measurements (1964–2008), and biomass measurements, were used to understand and assess the effects of precipitation and temperature on forest hydrology and carbon dynamics of the Santee Experimental Forest; the assessment includes Hurricane Hugo which destroyed the majority of the forest stands on the Santee Experimental Forest in 1989. Both the MIKE SHE and Forest-DNDC models have been tested and determined to be suitable for simulating the hydrology and C and nitrogen (N) dynamics in the catchment (Dai and others 2011a).

## DATA AND METHODS

### General Site Description

The Santee Experimental Forest was established in 1937 as a forest research facility representing the forested landscape of the lower Atlantic Coastal Plain of the Southeastern United States. The Santee Experimental Forest is characteristic of the subtropical region of the Atlantic Coast, with long, hot, humid summers, and short, warm, humid winters. The long-term annual average temperature (1946–2007) is 18.5 °C, and average annual precipitation is 1,370 mm. Over the last 60 years, the highest temperature was 40.5 °C, which was recorded twice, on June 26, 1952 and July 21, 1977. The lowest recorded temperature was -14 °C on January 21, 1985 (Dai and others 2011b).

Lands comprising the Santee Experimental Forest have been used for agriculture and forestry purposes since the early 1700s (Hawley 1949, Smith 2012). In September 1989, the Santee forest was severely impacted by Hurricane Hugo, a category 4 tropical storm, with breakage or uprooting of more than 80 percent of the dominant trees in the forest (Hook and others 1991, Nix and others 1996, Wilson and others 2006). The current vegetation comprises stands that have regenerated since Hurricane Hugo with bottomland hardwoods in the riparian zone, pine-dominated stands in the uplands, and mixed pine-hardwoods elsewhere. The dominant trees are loblolly (*Pinus taeda* L.), sweetgum (*Liquidambar styraciflua*), and a variety of oak species (*Quercus* spp.) in both uplands and bottomlands, a combination of tree species typical of the Atlantic Coastal Plain (Hook and others 1991). The soils have developed in marine sediments and have drainage varying from very poorly drained in the riparian zones to moderately well drained in the uplands (Long 1980).

### Environmental Monitoring Data

Long-term environmental monitoring on the Santee Experimental Forest consists primarily of weather data and hydrologic data from four gauged watersheds. The second-order watershed WS79 was the focus for this work; for a complete description of the hydrologic monitoring activities see Amatya and Trettin (2007a) or visit http://www.srs.fs.usda.gov/charleston for climatological and hydrology data available for downloading.

**Hydrology**—Watershed WS79 was gauged in 1963, has a drainage area of 500 ha, and consists of three first-order watersheds: WS77, WS80, and WS79b (which is between WS77 and WS80) (fig. 1). WS77 and WS80 serve as a paired watershed system, with WS77 as a treatment catchment, WS80 as a control, and WS79b as a mixed-use area. WS80 has not been actively managed for over five decades. Over the last three decades, this paired system has been used for studies on watershed hydrology, biogeochemistry, and forest management, including prescribed fire and thinning, as well as the effects of global and environmental changes on forest ecosystems. After Hurricane Hugo, the control watershed, WS80, remained unmanaged, without biomass removal or salvage logging (Amatya and Trettin 2007a, Dai and others 2010b, Harder and others 2007). Most fallen trees were removed from the remainder of WS79. The vegetation coverage in WS77 contains more pine than WS80 and WS79b. In recent years, silvicultural practices, including prescribed fire and thinning were conducted on WS77 and parts of WS79b. As a result, forest biomass in the treatment areas has been lowered, especially with respect to the understory layer and forest floor. Details of the chronological sequence of activities on these watersheds up to 2005 have been reported (Amatya and Trettin 2007a). The soils on WS79 are generally clay-loams; the clay content is generally ≤30 percent in topsoil (within 30 cm), and 40–60 percent in subsoil (>30 cm) (Long 1980). The soil is acidic, with a pH between 4.5 and 6.5. Details of the hydraulic properties of each soil have been reported (Harder and others 2007, Long 1980).

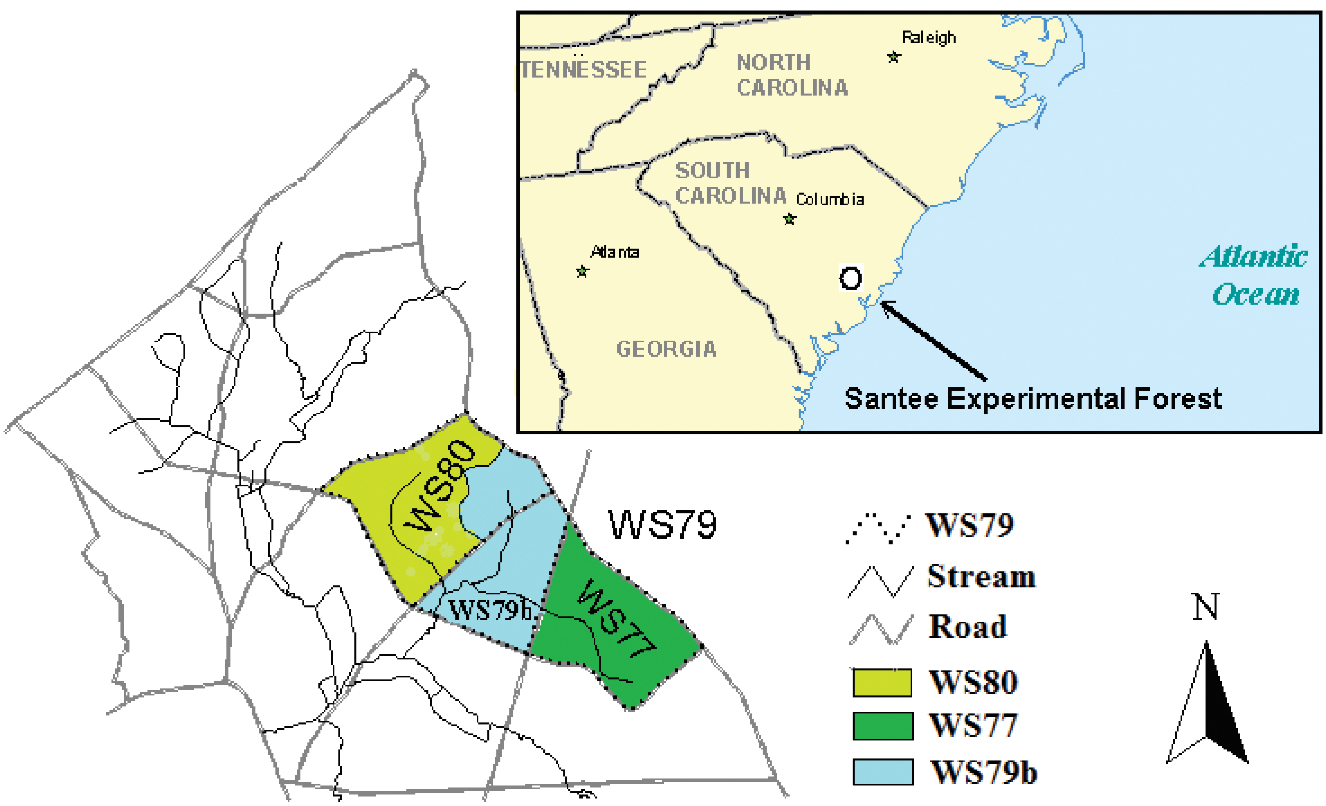



Figure 1—The Santee Experimental Forest is located in the Francis Marion National Forest, about 55 km northwest of Charleston, in Berkeley County, in the southeast Atlantic Coastal Plain of South Carolina.

**Precipitation and temperature**—Daily total precipitation and daily maximum and minimum temperature were manually measured at the weather station at the headquarters for the Santee Experimental Forest (hereafter referred to as Santee Headquarters) from 1946 to 1995. Those parameters and other climate parameters, including relative humidity, wind speed, wind direction, vapor pressure, and solar and net radiation, have been automatically measured at 30-minute intervals since 1995. There are three other weather stations, Met5 on WS77, Lotti, adjacent to WS79b, and Met25 on WS80 that have been maintained to provide information on the spatial variability of precipitation and temperature across the watershed. Daily precipitation was manually collected starting in 1963 at Met 5, 1964 at Lotti, and 1990 at Met25; daily temperature was manually recorded from 1996 at Met 5, 1971 at Lotti, 1997 at Met25. Since 2003, precipitation and temperature have been recorded automatically at hourly intervals at these weather stations (Amatya and Trettin 2007b).

Invariably, some precipitation and temperature data were missing due to instrument failure and other events, such as Hurricane Hugo in 1989. Most of the missing temperature data for Santee Headquarters were estimated using regression equations developed from the measurements of daily maximum and minimum temperature between 1972 and 2001 at Santee Headquarters and Lotti (about 3 km away from Santee Headquarters); the remaining missing temperature data for Santee Headquarters were estimated by using the regression equations developed from the measurements between 1950 and 2000 at Santee Headquarters near Moncks Corner, SC, and Charleston International Airport near Charleston, SC; Moncks Corner and Charleston International Airport are about 20 and 50 km away from Santee Headquarters, respectively. Temperature data between 2002 and 2008 at Santee Headquarters were compared to the data from the Witherbee weather station (about 2 km away, managed by Francis Marion National Forest) to calibrate the instrumental measurements. However, the missing temperature data for Met5 and Met25 remain missing because of the relatively short observation period of available records and a large number of data missing.

When we compared the precipitation data at the field weather stations with that at Charleston International Airport and Moncks Corner, most of the missing precipitation data occurred in 1991 and 1996–99. Although they are not far from Moncks Corner (about 20 km) or Charleston International Airport (50 km), the missing precipitation data could not be reliably estimated by using regression equations between stations due to the wide spatial variation in amount, frequency, and timing of precipitation among available stations. However, some of the missing data from Met5 and Met25 was estimated based on Lotti. For the simulation studies, missing temperature, and/or precipitation data on Lotti, Met5, or Met25 were estimated using the observations at Santee Headquarters.

**Streamflow and water table**—Stream stage has been measured at 10-minute intervals since 1963, 1966, and 1968 for watersheds WS77, WS79, and WS80, respectively. Streamflow was calculated using standard rating curve methods developed for these weirs (Amatya and Trettin 2007a), and the 10-minute values were integrated into daily, monthly, and annual flow in cubic meters per second (cms), and then normalized from cms to millimeters (mm) per day by dividing the watershed area to compare to daily precipitation (Amatya and others 2006b). The record is not continuous, with a hiatus in the early 1980s and periodic interruptions due to equipment failure.

Water table depth is measured on WS77 and WS80. Across watershed WS77A, 42 wells were installed; 24 wells were measured biweekly from 1964 to 1971, and 42 wells were measured between 1992 and 1995. However, data from three wells (11, 13, and 23) between 1964 and 1971 were missing and could not be included in this analysis. Across WS80, 33 manual wells were installed, and water table depth was collected weekly from 1992 to 1995. After 2002, four automatic wells were installed, two on WS77 and two on WS80, to collect water table depth data at 4-hour intervals. The water table depth was integrated into monthly and annual values.

**Biomass—**Biomass was inventoried on WS79T using 24 plots where total tree height (TH, m) and diameter at breast height (DBH, cm) were measured in 2006 and 2007. The plot size was 1022 $m^2$. The trees with DBH ≥10 cm and DBH <10 cm and shrub were measured, respectively. Four subplots (9 $m^2$ each) were set within each plot to measure aboveground biomass for trees <10 cm DBH; the trees were harvested, dried, and weighed. Shrub biomass was also collected in the four subplots for every plot, dried and weighted. Tree volume for trees DBH ≥10 cm was calculated using the equation developed by Saucier and Clark III (1985) for tree species in the Southern United States based on the DBH and total height. The aboveground biomass was estimated by using the equation developed by Smith and others (2003) on the basis of vegetation types in the Southeastern United States. The total wood biomass of a plot was the sum of the biomass of all trees in the plot, and then normalized to unit weight, C Mg $ha^{-1}$, by dividing the plot area (1012 $m^2$). There were four subplots in each plot for collecting litter and duff. The area of the basket for litter collection was 1470 $cm^2$, and the area for collecting duff was 729 $cm^2$. The litter and duff were dried under 60 °C and weighed. The impact of Hurricane Hugo on the biomass C storage in the stands on the entire Santee Experimental Forest was estimated by Hook and others (1996). The belowground biomass was estimated using the coefficient of roots relevant to aboveground biomass (IPCC 2003, Schroth 1995).

**Soil $CO_2$ efflux, temperature and moisture, and leaf area index**—Soil $CO_2$, moisture, and temperature were measured at eight plots on WS79 at monthly intervals for 2 years (2006–08) to calibrate and validate the biogeochemical model for simulating long-term atmospheric $CO_2$ sequestration to forested ecosystems on the Santee Experimental Forest (Dai and others 2011a). The polyvinylchloride (PVC) soil collars were installed permanently 3 cm into the mineral soils (Sulzman and others 2005). The measured soil $CO_2$ efflux values using a LI-COR 6200 were integrated into a plot average. Leaf biomass was collected monthly in the 24 inventory plots for 2 years to calculate biomass and leaf area index (LAI). LAI was also measured on eight plots using the LI-COR 2000. Tree height and DBH were measured in 2006 and 2007 at the 24 plots on WS79 to estimate biomass, and forest floor samples were collected on the same plots.

## Estimates of Potential Evapotranspiration

Daily potential evapotranspiration (PET) was estimated using standard Penman-Monteith (P-M) equation for a grass reference for 2003–2008 (Monteith 1965, Xu and Singh 2005) and the Hargreaves equation for 1950–2008 (Hargreaves and Samani 1985), because the observations for relative humidity, wind speed, vapor pressure, and solar and net radiation were not available for 1950–2002. The daily PET from Hargreaves equation, which may be somewhat higher than the standard P-M method, was verified and calibrated to an equivalent P-M value using the regression model developed from the daily PET estimated by P-M and Hargreaves for 2003 to 2008, as suggested by Amatya and others (1995). The Hargreaves PET ($PET_h$) for 1950–2008 was estimated using the following equations (Gavilan and others 2006, Sepaskhah and Razzaghi 2009):

$$PET_h = 0.408 * 0.0023 * Ra * (T_{mean} + 17.8) * (T_{max} - T_{min})^{0.5} \quad (1)$$

where

$T_{mean}$ = daily average

$T_{max}$ = daily maximum

$T_{min}$ = daily minimum temperature (°C)

Ra = extraterrestrial radiation for daily period estimated as (Allen and others 1998):

$$Ra = 24(60)/\pi * G_{sc} * d_r * [\omega_s * \sin(\varphi) * \sin(\delta) + \cos(\varphi) * \cos(\delta) * \sin(\omega_s)] \quad (2)$$

where

$G_{sc}$ = the solar constant

$d_r$ = the inverse relative distance from the Earth to the Sun

$\omega_s$ = sunset hour angle

$\varphi$ = the latitude of the study site

$\delta$ = the solar decimation.

The P-M-equivalent PET was used to compute the annual and monthly evapotranspiration (ET) for the entire study period of 1946–2008 to evaluate the water balance for this study.

## Estimate of Water Balance

Three approaches were applied to estimate water balance of watershed WS79: the Thornthwaite water balance (Flerchinger and Cooley 2000, Ward 1972), the hydrological model MIKE SHE (DHI 2005), and the biogeochemical model Forest-DNDC (Li and others 2000, Stang and others 2000).

**The MIKE SHE hydrological model—**MIKE SHE (Abbott and others 1986a, 1986b; DHI 2005; Graham and Butts 2005) is a distributed hydrological modeling system well designed and validated for applications in low-relief terrain. This model and its algorithms have been described in many publications (DHI 2005, Graham and Butts 2005, Sahoo and others 2006). For estimates of hydrological dynamics on the Santee Experimental Forest, MIKE SHE was coupled with the flow routing model MIKE 11 (Lu and others 2009, Sahoo and others 2006), a one-dimensional river/channel water movement model, to simulate the full hydrological cycle of the watershed, including evapotranspiration, infiltration, unsaturated flow, saturated flow, overland flow, and streamflow. Inputs for the model include spatial data on topography, soils, vegetation, and drainage network; and temporal data on daily precipitation and PET. The model was tested using streamflow and water table observations over a 2-year period (2003–04) by Lu and others (2006), and also tested over a 2-year period before Hurricane Hugo (1969–71) and a 5-year period afterwards (2003–08) by Dai and others (2010a).

**Thornthwaite water balance—**Water balance was estimated as (Flerchinger and Cooley 2000, Ward 1972):

$$E = P - (Q + ET + \Delta S) \quad (3)$$

where

P = precipitation

Q = streamflow

ET = evapotranspiration

$\Delta S$ = water storage in soils and aquifers

E = the estimation error (we assume that it is negligible).

ET is derived from PET, precipitation, soil moisture storage, and changes in soil moisture. The soil moisture is calculated using the following equation (Alley 1984) when precipitation is not less than PET:

$$SM_i = \min((SM_{i-1} + P_i - ET_i), SM_0) \quad (4a)$$

where

$SM_i$ = soil moisture at month i

$SM_{i-1}$ = soil moisture at month i-1

$SM_0$ = soil moisture capacity, a value of 150 mm was used in this study (McCabe and Markstrom 2007, Wolock and McCabe 1999)

$P_i$ = $i^{th}$ month precipitation

$ET_i$ = $i^{th}$ ET.

However, if P<PET, a soil moisture deficit will occur. The soil moisture is estimated as:

$$SM_i = SM_{i-1} \cdot EXP[-(PET_i - P_i)/SM_0] \quad (4b)$$

The changes in soil moisture ($\Delta SM$) can be shown as:

$$\Delta SM_i = SM_i - SM_{i-1} \quad (5)$$

We assumed that the long-term changes in the aquifer were small (Harder and others 2007, Heath 1975, Riekerk and others 1979), thus:

$$\Delta S = \Delta SM \quad (6)$$

The ET was estimated by using following equations if $P_i \geq ET_i$:

$$ET_i = PET_i \quad (7a)$$

and if $P_i < PET_i$:

$$ET_i = P_i + \Delta SM_i \quad (7b)$$

**Forest-DNDC—**Forest-DNDC (Li and others 2000, Stang and others 2000) is a soil C and nitrogen (N) dynamics model (Li and others 1992a, 1992b), coupled with a forest growth model based on PnET (Aber and Federer 1992). PnET is a process-based biogeochemical model used to simulate forest growth and C and N dynamics in forest ecosystems, including soil-borne trace gas emissions based on the balance of water, energy, and nutrition in forest ecosystems (Li and others 2000, Miehle and others 2006, Stang and others 2000). The model integrates photosynthesis, decomposition, nitrification-denitrification, carbon storage and consumption, and hydrothermal balance in forest ecosystems, and has been tested and used for estimating greenhouse gas emission from forested ecosystems in a wide range of climatic regions, including boreal, temperate, subtropical, and tropical (Kesik and others 2006, Kiese and others 2005, Kurbatova and others 2008, Li and others 2004, Stang and others 2000, Zhang and others 2002). The original Forest-DNDC was at field scale and used to simulate C and N dynamics in forests for uplands. To estimate C and N dynamics in wetland ecosystems, an empirical functionality for wetlands was added to the field scale version of the model by Zhang and others (2002). Although Cui and others (2005) linked the physically based hydrological model MIKE SHE to Forest-DNDC to further improve Forest-DNDC for simulating C and N dynamics in wetland ecosystems, the spatially hydrological characteristics supplied by MIKE SHE were projected to only one dimension, because they applied a field scale version of the model to their study. Recently the model has been modified to watershed scale, yielding a version that can utilize spatially and temporally physical and biogeochemical characteristics of catchments or regions (Dai and others 2011a), including soils, vegetation, hydrogeology, and climate. The modified model is a useful tool to assess carbon and nitrogen dynamics on watersheds with complex physical and biogeochemical characteristics.

**Model validation—**The performance of the model was evaluated employing widely used quantitative methods including coefficient of determination ($R^2$) (squared correlation coefficient) and model efficiency (E) (Moriasi and others 2007). The model performance efficiency is calculated as:

$$E=1- (O_i-P_i)^2/(O_i-O_{mean})^2 \quad (8)$$

where $O_i$, $O_{mean}$, and $P_i$ are the observed values, mean observation, and simulated values, respectively. The model evaluated was then used to simulate streamflow and water table dynamics with 58 years (1950–2007) of climate observations using MIKE SHE, and to estimate C dynamics using Forest-DNDC.

## RESULTS AND DISCUSSION

### Temperature and Precipitation

**Temperature variability**—Data on air temperature on the Santee Experimental Forest for 1946–2008 are presented in table 1. The annual mean temperature anomaly, which is the difference between annual mean temperature and the mean for 1946–2008, showed that the air temperature significantly increased (p<0.01) at an average rate of 0.19 °C per decade in the last 63 years (fig. 2A), which is approximately equal to the mean rate of 0.2 °C per decade for the 30-year period of 1976–2005 (Hansen and others 2006, Trenberth and others 2007), and higher than the rate of 0.17 °C per decade from 1976 to 2009 (Hansen and others 2010). Comparing similar periods, the warming rate on the Santee Experimental Forest was about 0.41 °C per decade between 1976 and 2000, considerably higher than the 0.2 rate reported by (Trenberth and others 2007) and 2.4 times as high as the global rate (0.17 °C) reported by IPCC (2001) for the same period. The annual mean temperature (table 1) also shows that the warming on the Santee Experimental Forest is not completely synchronous with trends globally or in North America. Prior to 2009, the warmest year on the Santee Experimental Forest occurred in 1990 and 1998. However, the warmest year in North America and globally was 2006 and 2005, respectively (Hansen and others 2010, Trenberth and others 2007).

Three periods are evident in the temperature trend based on the 5-year moving average in the 63-year period (fig. 2A). The temperature fluctuated but did not substantially increase in the first 23-year period of 1946–68; it increased rapidly in the second period (1969–80) and steadily increased in the third period (1981–2008). The warmest year in the first period was 1964, with a mean daily temperature (MDT) of 18.9 °C. The coolest year was 1958, with a MDT of 17.0 °C (fig. 2B). The annual mean temperature was 18 °C in the first 23-year period. Although there was a substantial temperature fluctuation over this period, the average temperature decreased slightly. Starting in 1969, the average temperature has increased. The warmest year in the second period was 1975; the MDT was 19.5 °C, about 0.6 °C higher than the MDT of the warmest year in the first period. The lowest MDT of the second period was recorded in 1979 (17.8 °C), and was about 0.8 °C higher than the MDT of the coolest year in the first period. The annual mean temperature in the 12-year period from 1969 to 1980 was 18.6 °C, about 0.6 °C higher than the first period. The temperature increase in the 12-year period was largely due to consecutive warm years between1970 and 1975.

Due to the strongest El Niño in the last century, 1998 was considered to be the warmest year between the late 1800s and the end of last century. The first warmest year on the Santee Experimental Forest from 1946 to 2008 was 1990. However, the MDT in both 1990 and 1998 was 20 °C, about 1.1 and 0.5 °C higher than the MDT of the warmest years in the first and second periods, and 2 and 1.4 °C higher than the annual mean temperature in these two periods, respectively. The coolest year in the third period occurred in 1988 with a MDT of 17.5 °C, 0.5 °C higher than the MDT of the coolest year in the first period, but 0.3 °C lower than that in the second period. The annual average temperature in this period was 18.8 °C, about 0.8 and 0.2 °C higher than that in first and second periods, respectively. Although the 2 years with the highest temperatures (1990 and 1998) occurred in this period, the increase of the annual mean temperature in the 28-year period (1981–2008) was less than the increase in the second period (12-year, 1969–80), a finding affected by the assignment of the periods and the inherent multi-decadal fluctuations. However, the mean temperature was still higher in the third period than the other two periods (fig. 2B).

Since 1946, there has been a significant linear increase in the annual average daily minimum temperature at a rate of 0.26 °C per decade ($p<0.001$) on the Santee Experimental Forest (fig. 2C), a higher rate of annual average temperature (0.19 °C per decade) in the same period. Although the increase in the annual average daily maximum temperature was significant ($p<0.02$), the increase in magnitude (about 0.13 °C per decade) was less than the average daily minimum temperature. These data demonstrate that the warming trend increases the daily minimum temperature more than daily maximum. The yearly minimum temperature rose linearly at a rate of 0.38 °C per decade in the last 63 years ($p<0.05$) (fig. 2D) and fluctuated widely. However, there was a decreasing trend in the yearly maximum temperature of about 0.19 °C per decade ($p<0.05$).

Over the last six decades on the Santee Experimental Forest, the annual average of diurnal temperature range (DTR) decreased at an average rate of 0.13 °C per decade ($p<0.05$) (fig. 2E). The DTR is the difference between the daily maximum and daily minimum temperatures. This value was larger than the global average rate in the 20$^{th}$ century (≈0.1 °C per decade, including urban and nonurban areas) (IPCC 2001) and lower than the DTR during 1913–98 in Venezuela and Colombia, as reported by Quintana-Gomez (1999). This decreasing trend in DTR was similar to the changes in northern China (at a latitude higher than the Southeastern United States) due to a stronger warming of the minimum temperature as opposed to the maximum, but different from the trends in southern China due to a cooling in maximum temperature with a slight warming in minimum temperature (Zhai and Ren 1999). There were larger decreases and fluctuation in the annual temperature range (ATR) among years than DTR (fig. 2E). Similar to DTR, the declining trend in ATR was mainly caused by a significant increase in yearly minimum temperature.

The temperature on the Santee Experimental Forest increased linearly during the summer (June–August) ($p<0.01$), autumn (September–November) ($p<0.001$), and winter months (November–January) ($p<0.05$) at a rate of about 0.13, 0.38, and 0.26 °C per decade, respectively. However, the average temperature in the spring months (March–May) remained unchanged. These results suggest that the warming yields not only hot summers, but also warmer autumns and winters in the area. Although there was not a significant increasing trend ($p<0.1$) in the number of days with high temperatures (>37 °C) in a year, the annual average number of days with higher than 37 °C temperature from 1970–2008 (2.1 days) were over twice as many as the average (0.83 days) during the period from 1946–69.

**Precipitation variability—**The year-to-year variability of precipitation amounts on the Santee Experimental Forest over the last 63 years ranged from a low of 835 mm in 1954 to a high of 2026 mm in 1994 (table 2). The average annual precipitation in the 63-year period was 1370 mm. There were three very dry years (1951, 1954, and 1956), with the annual precipitation in these years about 66, 61, and 68 percent, respectively, of the average annual precipitation in the 63-year period. Annual precipitation has not exhibited a significant increasing trend ($p>0.1$) since 1946 (fig. 3A). The three consecutive dry years in the 1950s contributed to the slightly increasing trend, but overall precipitation has not varied significantly.

The average monthly precipitation over the last six decades was about 114 mm. The highest recorded monthly precipitation was 436.5 mm in July 1964, and the lowest was 0 mm in October 2000. Precipitation in the summer months (June–August) was much higher than other seasons, accounting for 39 percent of annual precipitation in the last 63 years; there was no difference in the proportion of rainfall among the other seasons (20–21 percent). The changes in seasonal precipitation were extremely small over the last six decades, exhibiting only a slight upward trend in fall and winter months but a downward trend in spring and summer. Combined with the increasing temperatures, the spring and summer seasons are poised to experience more frequent occurrences of plant water stress caused by high evapotranspiration levels.

Table 1—Annual minimum, maximum, and mean temperature (minT, maxT, and meanT, respectively) at Santee Experimental Forest Headquarters (SHQ) and at Lotti (LT), an onsite weather station adjacent to Santee Experimental Forest watershed WS79b, 1946–2008

| Year | SHQ-maxT | SHQ-minT | SHQ-meanT | LT-maxT | LT-minT | LT-meanT |
|---|---|---|---|---|---|---|
| 1946 | 24.8 | 12.3 | 18.6 | N/A | N/A | N/A |
| 1947 | 23.6 | 11.6 | 17.6 | N/A | N/A | N/A |
| 1948 | 24.2 | 11.9 | 18.0 | N/A | N/A | N/A |
| 1949 | 25.1 | 12.4 | 18.7 | N/A | N/A | N/A |
| 1950 | 24.2 | 11.2 | 17.7 | N/A | N/A | N/A |
| 1951 | 25.0 | 11.3 | 18.2 | N/A | N/A | N/A |
| 1952 | 24.4 | 11.7 | 18.0 | N/A | N/A | N/A |
| 1953 | 24.6 | 12.0 | 18.3 | N/A | N/A | N/A |
| 1954 | 24.5 | 11.1 | 17.8 | N/A | N/A | N/A |
| 1955 | 24.4 | 11.6 | 18.0 | N/A | N/A | N/A |
| 1956 | 25.2 | 12.0 | 18.6 | N/A | N/A | N/A |
| 1957 | 24.5 | 12.3 | 18.4 | N/A | N/A | N/A |
| 1958 | 23.2 | 10.7 | 17.0 | N/A | N/A | N/A |
| 1959 | 24.4 | 12.4 | 18.4 | N/A | N/A | N/A |
| 1960 | 24.0 | 10.8 | 17.4 | N/A | N/A | N/A |
| 1961 | 24.3 | 11.3 | 17.8 | N/A | N/A | N/A |
| 1962 | 24.8 | 11.8 | 18.3 | N/A | N/A | N/A |
| 1963 | 24.6 | 11.4 | 18.0 | N/A | N/A | N/A |
| 1964 | 24.9 | 12.9 | 18.9 | N/A | N/A | N/A |
| 1965 | 24.1 | 11.2 | 17.6 | N/A | N/A | N/A |
| 1966 | 23.3 | 11.1 | 17.2 | N/A | N/A | N/A |
| 1967 | 24.5 | 11.7 | 18.1 | N/A | N/A | N/A |
| 1968 | 24.3 | 11.3 | 17.8 | N/A | N/A | N/A |
| 1969 | 23.8 | 11.9 | 17.8 | N/A | N/A | N/A |
| 1970 | 24.8 | 12.7 | 18.8 | N/A | N/A | N/A |
| 1971 | 24.7 | 13.3 | 19.0 | N/A | N/A | N/A |
| 1972 | 24.9 | 13.5 | 19.2 | 23.1 | 9.0 | 16.1 |
| 1973 | 24.6 | 13.2 | 18.9 | 24.6 | 10.8 | 17.7 |
| 1974 | 25.5 | 13.2 | 19.4 | 25.4 | 10.5 | 17.9 |
| 1975 | 25.3 | 13.6 | 19.5 | 24.9 | 10.6 | 17.7 |
| 1976 | 24.4 | 12.2 | 18.3 | 24.7 | 9.3 | 17.0 |
| 1977 | 24.5 | 12.5 | 18.5 | 24.3 | 9.2 | 16.8 |

*continued to next page*

**Table 1 (continued)—Annual minimum, maximum, and mean temperature (minT, maxT, and meanT, respectively) at Santee Experimental Forest Headquarters (SHQ) and at Lotti (LT), an onsite weather station adjacent to Santee Experimental Forest watershed WS79b, 1946–2008**

| Year | SHQ-maxT | SHQ-minT | SHQ-meanT | LT-maxT | LT-minT | LT-meanT |
|---|---|---|---|---|---|---|
| 1978 | 24.2 | 12.4 | 18.3 | 23.8 | 9.2 | 16.5 |
| 1979 | 23.7 | 11.9 | 17.8 | 23.5 | 9.2 | 16.4 |
| 1980 | 23.9 | 12.3 | 18.1 | 24.1 | 10.2 | 17.2 |
| 1981 | 24.1 | 11.6 | 17.9 | 24.1 | 9.3 | 16.7 |
| 1982 | 24.3 | 13.5 | 18.9 | 25.1 | 12.3 | 18.7 |
| 1983 | 23.8 | 12.6 | 18.2 | 25.1 | 11.5 | 18.3 |
| 1984 | 24.5 | 12.5 | 18.5 | 24.9 | 11.0 | 17.9 |
| 1985 | 24.5 | 13.0 | 18.8 | 26.0 | 12.6 | 19.3 |
| 1986 | 24.8 | 13.7 | 19.3 | 27.1 | 13.9 | 20.5 |
| 1987 | 23.7 | 12.6 | 18.1 | 25.1 | 12.0 | 18.5 |
| 1988 | 23.4 | 11.6 | 17.5 | 23.8 | 10.3 | 17.0 |
| 1989 | 24.4 | 13.1 | 18.7 | 24.2 | 11.7 | 17.9 |
| 1990 | 25.9 | 14.1 | 20.0 | 26.6 | 12.3 | 19.5 |
| 1991 | 24.4 | 15.1 | 19.7 | 26.2 | 13.3 | 19.7 |
| 1992 | 24.4 | 13.5 | 19.0 | 22.8 | 9.7 | 16.3 |
| 1993 | 25.4 | 13.0 | 19.2 | 26.8 | 12.3 | 19.5 |
| 1994 | 25.6 | 12.9 | 19.2 | 27.0 | 12.9 | 19.9 |
| 1995 | 25.4 | 12.8 | 19.1 | 26.3 | 12.3 | 19.3 |
| 1996 | 24.6 | 12.0 | 18.3 | 25.7 | 9.8 | 17.7 |
| 1997 | 25.1 | 12.3 | 18.7 | 25.6 | 10.5 | 18.0 |
| 1998 | 26.6 | 13.4 | 20.0 | 26.9 | 11.6 | 19.2 |
| 1999 | 26.1 | 12.0 | 19.0 | 27.2 | 10.4 | 18.8 |
| 2000 | 24.8 | 11.8 | 18.3 | 25.4 | 9.9 | 17.6 |
| 2001 | 24.9 | 13.1 | 19.0 | 25.4 | 10.7 | 18.1 |
| 2002 | 24.9 | 13.7 | 19.3 | 25.6 | 11.1 | 18.4 |
| 2003 | 24.3 | 12.6 | 18.4 | 24.8 | 10.9 | 17.9 |
| 2004 | 25.0 | 12.7 | 18.9 | N/A | N/A | N/A |
| 2005 | 24.7 | 12.6 | 18.7 | N/A | N/A | N/A |
| 2006 | 25.3 | 12.4 | 18.8 | N/A | N/A | N/A |
| 2007 | 25.4 | 12.7 | 19.1 | N/A | N/A | N/A |
| 2008 | 25.2 | 13.6 | 19.4 | N/A | N/A | N/A |

N/A = no available data.

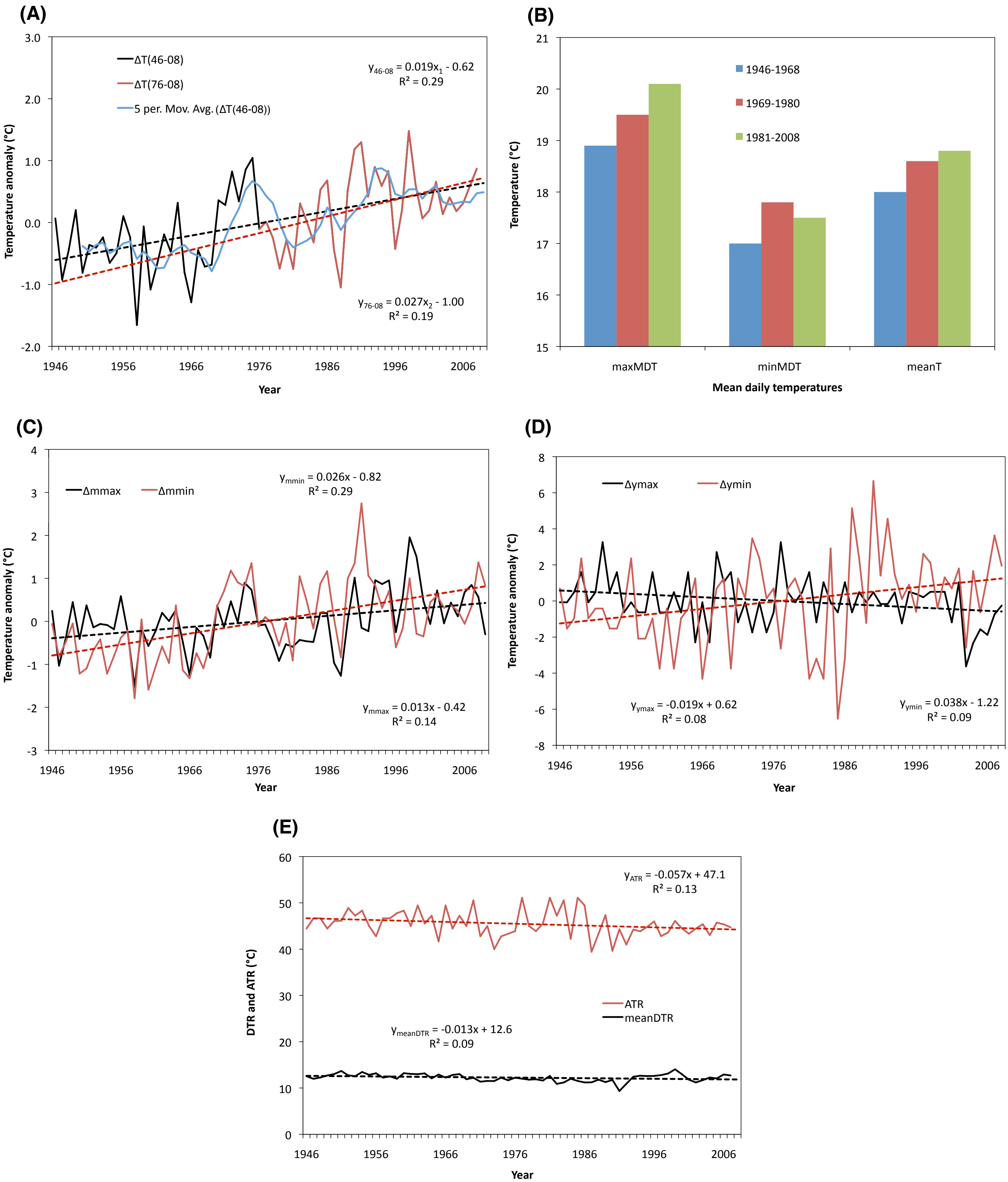



Figure 2—Long-term trends in air temperature measured at the Santee Experimental Forest Headquarters weather station, showing (A) temperature trend [ΔT(46-08) represents the changes in temperature between 1946 and 2008; ΔT(76-08) represents the changes in temperature between 1976 and 2008—globally, 1976–2008 is the period of greatest recorded increase in temperature, with an increase of 0.2 °C per decade, the rate of increase in temperature on Santee Experimental Forest during the same period was 0.27 °C per decade; thin blue line represents 5-year running average; red dash line indicates changes in temperature from 1976 to 2008; $x_1$ represents the year between 1946 and 2008, $x_2$ represents the year between 1976 and 2008], (B) maximum, minimum, and mean temperature during 1946–2008 (maxMDT is maximum mean daily temperature; minMDT is minimum mean daily temperature; meanT is average daily temperature), (C) annual mean daily maximum and minimum temperatures relative to the mean at Santee Experimental Forest Headquarters from 1946 to 2008, (D) yearly maximum and minimum temperatures relative to the mean from 1946 to 2008 (ymax and ymin are the maximum and minimum temperature in a year, respectively), and (E) the diurnal and annual temperature range during the 63-year period (DTR is diurnal temperature range; ATR is annual temperature range; meanDTR is the annual mean DTR averaged from 1946 to 2008).

**Table 2—Annual precipitation (reported in mm) at Santee Experimental Forest Headquarters (SHQ) and three onsite weather stations (Lotti adjacent to watershed WS79b, Met5 on watershed WS77, and Met25 on watershed WS80), 1946–2008[a]**

| Year | SHQ | Lotti | Met5 | | Year | SHQ | Lotti | Met5 | Met25 |
|---|---|---|---|---|---|---|---|---|---|
| 1946 | 1106.9 | N/A | N/A | | 1978 | 1225.4 | 1066.4 | N/A | N/A |
| 1947 | 1677.2 | N/A | N/A | | 1979 | 1546.3 | 1414.6 | N/A | N/A |
| 1948 | 1632.5 | N/A | N/A | | 1980 | 1413.7 | 1197.0 | N/A | N/A |
| 1949 | 1387.9 | N/A | N/A | | 1981 | 1154.5 | 1088.4 | N/A | N/A |
| 1950 | 1474.7 | N/A | N/A | | 1982 | 1663.5 | 1579.3 | N/A | N/A |
| 1951 | 900.7 | N/A | N/A | | 1983 | 1710.7 | 1286.6 | N/A | N/A |
| 1952 | 1262.8 | N/A | N/A | | 1984 | 1364.5 | N/A | N/A | N/A |
| 1953 | 1442.5 | N/A | N/A | | 1985 | 1349.6 | 1141.3 | N/A | N/A |
| 1954 | 834.6 | N/A | N/A | | 1986 | 1367.2 | 1122.1 | N/A | N/A |
| 1955 | 1190.6 | N/A | N/A | | 1987 | 1660.5 | 1570.3 | N/A | N/A |
| 1956 | 937.3 | N/A | N/A | | 1988 | 1141.8 | 950.2 | N/A | N/A |
| 1957 | 1200.4 | N/A | N/A | | 1989 | 1595.4 | 1291.7 | N/A | N/A |
| 1958 | 1459.9 | N/A | N/A | | 1990 | 1095.1 | 769.0 | 943.2 | N/A |
| 1959 | 1780.0 | N/A | N/A | | 1991 | 1252.7 | 1169.3 | 1252.0 | 1351.7 |
| 1960 | 1162.4 | N/A | N/A | | 1992 | 1472.7 | 1527.0 | 1358.1 | 1434.4 |
| 1961 | 1553.7 | N/A | N/A | | 1993 | 1246.9 | 1101.0 | 996.8 | N/A |
| 1962 | 1300.5 | N/A | N/A | | 1994 | 2026.4 | N/A | 1465.7 | N/A |
| 1963 | 1036.1 | N/A | N/A | | 1995 | 1525.1 | N/A | 1083.3 | N/A |
| 1964 | 1888.1 | N/A | 1895.0 | | 1996 | 1208.1 | N/A | 1121.7 | N/A |
| 1965 | 1241.2 | 1199.5 | 1307.2 | | 1997 | 1659.5 | N/A | N/A | N/A |
| 1966 | 1554.4 | 1488.9 | N/A | | 1998 | 1291.6 | N/A | N/A | N/A |
| 1967 | 1238.9 | 1027.7 | N/A | | 1999 | 1466.9 | N/A | N/A | N/A |
| 1968 | 1225.4 | 1143.6 | N/A | | 2000 | 1167.5 | N/A | N/A | N/A |
| 1969 | 1408.0 | N/A | N/A | | 2001 | 1016.1 | N/A | N/A | N/A |
| 1970 | 1361.7 | N/A | N/A | | 2002 | 1555.7 | N/A | N/A | N/A |
| 1971 | 1694.4 | N/A | N/A | | 2003 | 1690.4 | N/A | N/A | 1670.4 |
| 1972 | 1093.7 | 1156.3 | N/A | | 2004 | 1118.1 | 938.9 | 934.0 | 961.8 |
| 1973 | 1428.8 | 1296.3 | N/A | | 2005 | 1637.9 | 1473.9 | 1532.0 | 1509.5 |
| 1974 | 1412.8 | 1172.2 | N/A | | 2006 | 1264.5 | 1197.4 | 1200.4 | 1258.2 |
| 1975 | 1439.8 | 1258.1 | N/A | | 2007 | 1041.3 | 981.5 | 987.6 | 998.6 |
| 1976 | 1448.9 | 1442.0 | N/A | | 2008 | 1476.2 | N/A | 1502.3 | 1561.6 |
| 1977 | 1273.5 | 1085.3 | N/A | | N/A | N/A | N/A | N/A | N/A |

N/A = no available data.
[a] Data not available for Met25 before 1978.

There was no relationship between the annual precipitation and temperature ($p>0.1$) (fig. 3B). While other researchers have suggested that the regional may cause increased precipitation in subtropical areas (Najjar and others 2000, Zhang and others 2007), the record from the Santee Experimental Forest does not support that relationship. Accordingly, the hydrology in wetland-dominated watersheds on this lower coastal plain is likely to change with sustained warming due to the increase in evapotranspiration demand.

**Spatial differences in temperature and precipitation—** Comparison of temperature and precipitation among onsite weather stations on the Santee Experimental Forest showed that there were small differences in average temperature among the onsite weather stations from 1996 to 2001, about 0.1 and 0.4 °C higher at Lotti than at Met5 and Met25, respectively. However, there were slightly larger differences between Santee Headquarters and the onsite weather stations. The mean temperature at Santee Headquarters was about 0.6–0.7 °C higher than that at Lotti and Met5 from 1971 to 2000 (fig. 4A) and about 1 °C higher than Met25.

The higher mean temperature at Santee Headquarters was mostly due to the lower daily minimum temperature at the onsite weather stations. The daily maximum temperature at Lotti, Met25, and Met5 was 0.5, 0.8, and 0.9 °C higher than that at Santee Headquarters, but the minimum was 1.8, 1.9, and 2.2 °C lower than at Santee Headquarters, respectively. These results indicate that the daytime temperature in woodland setting on the Santee Experimental Forest is warmer than Santee Headquarters and that nights are cooler. These results are similar to the findings of Laughlin (1982), Morecroft and others (1998), and Karlsson (2000), who reported temperatures in forested area were lower than the neighboring open area. However, this seemingly large variation in temperature within a relatively small geographic area merits further study to reconcile the cause(s) of the differences.

The spatial variability in precipitation on the Santee Experimental Forest is likely large, especially in summer months (La Torre Torres 2008). Due to incomplete yearly sets for the onsite stations, monthly synchronized observations of precipitation were used to compare spatial precipitation. The observed average monthly precipitation at Santee Headquarters was about 7, 8, and 11 mm higher than that at Met5 (198 months of record), Met25 (158 months of record), and Lotti (432 months of record), respectively. These values indicate that the precipitation at Santee Headquarters might be substantially higher than that at the onsite weather stations; the difference translates to 80, 90, and 130 mm per year higher than at Met5, Met25, and Lotti, respectively. To assess whether the difference between the stations may be a result of the measurement technique before 2000, we also compared the precipitation data from all weather stations recorded from 2003 to 2008 when all of the stations were instrumented with automated recording rain gauges (fig. 4B). However, the results from automatically recorded measurements showed that precipitation at Santee Headquarters was indeed higher than the onsite stations, about 110, 100, and 80 mm per year higher than that at Lotti, Met5, and Met25, respectively, and the differences among onsite stations were small.

**Effect of warming on large precipitation events—** Although air temperature on the Santee Experimental Forest increased significantly over the last six decades, we found that the warming did not bring about increased precipitation, contrary to the findings by Wentz and others (2007) and Lambert and others (2008), who suggested that global warming can bring more rain. However, the annual average storm events with >25 mm precipitation and >50 mm between 1970 and 2008 were about 13 percent and 21 percent higher, respectively, than those in 1946–69 (the period without a significant increase in temperature). Although there has not been a significant upward trend in potential storm events in the last 63 years (fig. 5), the annual average storm events (>50 mm) increased from 4.4 times per year from 1946 to 1981 (fig. 5) to 5.7 times per year from 1982 to 2008.

## Streamflow and Water Table Dynamics

**The role of climate variability on streamflow and water table—**Data on monthly streamflow as measured at the three gauging stations on the Santee Experimental Forest are presented in figure 6A. Monthly streamflow ranged from 0 to 336 mm a month. No-flow conditions occur when low precipitation periods leave these headwater watersheds with insufficient water to satisfy evapotranspiration demand. There was a significant relationship ($p<0.01$) between monthly precipitation and monthly streamflow on these watersheds on the Santee Experimental Forest (fig. 6B). This relationship indicates that the streamflow on these catchments depends heavily on precipitation. Annual flow rate, which is the percentage of annual streamflow to annual precipitation, ranged from 5.5 to 44.7 (percent) in the 29 years from 1965–81, 1990–94, 1996–98, and 2003–07; the higher the annual precipitation, the larger the flow rate ($R^2 = 0.25$, $p<0.01$). The low annual flow rates are attributed to canopy interception and evapotranspiration. These relationships suggest that warming will further reduce streamflow due to an increase in evapotranspiration demands, if the increased demand is not offset by additional precipitation.

The changes in water table (WT) depth on the first-order watersheds on the Santee Experimental Forest were complex (figs. 7A–C), although annual mean water table level increases significantly with an increase in annual precipitation (fig. 7D) ($p<0.02$). Higher water table levels in summer and fall are mostly attributed to precipitation inputs. The water table depth in dry periods, especially in dry summers, can be more than 2 m below the ground

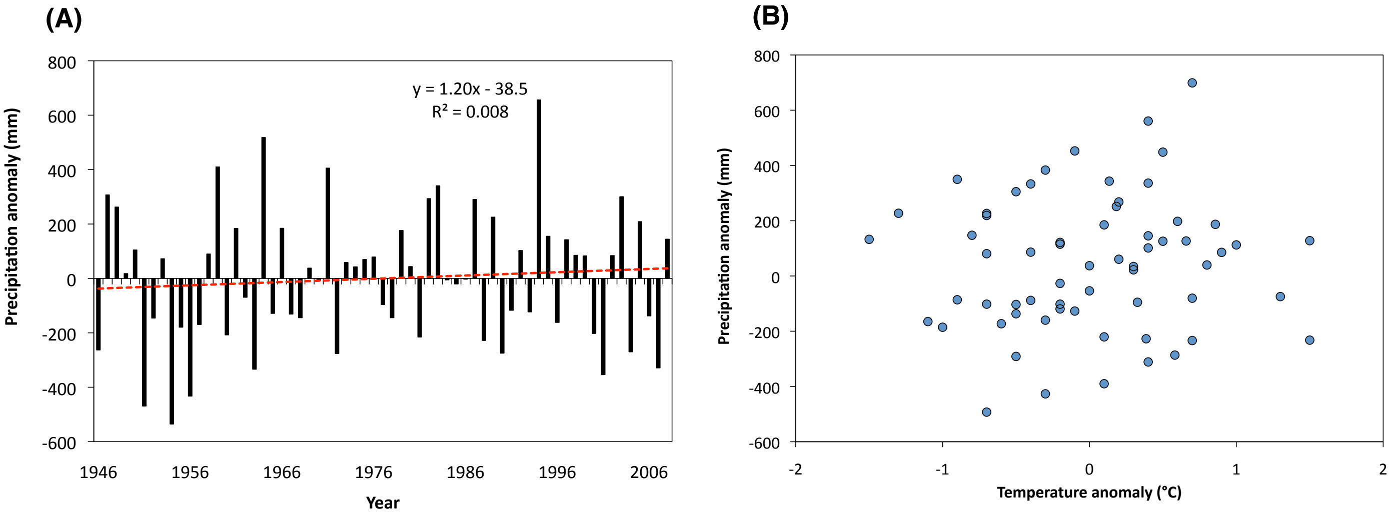



Figure 3—Long-term trends in precipitation measured at the Santee Experimental Forest Headquarters weather station, showing (A) deviation of precipitation from the long-term average (1370 mm) from 1946 to 2008 and (B) comparison of temperature and precipitation anomalies between 1946 and 2008.

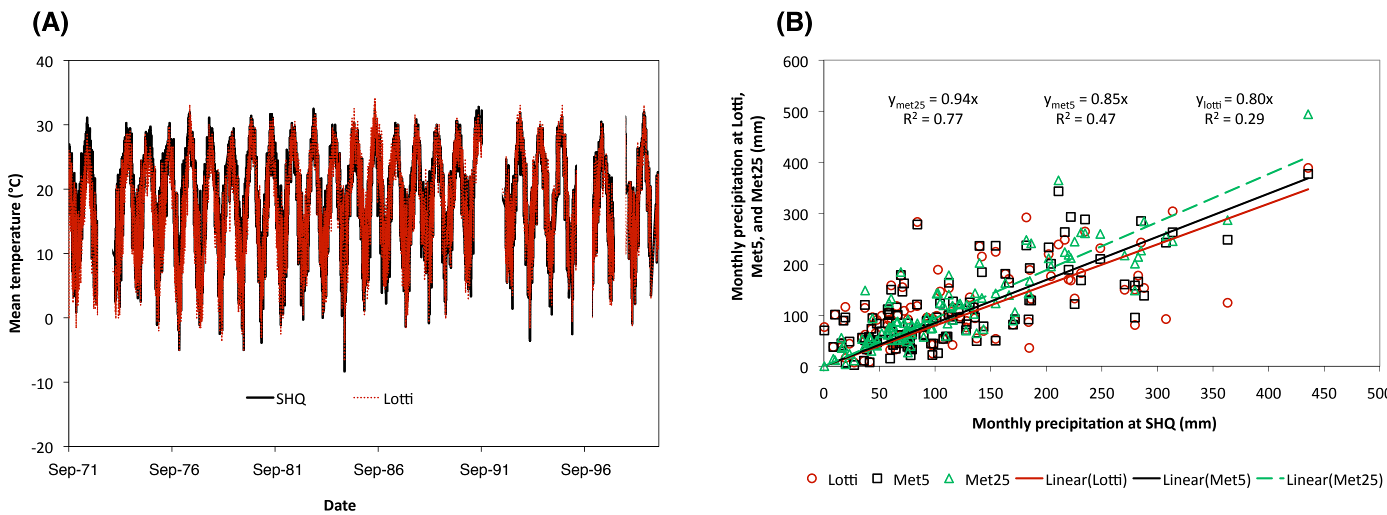



Figure 4—(A) Average daily temperature observed at Santee Headquarters (SHQ) and Lotti weather stations (synchronized by date), and (B) comparison of monthly precipitation at the three field stations (Lotti, Met5, Met 25) with the SHQ weather station.

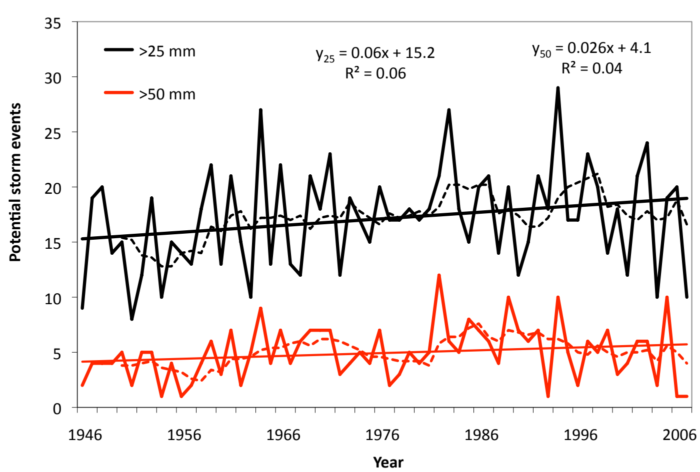



Figure 5—Number of small (>25 mm) and large (>50 mm) storm events per year recorded at the Santee Experimental Forest from 1946 to 2008 (dashed line and equation is the 5-year running average).

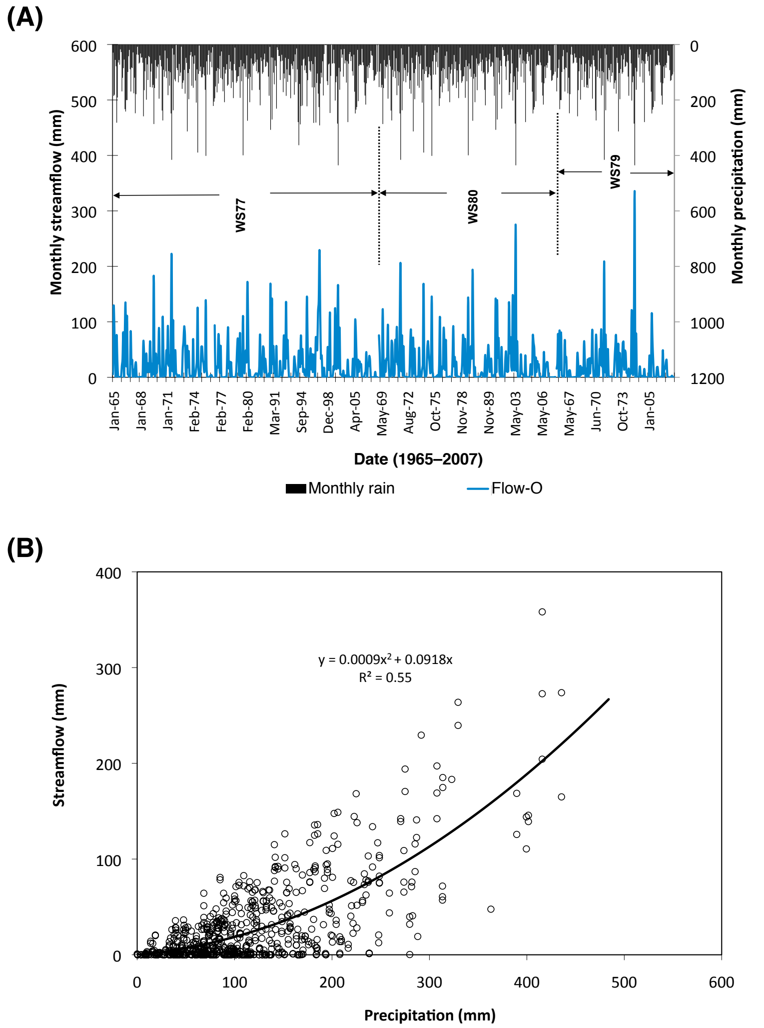



Figure 6—(A) Observed monthly streamflow of watersheds WS77, WS80, and WS79 on the Santee Experimental Forest for 1965–2007, and (B) observed relationship of monthly precipitation with monthly streamflow observed on all watersheds on the Santee Experimental Forest for 1965–2007.

surface. However, a large area of the watershed WS79 is saturated following heavy rains and wet periods (Dai and others 2010b). The water table level was high during most of the winter–spring months (December–February) (fig. 7A-C). However, precipitation in these seasons is much lower than in the summers. The high water table level in winters and/or springs is primarily as a result of a low evapotranspiration (ET) demand, especially in winters, which demonstrates that ET is the key factor influencing the WT on these first-order watersheds. These relationships further indicate that warming should be expected to influence water table dynamics in the watersheds on the lower coastal plain and that wetlands within these first order watersheds could experience altered hydro-periods that may affect their status.

**Hurricane effects on forest hydrology—**The lower coastal plain of South Carolina is within the hurricane threat area of the southeastern Atlantic Coastal Plain of the United States. While tropical storms deliver large amounts of precipitation in a short time period, they can also affect local hydrologic conditions by affecting evapotranspiration as a result of impacts to the vegetation. Accordingly, the relationship between observed streamflow and precipitation from 1965 to 2008 (fig. 8) were used to assess the effect of Hurricane Hugo in 1989 on surface water hydrology. The blank diamonds in figure 8 represent the observed relationship between annual streamflow and precipitation within 14 years (1990–2003) following the hurricane in 1989 (only 10 observations were available due to missing data). This data shows that the observed streamflow within the 14-year period after the hurricane is above the trend line. However, the average annual precipitation in those years was about 45 mm lower than the average over the entire observation period (1965–2007) and 70 mm lower than the long-term average (1370 mm). The higher observed streamflow rate in those years following the hurricane was because the

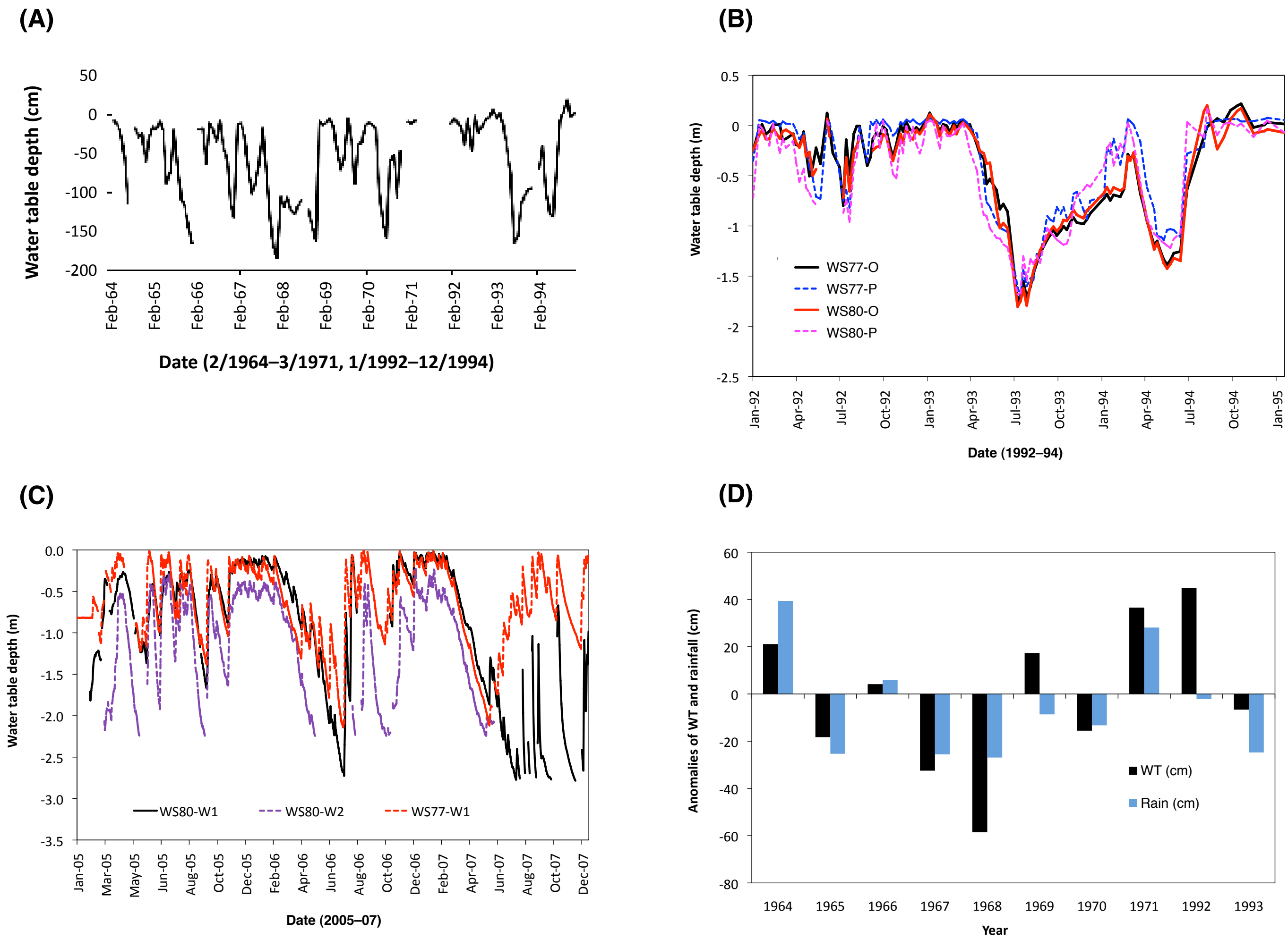



Figure 7—Water table trends for (A) monthly average water table depth on the watershed WS77 from 1964 to 1971 and from 1992 to 1994, (B) observed and simulated water table depth on watersheds WS77 and WS80 on the Santee Experimental Forest from 1992 to 1995 (-O is observed; -P is simulated), (C) daily water table depth on watersheds WS77 and WS80 from wells H (WS80-W1), D (WS80-W2), and J (WS77-W1) in 2005–07, and (D) comparison among deviations of annual precipitation on annual mean water table on the watershed WS77 with their average between 1964 and 1993 [WT is water table depth (cm); rain is annual precipitation (cm)].

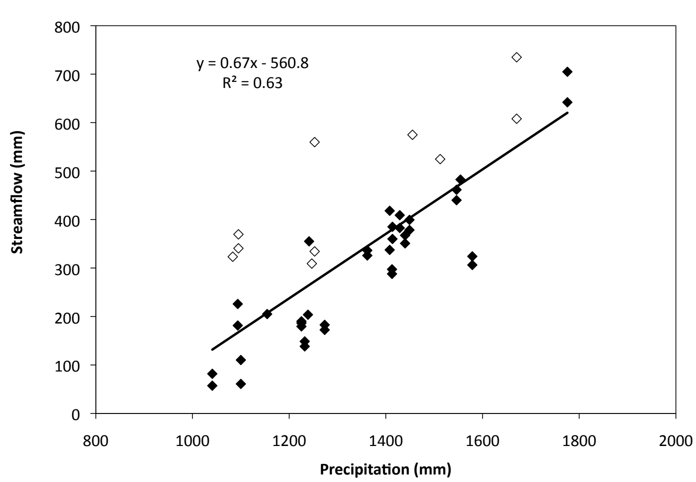



Figure 8—Relationship between annual precipitation and annual streamflow on watersheds WS77 and WS80 on the Santee Experimental Forest between 1965 and 2007; the filled diamonds represent 1990 through 2003.

hurricane destroyed over 80 percent of pre-hurricane canopy in this site (Hook and others 1991, 1996; Nix and others 1996), which caused a decrease in ET.

## Potential Evapotranspiration

Data on potential evapotranspiration (PET) calculated using the Penman-Montieth (P-M) method are presented in table 3. These data indicate that PET fluctuated between 969.9 and 1303.7 mm, with an average of 1136.5 mm and a standard deviation of 68.7 mm. Figure 9 shows that the PET increased significantly ($p<0.01$) at a linear rate about 15.4 mm per decade. The mean PET from 1946 to 1969 was 1093.1 mm, but from 1970 to 2008 the mean PET was 1163.2 mm, with an average increase of 6.4 percent. However, the precipitation has not increased significantly since 1946 (see the Precipitation Variability section above). These relationships further indicate that the flow and water table on the Santee Experimental Forest may decrease due to higher ET demands without an increase in precipitation.

**Table 3—Annual rainfall, potential evapotranspiration, streamflow, and temperature on Santee Experimental Forest, 1946–2008**

| Year | Rainfall (mm) | PET (mm) | ET (mm) | FlowE (mm) | MS (mm) | FD (mm) | FlowO (mm) | DTR (°C) | meanT ( °C) |
|---|---|---|---|---|---|---|---|---|---|
| 1946 | 1106.9 | 1161.7 | 1025.8 | 39.5 | N/A | N/A | N/A | 12.6 | 18.6 |
| 1947 | 1677.2 | 1070.7 | 1012.3 | 596.4 | N/A | N/A | N/A | 12.0 | 17.6 |
| 1948 | 1632.5 | 1103.3 | 1084.7 | 547.8 | N/A | N/A | N/A | 12.3 | 18.0 |
| 1949 | 1387.9 | 1162.1 | 1130.1 | 279.2 | N/A | N/A | N/A | 12.7 | 18.7 |
| 1950 | 1474.7 | 1102.1 | 994.4 | 458.8 | 308.7 | 305.1 | N/A | 13.0 | 17.7 |
| 1951 | 900.7 | 1089.1 | 962.6 | 0.0 | 61.3 | 22.2 | N/A | 13.7 | 18.2 |
| 1952 | 1262.8 | 1081.7 | 973.2 | 227.7 | 227.5 | 194.1 | N/A | 12.7 | 18.0 |
| 1953 | 1442.5 | 1147.9 | 1086.8 | 355.7 | 379.0 | 365.9 | N/A | 12.5 | 18.3 |
| 1954 | 834.6 | 1062.9 | 843.7 | 0.0 | 99.9 | 88.6 | N/A | 13.4 | 17.8 |
| 1955 | 1190.6 | 1082.1 | 981.3 | 200.2 | 243.4 | 218.3 | N/A | 12.8 | 18.0 |
| 1956 | 937.3 | 1141.2 | 996.0 | 25.2 | 97.5 | 76.1 | N/A | 13.2 | 18.6 |
| 1957 | 1200.4 | 1151.9 | 1012.3 | 104.3 | 202.7 | 174.3 | N/A | 12.2 | 18.4 |
| 1958 | 1459.9 | 981.6 | 963.6 | 496.3 | 392.8 | 406.2 | N/A | 12.5 | 17.0 |
| 1959 | 1780.0 | 1139.3 | 1073.9 | 706.1 | 636.8 | 747.1 | N/A | 12.0 | 18.4 |
| 1960 | 1162.4 | 1025.6 | 906.6 | 291.8 | 277.6 | 277.9 | N/A | 13.2 | 17.4 |
| 1961 | 1553.7 | 1039.8 | 1039.8 | 477.9 | 305.8 | 364.7 | N/A | 13.1 | 17.8 |
| 1962 | 1300.5 | 1126.6 | 1041.2 | 259.3 | 229.8 | 243.2 | N/A | 13.0 | 18.3 |
| 1963 | 1036.1 | 1114.2 | 909.3 | 171.7 | 198.3 | 174.9 | N/A | 13.2 | 18.0 |
| 1964 | 1888.1 | 1179.3 | 1136.8 | 706.4 | 771.8 | 800.7 | N/A | 12.1 | 18.9 |
| 1965 | 1241.2 | 1072.2 | 997.9 | 309.9 | 318.8 | 314.6 | 355.1 | 12.9 | 17.6 |
| 1966 | 1554.4 | 969.9 | 952.4 | 535.3 | 359.8 | 299.8 | 482.5 | 12.2 | 17.2 |
| 1967 | 1238.9 | 1118.8 | 1055.2 | 248.8 | 241.5 | 243.5 | 203.7 | 12.8 | 18.1 |
| 1968 | 1225.4 | 1058.3 | 963.7 | 196.5 | 236.5 | 263.9 | 186.5 | 13.0 | 17.8 |
| 1969 | 1408.0 | 1052.2 | 1011.2 | 396.8 | 387.6 | 380.8 | 418.1 | 11.9 | 17.8 |
| 1970 | 1361.7 | 1161.7 | 1021.7 | 340.0 | 354.9 | 343.8 | 336.3 | 12.2 | 18.8 |
| 1971 | 1694.4 | 1161.1 | 1123.7 | 621.3 | 594.8 | 595.4 | 704.9 | 11.4 | 19.0 |
| 1972 | 1093.7 | 1200.3 | 1023.2 | 42.3 | 209.5 | 228.3 | 217.9 | 11.5 | 19.2 |
| 1973 | 1428.8 | 1187.3 | 1103.7 | 325.1 | 356.2 | 337.9 | 382.7 | 11.4 | 18.9 |
| 1974 | 1412.8 | 1265.4 | 1160.5 | 252.3 | 331.1 | 283.9 | 287.8 | 12.2 | 19.4 |
| 1975 | 1439.8 | 1262.5 | 1200.8 | 266.9 | 382.6 | 392.9 | 350.9 | 11.7 | 19.5 |
| 1976 | 1448.9 | 1150.7 | 1053.8 | 367.1 | 371.6 | 363.3 | 399.4 | 12.2 | 18.3 |
| 1977 | 1273.5 | 1131.1 | 1047.2 | 226.3 | 314.5 | 285.8 | 172.4 | 12.0 | 18.5 |
| 1978 | 1225.4 | 1107.3 | 1041.0 | 184.4 | 214.3 | 206.7 | 179.5 | 11.8 | 18.3 |

*continued to next page*

## Water Balance

**Model validation for MIKE SHE hydrological simulations—**MIKE SHE was calibrated and validated using daily and monthly flow measurements on WS79 for two time periods, 1969–71 and 2005–07, and water table measurements on WS77 and WS80 from 1992 to 1995 and from 2005 to 2007 (Dai and others 2011b). The results are given in table 4, figures 7B and C, and figures 10A and B, which show that MIKE SHE was applicable for predicting streamflow on WS79. The model performance efficiency (E≤1) (Moriasi and others 2007) was 0.85 and 0.80 for daily water table depth on WS77 and WS80, respectively, for 1992–94, and 0.53 and 0.79, respectively, for 2005–07. The $R^2$ was 0.87 and 0.81 for WS77 and WS80, respectively, for 1992–94, and 0.69 and 0.82 for WS77 and WS80, respectively, for 2005–07; the ratio of the root mean squared error (RMSE) to SD (standard deviation) (good rating range: RSR≤0.7) was 0.42 for WS77 and 0.62 for

**Table 3 (continued)—Annual rainfall, potential evapotranspiration, streamflow, and temperature on Santee Experimental Forest, 1946–2008**

| Year | Rainfall (mm) | PET (mm) | ET (mm) | FlowE (mm) | MS (mm) | FD (mm) | FlowO (mm) | DTR (°C) | meanT ( °C) |
|---|---|---|---|---|---|---|---|---|---|
| 1979 | 1546.3 | 1077.6 | 1031.5 | 514.8 | 537.5 | 534.5 | 439.9 | 11.8 | 17.8 |
| 1980 | 1413.7 | 1078.8 | 1049.8 | 363.9 | 412.0 | 417.9 | 360.0 | 11.6 | 18.1 |
| 1981 | 1154.5 | 1065.1 | 984.2 | 170.3 | 172.1 | 146.2 | 131.8 | 12.5 | 17.9 |
| 1982 | 1663.5 | 1182.5 | 1171.6 | 491.9 | 536.9 | 557.3 | N/A | 10.8 | 18.9 |
| 1983 | 1710.7 | 1072.5 | 1015.6 | 695.1 | 665.3 | 720.5 | N/A | 11.2 | 18.2 |
| 1984 | 1364.5 | 1138.5 | 1085.2 | 363.6 | 361.9 | 342.3 | N/A | 12.0 | 18.5 |
| 1985 | 1349.6 | 1167.9 | 1036.8 | 228.6 | 343.3 | 353.5 | N/A | 11.5 | 18.8 |
| 1986 | 1367.2 | 1194.2 | 1061.0 | 306.2 | 473.4 | 509.9 | N/A | 11.1 | 19.3 |
| 1987 | 1660.5 | 1075.3 | 1052.8 | 622.5 | 591.4 | 614.1 | N/A | 11.2 | 18.1 |
| 1988 | 1141.8 | 1008.4 | 913.1 | 240.9 | 315.1 | 302.3 | N/A | 11.8 | 17.5 |
| 1989 | 1595.4 | 1179.7 | 1127.7 | 440.6 | 513.1 | 574.7 | N/A | 11.3 | 18.7 |
| 1990 | 1095.1 | 1303.7 | 1031.2 | 83.4 | 355.9 | 386.5 | 369.5 | 11.7 | 20.0 |
| 1991 | 1252.7 | 1244.0 | 1100.5 | 248.6 | 485.1 | 513.4 | 304.6 | 9.4 | 19.7 |
| 1992 | 1472.7 | 1168.3 | 1096.9 | 261.9 | 341.4 | 309.7 | 187.7 | 10.9 | 19.0 |
| 1993 | 1246.9 | 1172.9 | 1080.8 | 180.4 | 301.5 | 292.3 | 272.2 | 12.4 | 19.2 |
| 1994 | 2026.4 | 1188.8 | 1124.6 | 885.6 | 349.9 | 352.9 | 323.3 | 12.7 | 19.2 |
| 1995 | 1525.1 | 1212.2 | 1052.0 | 473.1 | 461.2 | 464.9 | N/A | 12.6 | 19.1 |
| 1996 | 1208.1 | 1115.3 | 1027.5 | 180.6 | 222.5 | 182.0 | 247.2 | 12.6 | 18.3 |
| 1997 | 1659.5 | 1162.3 | 1122.4 | 537.0 | 477.1 | 515.2 | 524.7 | 12.8 | 18.7 |
| 1998 | 1291.6 | 1267.7 | 962.6 | 437.5 | 543.0 | 579.6 | 574.9 | 13.1 | 20.0 |
| 1999 | 1466.9 | 1184.5 | 1168.4 | 192.4 | 482.3 | 383.4 | N/A | 14.0 | 19.0 |
| 2000 | 1167.5 | 1138.3 | 974.2 | 193.3 | 218.0 | 212.5 | N/A | 13.0 | 18.3 |
| 2001 | 1016.1 | 1178.7 | 1020.0 | 106.5 | 143.6 | 145.2 | N/A | 11.8 | 19.0 |
| 2002 | 1555.7 | 1242.5 | 1084.7 | 360.6 | 444.3 | 448.7 | N/A | 11.2 | 19.3 |
| 2003 | 1690.4 | 1121.3 | 1106.8 | 604.9 | 693.5 | 783.8 | 608.0 | 11.7 | 18.4 |
| 2004 | 1118.1 | 1163.8 | 1018.6 | 144.4 | 130.7 | 126.0 | 60.9 | 12.3 | 18.9 |
| 2005 | 1637.9 | 1151.9 | 1114.0 | 475.7 | 292.5 | 237.3 | 324.1 | 12.1 | 18.7 |
| 2006 | 1264.5 | 1144.1 | 1052.0 | 212.7 | 207.8 | 191.8 | 148.6 | 12.9 | 18.8 |
| 2007 | 1041.3 | 1122.9 | 975.7 | 74.2 | 74.9 | 50.9 | 81.8 | 12.7 | 19.1 |
| 2008 | 1476.2 | 1213.0 | 1159.5 | 331.4 | N/A | N/A | 387.3 | 11.6 | 19.4 |

PET = P-M equivalent; ET and FlowE are estimated by using Thornthwaite water balance approach; MS and FD = the flow from MIKE SHE and Forest-DNDC, respectively; FlowO = observed; DTR = annual averaged diurnal temperature range.

N/A = no available data.

**Table 4—Observed and simulated streamflow for the two first-order watersheds WS77 and WS80 and the second-order watershed WS79 consisting of WS77, WS79b, and WS80, and model efficiency in two validation periods, 1969–71 and 2005–07**

| Watershed | | 1969–71 O | P | $R^2$ | E | RSR | PB | 2005–07 O | P | $R^2$ | E | RSR | PB |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| WS77 | daily | 1.35 | 1.35 | 0.82 | 0.80 | 0.44 | 0.69 | 0.51 | 0.52 | 0.61 | 0.52 | 0.63 | -1.0 |
| | monthly | 41.2 | 41.0 | 0.94 | 0.94 | 0.20 | 0.69 | 15.4 | 15.6 | 0.91 | 0.91 | 0.31 | -1.0 |
| WS80 | daily | 1.26 | 1.34 | 0.69 | 0.66 | 0.58 | -6.5 | 0.46 | 0.52 | 0.75 | 0.75 | 0.50 | -12 |
| | monthly | 38.4 | 40.9 | 0.93 | 0.92 | 0.30 | -6.5 | 14.0 | 15.7 | 0.96 | 0.94 | 0.24 | -12 |
| WS79 | daily | 1.18 | 1.37 | 0.78 | 0.77 | 0.48 | -16 | 0.53 | 0.63 | 0.68 | 0.64 | 0.44 | -14 |
| | monthly | 36.0 | 41.8 | 0.90 | 0.88 | 0.37 | -16 | 16.2 | 19.1 | 0.96 | 0.95 | 0.35 | -14 |

O = mean observation; P = mean prediction; $R^2$ = coefficient of determination; E = model efficiency; RSR = the ratio of root mean squared error to standard deviation; PB = percent bias between observation and simulation (PBIAS).

WS80; the percent bias (good rating range: -25 percent ≤PBIAS≤25 percent) (Moriasi and others 2007) was 3.9 and -0.08 percent for WS77 and WS80, respectively, for the same periods; and the difference in mean water table depth between the observation and simulation for the two validation periods was <10 cm (between -8.6 and 1.6 cm for WS77 and between -3.5 and 3.9 cm for WS80). These qualitative (figs. 7B and C, and fig. 10B) and quantitative assessments show that MIKE SHE is applicable to model water table dynamics for this site.

**Evapotranspiration—**Data on the estimated annual ET are presented in table 3 and figure 11. The average annual ET estimated by using the Thornthwaite water balance approach (WBA) (1043.4 mm) was about 90.8 percent of the PET (1136.5 mm) during the last 63 years. The ET increased significantly ($p<0.02$) at a linear rate of 11.9 mm per decade in the last 63 years. Moreover, annual precipitation substantially influenced the annual ET, thereby increasing significantly with an increase in logarithmic annual precipitation ($p<0.01$). This relation between ET and precipitation implies that flow and water table level can be significantly influenced by a substantial increase in ET without an increase in precipitation. However, the ET may be overestimated using the WBA, especially for dry years, such as 1951, 1954, and 1956, because the streamflow might be underpredicted (see the discussion below) for the same years by using the WBA.

The annual ET from MIKE SHE (973.6 mm) for the same 63-year period was 70 mm (about 6.7 percent) lower than the values from WBA, although the PET used to simulate the hydrology using MIKE SHE for this watershed was also P-M-equivalent, the same as that applied for ET estimation using WBA. The difference may be because MIKE SHE calculates ET while taking into consideration the impacts of vegetation, including plant rooting depth, interception, evaporation on leaves, and soil moisture stress during dry periods. However, ET levels were likely to be slightly underestimated by MIKE SHE, because the Two-Layer Water Balance method was used to simulate the ET and the unsaturated flow in soils for this watershed. This method divides the unsaturated zone into a root-zone where ET can occur, and a below-root-zone where ET does not occur (Yan and Smith 1994). Therefore, MIKE SHE may underpredict ET for extremely dry periods during growing seasons, especially in summers, due to low water table level during low precipitation with high evapotranspiration demand periods.

Evapotranspiration simulated by Forest-DNDC was 1020.9 mm, about 2.1 percent less than the value estimated using the WBA in the same period, but about 4.6 percent higher than MIKE SHE. The annual ET from Forest-DNDC is between the values from MIKE SHE and from the WBA. However, Forest-DNDC employed the PET that was different from MIKE SHE and WBA to estimate ET. Both MIKE SHE and WBA utilize Penman-Monteith-equivalent PET as their inputs to calculate ET, but Forest-DNDC calculates PET using Thornthwaite-based equation for ET estimation without a site-specific Penman-Monteith-equivalent correction factor. Therefore, the ET is likely to be slightly overestimated using Forest-DNDC.

Although there are differences in ET estimated by using different methods, it can be considered that the average ET over the last 63 years was likely within 970-1040 mm, about 1000 mm. This estimation is slightly higher than the values (950 mm and 969 mm) estimated by Amatya and Trettin (2007b), and Lu and others (2003), and approximate to the result reported by Turner (1991) from 1964 to 1976, before the strong air temperature rise in this area. The ET estimated using different approaches was lower than the P-M-equivalent PET in this forest area, which indicates that soil moisture deficit can occur during low precipitation periods although mean annual precipitation (1370 mm) is higher than the annual PET (1136 mm).

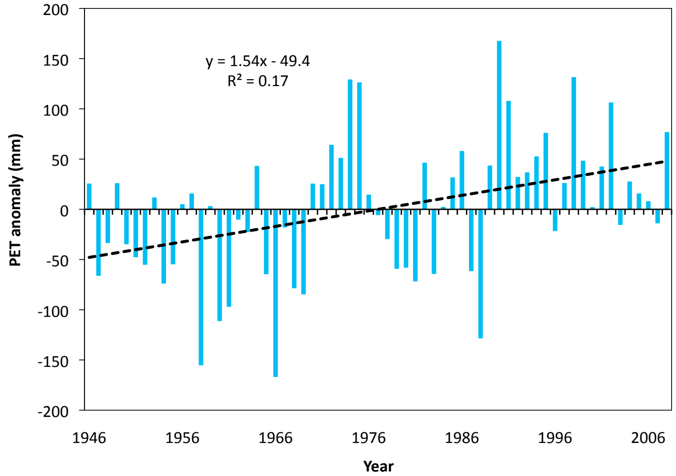



Figure 9—Deviation in potential evapotranspiration (PET) from the long-term average measured at the Santee Headquarters from 1946 through 2008.

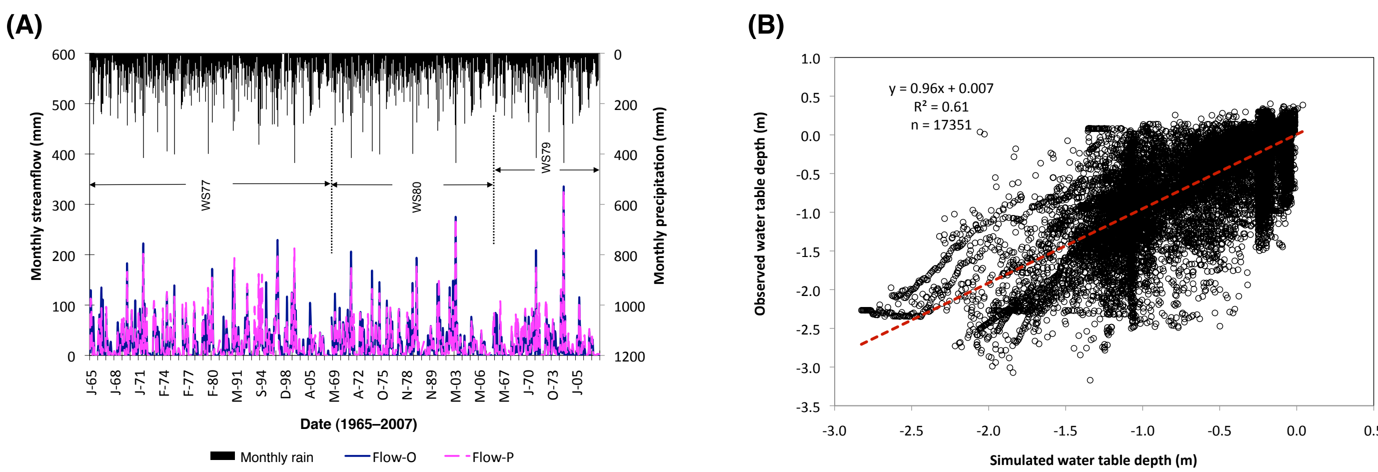



Figure 10—(A) Predicted and observed monthly streamflow on the watershed WS79 and its sub-watersheds WS77 and WS80 for 1965 to 2007 and (B) observed and simulated water table below the soil surface on watersheds WS77 (44 wells) and WS80 (35 wells) for all water table observation periods between 1964 and 2007.

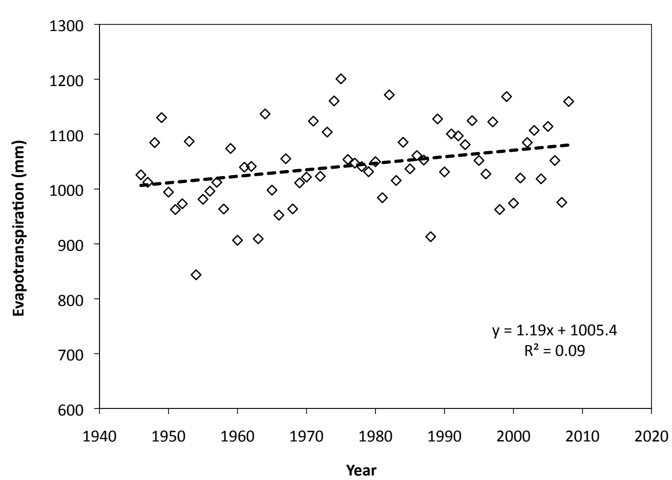



Figure 11—Estimated annual evapotranspiration (ET) calculated for the Santee Headquarters for 1946 to 2008, using the Thornthwaite water balance approach (Flerchinger and Cooley 2000, Ward 1972).

**Streamflow—**Data on estimated streamflow from the different approaches are presented in table 3 and figures 12A and B. The figures show some differences in flow among the four estimation methods. The results from MIKE SHE were 4.5, 9.6, and 2.4 percent higher than the observations, WBA, and Forest-DNDC, respectively, in 1965–2007. The flow predicted by MIKE SHE might be related to the artifact of MIKE SHE that does not allow a river/stream to dry out (Dai and others 2010b, Lu and others 2006). In the case of intermittent streams, it is typical to have no-flow periods, such as the dry period from the fall of 2003 to the summer of 2004 and the summer of 2007; however, in these cases, MIKE SHE maintained a very low streamflow.

The flow estimated by WBA was 5.4 percent lower than the actual measured level. The lower levels are mostly due to an overestimation of ET, especially for the years after Hurricane Hugo, due to the destruction of the forest leading to a low ET demand within several years (Dai and others 2011b). The underprediction showed that a simple water balance method did not capture the impact of hurricanes on the hydrology in the watershed. However, the results from both models (MIKE SHE and Forest-DNDC) and the hydrological observations exhibited the impact of the hurricane. The flow estimated by Forest-DNDC was about 2.2 percent higher than the measurements, more approximate to the observed than the results from MIKE SHE and WBA.

**Water storage (changes in water table depth)—**Data on changes in estimated water storage using WBA for the last 63-year period of 1946–2008 are presented in figure 13, and show that changes in annual soil water storage fluctuated largely in last 63-year period on these first-order watersheds on the Santee Experimental Forest. The storage significantly altered with changes in logarithmic annual precipitation ($p<0.01$). Therefore, the less precipitation an area gets, the larger the soil moisture deficit, and vice versa. However, the change in the long-term average soil water storage was small, only 0.4 mm $yr^{-1}$, in agreement with the change in annual precipitation, which was 1.2 mm $yr^{-1}$. This result indicates that the change in annual soil water storage on this wetland-dominated watershed with a shallow water table is highly influenced by precipitation, consistent to the water table (WT) level dynamics simulated using MIKE SHE for the 58-year period of 1950–2007 that varied significantly with logarithmic annual precipitation ($p<0.02$); the WT on this watershed increases or decreases with an increment or decrement in precipitation.

Figure 14 shows the temporal changes in WT on WS79 (higher WT, more water stored in soils), which indicates that the inter-annual change in soil water storage is complex due to interactions among temperature and precipitation. For example, the highest WT level occurred in 1998, but that year was one of the warmest (20 °C of mean daily temperature) since 1946. A high WT in 1998 was likely related to an abnormal annual precipitation pattern, because over 78 percent of annual precipitation occurred in January, February, and December (winter), and March through May (spring) while the ET demand was low. This result demonstrates that the soil water storage on WS79 can be substantially influenced by the changes in seasonal precipitation.

The WT level in 1958 (with 1460 mm precipitation) was the second highest in the 58-year period, but the ground water level in 1959 (with 1780 mm precipitation) was about 29 cm lower than 1958. It is an example of a reversed pattern of the expected normal relationship between WT and precipitation in this area, i.e., the water table level rises usually with an increase in precipitation. This phenomenon was likely a result of two factors, storms and temperature. The coolest year in the 63-year period of 1946–2008 was 1958 (figs. 2A and B), with an average daily temperature of 17 °C. The average daily temperature in 1959 was 1.5 °C higher than in 1958, most likely resulting in a higher ET demand with a subsequently lower water table than in 1958. Another potential factor could be the magnitude of summer storms, because there were no differences in precipitation in the winter, spring, and fall between these years. There were six storms with over 70 mm precipitation and two storms with over 100 mm in 1959; but there were only two storms with over 55 mm precipitation in 1958. High precipitation in 1959 that was mainly caused by the larger summer storms might not have resulted in a substantial high water table for these headwater areas in that year. Therefore, storms with high precipitation in the summer contribute to a small increase in the water table on these first-order watersheds, although the water table generally rises with an increase in precipitation in this area.

The comparison of the WT in 1988 and 1990 indicates that temperature substantially influences the WT dynamics on these first-order watersheds. The WT in 1988 was substantially higher than that in 1990. However, there was not a substantial difference in precipitation between these 2 years, including no differences in annual and seasonal precipitation and storms; the main difference between these 2 years was temperature and biomass. The average temperature in 1988 was 2.5 °C lower than 1990, and biomass in 1990 was lower than 1988, due to the destruction of the forest canopy by Hurricane Hugo in 1989 (Hook and others 1991). Generally, the water table and the rate of annual streamflow to annual precipitation in 1990 should be higher than in 1988 due to low demand in transpiration if climate conditions were similar between these 2 years, but the result was reversed for the water table, and in agreement for the streamflow. This result suggests that the WT on the Santee Experimental Forest was influenced by the synergy of temperature and the hurricane. Similarly, the difference in WT levels between 1969 and 1970 also indicated the impact of temperature

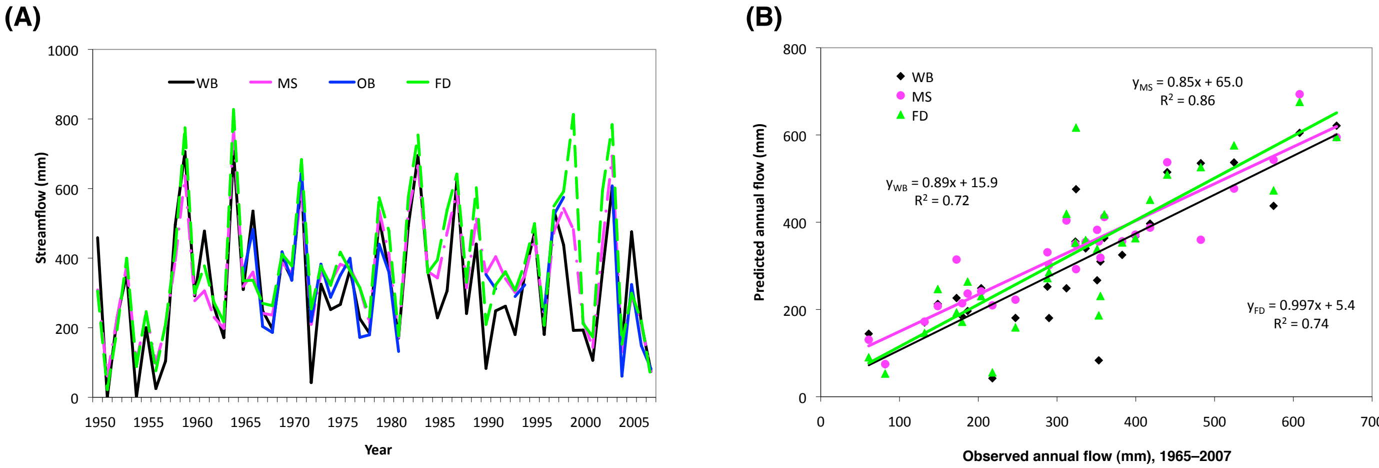



Figure 12— (A) Annual streamflow for the watershed WS79, 1950–2007, as measured (OB) and predicted using different models (WB is Thornthwaite water balance; MS is MIKE SHE; FD is Forest-DNDC); (B) relationship between observed and estimated annual streamflow for the watershed WS77, 1965–2007, using MIKE SHE (MS), Forest-DNDC (FD), and Thornthwaite water balance approach (WB).

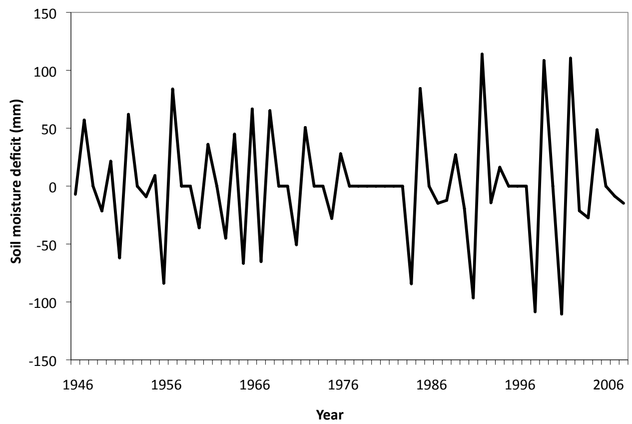



Figure 13—Soil water deficit estimated using Thornthwaite water balance approach (Flerchinger and Cooley 2000, Ward, 1972) for watershed WS79 from 1946 to 2008.

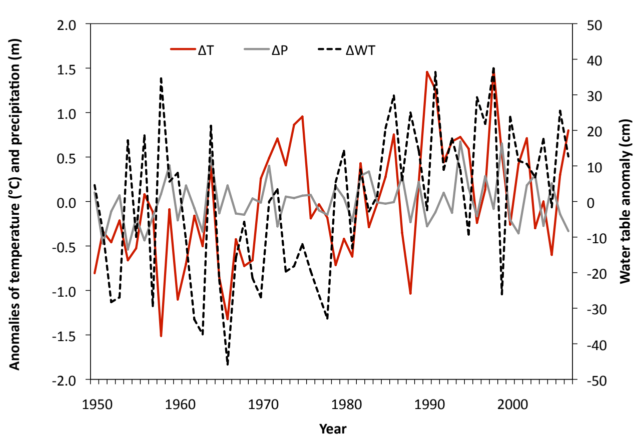



Figure 14—Comparison of annual temperature, precipitation, and soil water storage anomalies on watershed WS79 between 1950 and 2007.

on the WT. There was neither a substantial difference in biomass between the 2 years, nor a significant difference in precipitation. However, temperature in 1969 was 1 °C lower than 1970. The WT levels from observation and simulation in 1969 were substantially (over 20 cm) higher than in 1970. These results indicate that temperature is one of the important factors influencing the WT on these first-order watersheds, and that warming without increased precipitation can reduce the WT level on this study catchment.

### Modeling the Role of Climate Variability on Carbon Dynamics in Forests

**DNDC model validation for estimating carbon sequestration—**Forest-DNDC was validated against soil $CO_2$ efflux, soil temperature, soil moisture, and biomass observations within watershed WS79 (table 5; figs. 15A–E), with reasonable model performance efficiencies (0.67, 0.70, 0.40, and 0.86, respectively) (Dai and others 2011a). For this study, the model was validated using biomass measurements on 24 plots in 2006 and the estimation of biomass loss to Hurricane Hugo (Hook and others 1996). The simulated biomass loss to the hurricane (79.3 and 12.1 C Mg ha$^{-1}$ for pre- and post-hurricane) was in good agreement with the estimation (78.0 and 13.9 C Mg ha$^{-1}$). The observed spatial difference in biomass (from observation at 24 plots) in 2006 ranged from 44.8 to 136.2 C Mg ha$^{-1}$ (fig. 15E), and the arithmetic average and geometric mean were 75.6 and 73.7 C Mg ha$^{-1}$, respectively. However, the simulated biomass for the same plots ranged from 59.3 to 117 C Mg ha$^{-1}$ with arithmetic and geometric means of 74.2 and 73.1 C Mg ha$^{-1}$, respectively. Although the difference between the measured and simulated mean was small (arithmetic mean: 75.6 vs. 74.2; geometric mean: 73.7 vs. 73.1), there were larger differences in both minimums and maximums. Those differences can be attributed to using an average canopy loss [85 percent as estimated by Hook and others (1991)] in response to Hurricane Hugo in 1989—this average was used for simulating carbon dynamics on this catchment due to lack of available data on the actual spatial canopy damage from the hurricane. In fact, the hurricane heterogeneously destroyed the pre-hurricane dominant canopy on WS79 in 1989, causing the canopy damage in some of the simulation cells to be higher than the average and some lower. However, the total error from the simulation that used average hurricane damage was small because the simulation for most observation plots was in agreement with the actual measurement, which was about 3.8 percent lower than the observed. The model performance efficiency ($E \leq 1$) was 0.86, in the "very good" rating range ($E > 0.75$) for assessing carbon storage in wood biomass in this catchment. The results from model validation showed that the Forest-DNDC is applicable for estimating carbon dynamics on this site with acceptable model performance efficiency.

**Biomass carbon—**Spatial biomass distribution on WS79 was varied. The simulated spatial difference in biomass for WS79 ranged from 44.8 to 137.6 C Mg ha$^{-1}$, with arithmetic average of 74.5, geometric mean of 71.5, and median of 65.8 C Mg ha$^{-1}$ in 2006, which is near to the measured range and average (fig. 15E). The simulation results show that the spatial difference in biomass over WS79 is larger than on WS80—the maximum value is about 3 times the minimum on WS79, and twice on WS80. The difference can be attributed to the spatial heterogeneity in the vegetation type, and forest management. WS80 is a control forested watershed in this paired watershed system (WS79 consisted of three sub-watersheds, WS77 as treatment, WS80 as control, and WS79b as mixture). As a reference watershed, WS80 has not been managed, including no salvage logging, for nearly six decades. Current vegetation coverage was regenerated naturally after Hurricane Hugo in 1989. However, there are fewer pine stands on WS80 than on WS77. Prescribed fire and thinning were used on WS77 and part of WS79b (Amatya and Trettin 2007b; Richter and others 1983a, 1983b).

**Soil carbon efflux—**The cell-based (simulation unit) annual average soil $CO_2$ flux in watershed WS79 ranged from 2.34–4.65 C Mg ha$^{-1}$ from 1950 to 2007 (fig. 16),

**Table 5—Observed and predicted averages for soil $CO_2$, temperature and moisture, and biomass on watershed WS79 consisting of WS77, WS79b, and WS80, and model efficiency and the slope of regression between observations and simulations**

| Parameter | O | P | E | *b* |
|---|---|---|---|---|
| Soil $CO_2$ (C kg ha$^{-1}$d$^{-1}$) | 43.3 | 42.6 | 0.67 | 0.94 |
| Soil temperature (°C) | 20.4 | 18.6 | 0.70 | 0.91 |
| Soil moisture (m$^3$m$^{-3}$) | 0.48 | 0.46 | 0.40 | 1.02 |
| Biomass (C Mg ha$^{-1}$) | 55.0 | 58.9 | 0.86 | 1.13 |

O = observed mean; P = predicted mean; E = model efficiency; *b* = the slope of regression model between observations and simulations.

Source: Nash and Sutcliffe (1970).

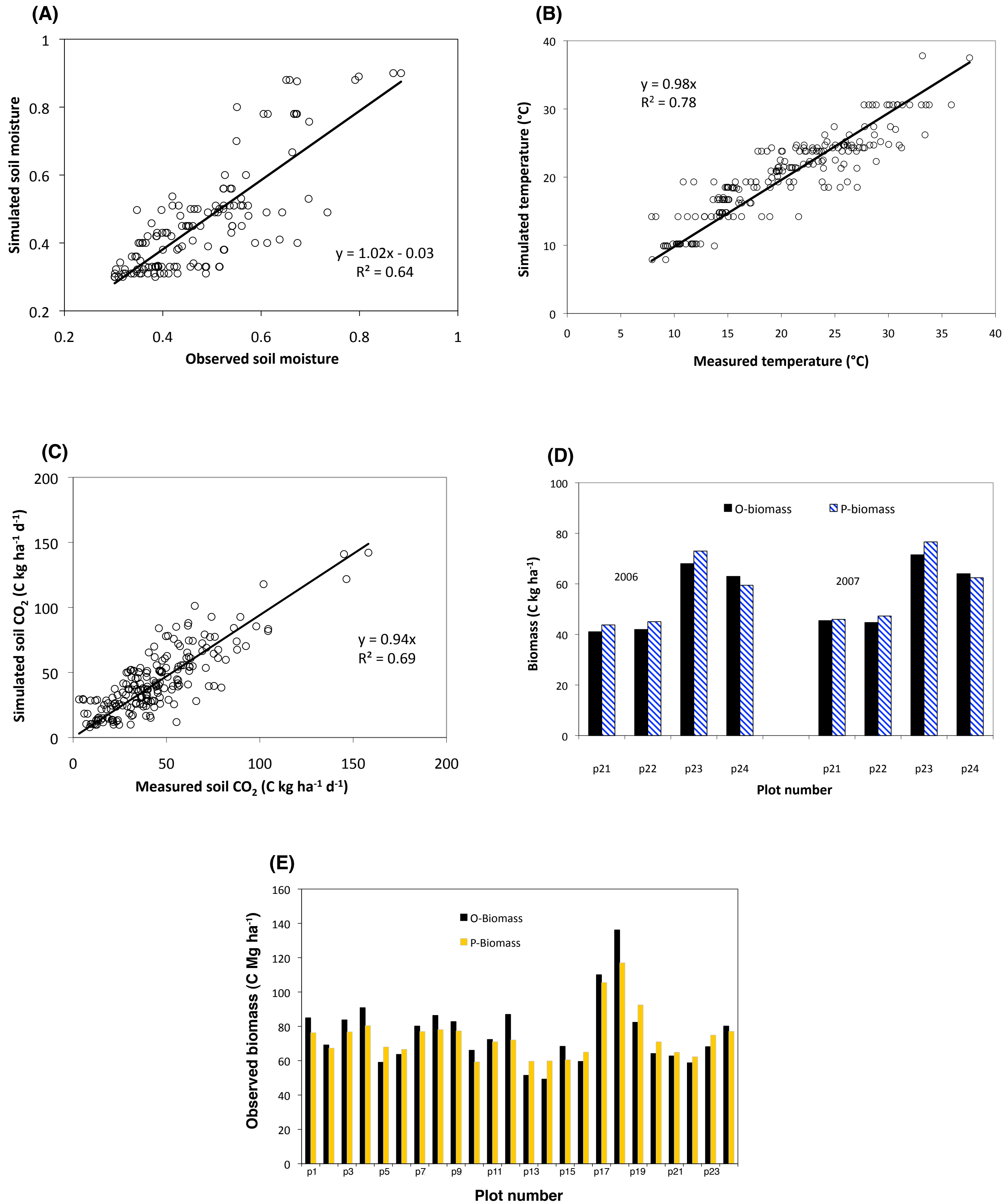



Figure 15—Comparison of Forest-DNDC predicted with observed parameters on (A) soil moisture on watershed WS79 in 2006–2008, (B) soil temperature on watershed WS79 in 2006–08, (C) soil $CO_2$ efflux on the watershed WS79 between 2006 and 2008, (D) aboveground biomass for plots 21–24 on watershed WS80 in 2006 and 2007, and (E) above- and belowground biomass in 2006 for watershed WS79.

demonstrating a substantial spatial difference in the flux within the watershed. The main difference in soil $CO_2$ efflux is likely related to soil properties including soil moisture, soil organic carbon content, and vegetation distribution (Miller and Johnson 2002, Xu and Qi 2001). The arithmetic mean, median, and geometric mean of the 58-year soil $CO_2$ efflux on this catchment were the same, 3.8 C Mg $ha^{-1}$, indicating a spatially normal distribution in this watershed. However, the spatial difference in the long-term average flux in this watershed was smaller than the variation found by Xu and Qi (2001) in a ponderosa pine plantation in California, the coefficient of variation (CV) was <10 percent from this study, while >30 percent was found on the pine plantation site. The difference in CVs between two studies is likely related to the length of each observation period and differences in site characteristics including vegetation, soils, and climate. However, the CV from our watershed would be about 20 percent if the time period in both studies was the same, from June 1998 to August 1999.

There were large spatial differences in the annual average $CH_4$ flux in this forest, ranging from -4.6 to 391.8 C kg $ha^{-1}$ with an arithmetic mean of 81 kg and median of 54.4 kg $ha^{-1}$ between 1950 and 2007 (fig. 17). Large differences in annual $CH_4$ flux between arithmetic mean and median indicated that the spatial distribution of $CH_4$ flux was substantially skewed, and similar to other results (Trettin and others 2006). However, the geometric mean was not applicable as a representation of the average $CH_4$ flux level on WS79 because there were zero and negative fluxes in this catchment. The large spatial difference in $CH_4$ flux was regulated by the differences in biogeochemical environment of methane production in the site. For example, $CH_4$ flux from the cells near the stream outlet is consistently high because they are the lowest areas of the watershed; $CH_4$ flux from a local depression located at the northwest of this catchment is also high because the bottom of the depression is about 50 cm lower than its surface runoff outlet (based on the topographic data). However, the $CH_4$ flux was small or negative at those places with slopes (≥1 percent) in this watershed. These results indicate that those biogeochemical hotspots of $CH_4$ production and emission can produce a high $CH_4$ flux, and those hotspots are likely to occupy only a small fraction of the watersheds (23 percent in this catchment). The results indicate that the spatial heterogeneity in $CH_4$ production and emission is critical to assess $CH_4$ flux using a modeling approach, especially for those catchments with a mosaic of wetlands and uplands. Failure to consider the spatial heterogeneity to assess $CH_4$ flux could induce a large error when applying a field scale modeling approach with averaged spatial and temporal conditions of study sites.

**Impact of climate variability on carbon sequestration in forests—**Climatic conditions in the 39-year period before Hurricane Hugo were related to forest C sequestration. A multivariate analysis indicates that the combination of air temperature and precipitation have a significant correlation with forest carbon sequestration ($R^2$=0.96, n=39, *df*=3, *F*=1894, p<0.001). Correspondingly, if air temperature increases by one degree Celsius on the basis of the current temperature condition without an increase in precipitation, carbon sequestration due to the forest product on WS79 is predicted to decrease by about 300 kg $ha^{-1}yr^{-1}$ based on that multivariate analysis. However, forest production could slightly rise if precipitation increased. These relationships indicate that warming may decrease C sequestration within the forest because precipitation levels have not increased in conjunction with the observed warming in this area.

Climate variability can influence C sequestration in other components of the forest. The annual soil $CO_2$ efflux from the study catchment between 1950 and 2007 indicated that the annual flux fluctuated and linearly increased at an average rate of about 28 C kg $ha^{-1}yr^{-1}$ before the hurricane (fig. 18). The slow and linear increase in soil $CO_2$ efflux before the hurricane likely resulted from two factors, an increase in biomass (fig. 19) and the increase in air temperature. The increase in biomass, including root and leaf material, can increase soil $CO_2$ efflux; the temperature increased at an average rate of 0.21 °C per decade between 1950 and 1988 (the pre-hurricane period) (Dai and others 2011b), which can lead to an increase in soil organic matter decomposition (Xu and Qi 2001). However, the inter-annual soil $CO_2$ efflux fluctuation in the same period was principally related to the changes in soil moisture regime. Annual soil $CO_2$ efflux decreased insignificantly at an exponential rate with an increase in annual precipitation [4.24*exp(-0.199*AP), 0.1≥p>0.05, where AP is annual precipitation (m)]. For example, soil $CO_2$ efflux in 2007 on WS79 was 1.1 C Mg $ha^{-1}$ higher than the flux in 2006 because 2007 was a dry year, with 333 mm less precipitation than in 2006; the flux in 1997 was 2.2 C Mg $ha^{-1}$ lower than that in 1998 as air temperature was 1.3 °C higher and precipitation was 360 mm lower in 1998 than 1997, respectively. These results show that an increase in air temperature and decrease in precipitation can cause an increase in soil $CO_2$ efflux on WS79, which are similar to findings of Pietsch and others (2003), who found that the WT level decrease in their sites led to an increase in soil carbon loss. These results suggests that warming could induce more soil $CO_2$ release from this type of forested watershed because the general warming trend does not correspond with additional rain in this subtropical area (Dai and others 2011b, Zhang and others 2007).

Temporal changes in annual $CH_4$ flux from this watershed were large, watershed-based arithmetic mean annual flux ranged from -2.7 to 103.5 C kg $ha^{-1}$ from 1950 to 2007. The large difference in the flux year-to-year over the 58-year period was mainly influenced by temperature and precipitation regulating biogeochemical conditions of $CH_4$ production and emission. Although there is not a correlation between daily precipitation and daily $CH_4$

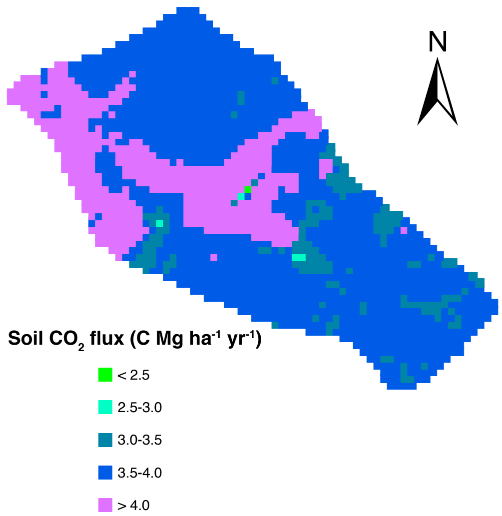



Figure 16—Average annual soil $CO_2$ efflux on watershed WS79 from 1950 to 2007.

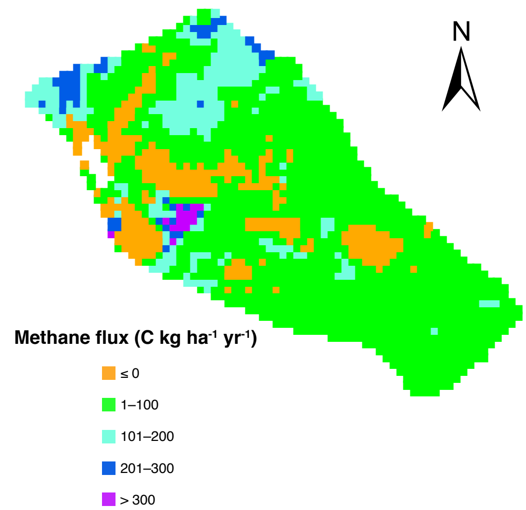



Figure 17—Average annual methane ($CH_4$) flux on watershed WS79 from 1950 to 2007.

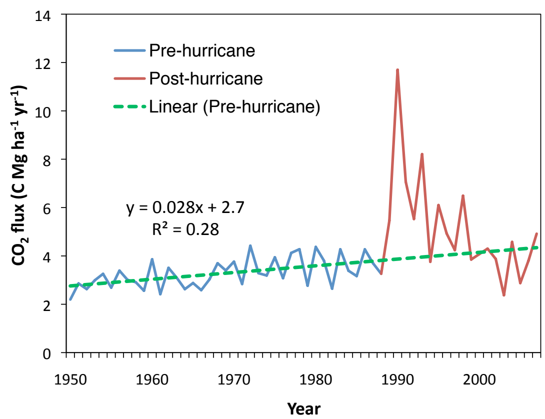



Figure 18—Predicted change in annual soil $CO_2$ flux on the watershed WS79 between 1950 and 2007 using Forest-DNDC.

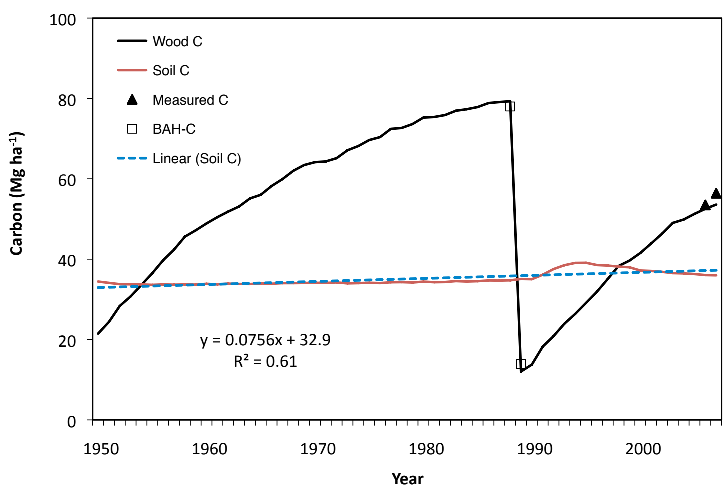



Figure 19—Average annual biomass and soil carbon accumulation on watershed WS79 from 1950 to 2007 as predicted using Forest-DNDC. The blank square (☐) indicates pre- and post-Hurricane Hugo biomass reported by Hook and others (1996); the triangle (▲) indicates the aboveground biomass measured in 2006 and 2007.

flux from this watershed (p>0.1), annual $CH_4$ flux was significantly correlated to annual precipitation (p<0.01) (fig. 20A). This result is similar to the findings of Inubushi and others (2003), who found that the $CH_4$ flux was correlated to monthly precipitation in the coastal area of South Kalimantan. Methane production and emission from this watershed highly depends on the WT level regulating biogeochemical soil conditions, aerobic or anaerobic. However, the WT level in these first-order watersheds is in turn regulated by precipitation (Amatya and others 2003, Dai and others 2010a). Therefore, precipitation becomes one of the important factors influencing $CH_4$ production and emission in the catchment. This watershed can act as a $CH_4$ sink in extreme dry years, as was the case in 1951, when there was only 901 mm of precipitation, about 470 mm less than the long-term average, such that the annual $CH_4$ flux was -2.7 C kg ha$^{-1}$.

The impact of temperature variability on $CH_4$ flux was linear (fig. 20B). An increase in temperature might raise the flux due to an increase in soil organic carbon decomposition (Xu and Qi 2001). However, the increase in methane flux with temperature rise is influenced by changes in precipitation. If precipitation does not significantly increase with an increase in temperature, the WT level will obviously decrease due to an increase in ET caused by a large increase in temperature, which leads to a decrease in $CH_4$ flux in the watershed with a shallow water table. For instance, $CH_4$ flux was lower in the two warmest years (1990 and 1998) in the last 58-year period, with an average temperature of 20 °C in both years, causing a decrease in the water table. These results suggest that prolonged warming might convert this catchment from a $CH_4$ resource to a sink, because wetlands within the catchment may be diminished due to a decrease in the water table.

**Impact of Hurricane Hugo on $CO_2$ sequestration—**The simulation results show that the carbon sequestration within the forests on watershed WS79 did not monotonously change because there was a large disturbance brought by the hurricane (figs. 18 and 19). Carbon sequestration across the watershed recovered quickly after a significant proportion of the overstory canopy was destroyed. The hurricane did not only destroy the forest in this catchment, but it also added a large amount of coarse woody debris (CWD) to forest floor and dead roots to mineral soil. Therefore, organic C in mineral soils (SOC), excluding CWD, litter, and duff, increased after the hurricane (fig. 19), which was primarily a result from the dead roots. However, figure 19 also shows that the impact of dead roots added by the hurricane has likely been small to the present time. Accordingly, the hurricane significantly influenced soil $CO_2$ flux due to the large amount of litter left by the storm, and those residues decomposed quickly under the subtropical climate and produced a high soil $CO_2$ flux within a short period after the hurricane (fig. 18).

Unlike C sequestration to wood product and soil $CO_2$ flux, annual $CH_4$ flux from this catchment was not substantially influenced by Hurricane Hugo. The cause is likely a reflection that precipitation regimes are independent of single storm events. Although most of the overstory was destroyed, the water table did not exhibit a sustained effect because of transpiration from the understory and regenerating trees. Hurricanes cause a large increase in detrital organic matter to the forest floor, which could be a potential C resource for $CH_4$ production. However, the potentiality will interact with biogeochemical conditions in this watershed.

The spatial variation of net ecosystem exchange (NEE) in the catchment was large. The cell-based annual average NEE ranged from -0.99 to -3.49 C Mg ha$^{-1}$ with an arithmetic mean of -1.6 and geometric value of -1.47 from 1950 to 2007. Although there are large differences in NEE on this catchment, the spatial distribution was normal. However,

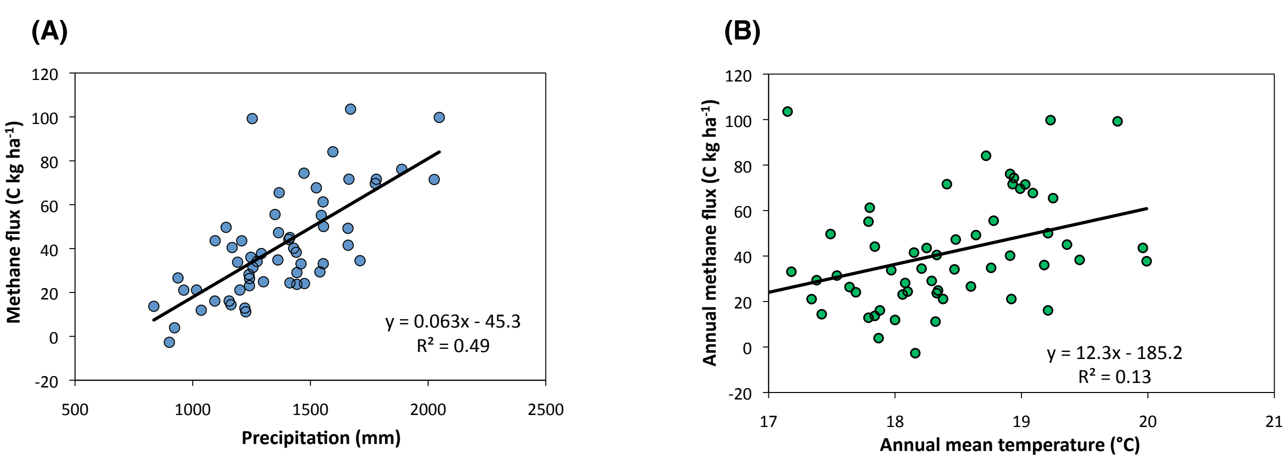



Figure 20—Methane ($CH_4$) flux predicted using Forest-DNDC on watershed WS79 in relation to (A) annual precipitation and (B) annual mean temperature from 1950 to 2007.

net primary productivity (NPP) was not low (fig. 21) and spatially ranged from 2.1 to 9.6 with an arithmetic mean of 4.86 C Mg ha$^{-1}$. The high NEE likely resulted from the decomposition of the large amount of litter left by Hurricane Hugo in 1989. This is because $CO_2$ released from the decomposition of the litter left by the hurricane was much higher than the $CO_2$ amount consumed by the regenerated forest within a few years after the storm (fig. 21).

The NEE increased significantly with a decrease in precipitation before Hurricane Hugo in this forested watershed ($p<0.02$) (fig. 22A), but insignificantly with an increase or decrease in temperature ($R^2=0.01$) (fig. 22B), indicating that NEE can be substantially influenced by the changes in soil moisture regime regulated by precipitation in this watershed. Soil $CO_2$ flux was lower in the wet years than dry years in this site (Dai and others 2011a) because the soil was saturated for longer periods in wet years (Dai and others 2010b). These results imply that warming can reduce carbon sequestration to this forest because the warming does not bring more rain to this subtropical area (Dai and others 2011b, Zhang and others 2007).

## CONCLUSIONS AND IMPLICATIONS

The daily mean temperature increased on the Santee Experimental Forest at a rate of 0.19 °C per decade over the last 63-year period, substantially higher than the global average of 0.07 °C per decade in 20th century (IPCC 2001). The temperature data from the Santee Experimental Forest suggest that the increase in warming in this area began in 1970, 6 years earlier than reported elsewhere (Hansen and others 2006). The warming conditions affect the surface hydrology on the Santee Experimental Forest, specifically

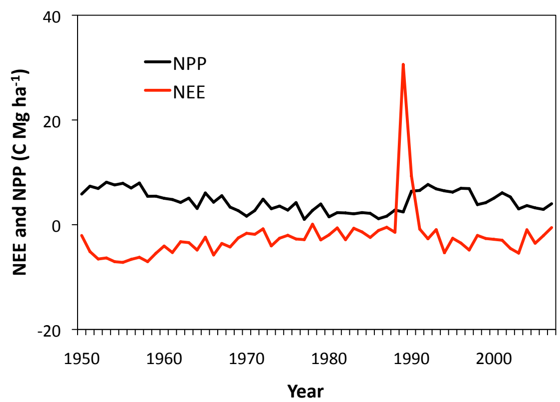



Figure 21—Net ecosystem exchange (NEE) and net primary production (NPP) on watershed WS79 estimated by Forest-DNDC from 1950 to 2007.

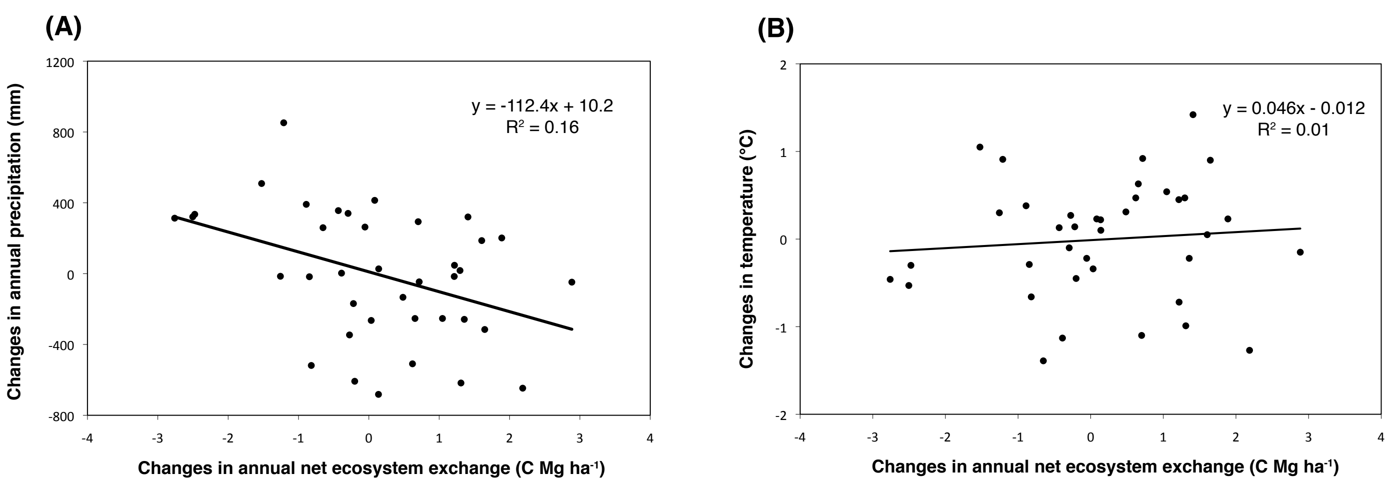



Figure 22—Relationship between net ecosystem exchange (NEE) on watershed WS79 with (A) precipitation and (B) temperature from 1950 to 1988.

streamflow and water table level. A continued warming trend will further affect forest hydrology by decreasing streamflow and water table in the summer and fall, especially if precipitation remains constant.

Although there is not enough observed data to demonstrate that hurricanes can substantially affect the water table in this watershed, streamflow did change and remained affected for several years following Hurricane Hugo. Large impacts to forest cover from destructive winds led to decreased transpiration and large water surplus conditions, in turn sustaining larger streamflow volumes for 5 to 8 years following the hurricane. From data collected from other large, yet non-destructive storm events, both streamflow and water table on those coastal forest landscapes on the southeast Atlantic Coastal Plain can increase in a short period in response to the large storm water volume.

The results from water balance budgets using different methods are similar. The mean streamflow was about 24 percent of water from precipitation, and ET occupied about 76 percent from 1946 to 2008, indicating that the eco-hydrology in this watershed is highly dependent on precipitation and ET. Based on the projections of the hydrologic changes of this forested watershed, using the synthesis of the observations and simulations, the extent of areas with wetland hydrology, dependent on shallow water table regulated by precipitation, will either shrink or disappear in the future; this is because the trend of increasing air temperature will cause an increase in ET demand.

The C dynamics simulated for this catchment using Forest-DNDC show that the model performs well for estimating biomass and soil C, and can be employed to assess the impacts of destructive winds on C sequestration to the forest ecosystems on the Santee Experimental Forest and similar landscape settings. The spatial differences in C dynamics, including soil $CO_2$, $CH_4$, and biomass in this watershed indicate that those biogeochemical "hot spots" influence C dynamics. Those spots cannot be negligible for evaluating C sequestration to and greenhouse emissions from the landscape mosaic with wetlands and uplands using biogeochemical models. These results also show that long-term climatic and hydrologic observations are of high value for multiple areas of study, and are specifically useful for the calibrations and validations of models, including hydrologic and biogeochemical models.

## ACKNOWLEDGMENTS

We acknowledge our predecessors on the Santee Experimental Forest who were responsible for initiating the long-term monitoring. We thank Charles Harrison, who has sustained the hydrologic and climatological monitoring stations since the late 1990s, and we thank Julie Arnold for maintaining the forest inventory studies. We also thank Tim Callahan, of the College of Charleston, and Bo Song, of Clemson University, for their helpful review of our manuscript.

## LITERATURE CITED

Aber, J.D.; Federer, C.A. 1992. A generalized, lumped-parameter model of photosynthesis, evapotranspiration, and net primary production in temperate and boreal forest ecosystems. Oecologia. 92: 463-474.

Abbott, M.B.; Bathurst, J.C.; Cunge, J.A. [and others].1986a. An introduction to the European Hydrological System–Systeme Hydrologique Europeen, "SHE",1: History and philosophy of a physically based, distributed modeling system. Journal of Hydrology. 87: 45-59.

Abbott, M.B.; Bathurst, J.C.; Cunge, J.A. [and others]. 1986b. An introduction to the European Hydrological System–Systeme Hydrologique Europeen, "SHE", 2: Structure of a physically based, distributed modelling system. Journal of Hydrology. 87: 61-77.

Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. 1998. Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. Rome, Italy: Food and Agriculture Organization.

Alley, W.M. 1984. On the treatment of evapotranspiration, soil moisture accounting, and aquifer recharge in monthly water balance methods. Water Resources Research. 20: 1137-1149.

Amatya, D.M.; Miwa, M.; Harrison, C.A. [and others]. 2006a. Hydrology and water quality of two first order forested watersheds in coastal South Carolina. In: Williams, T., ed. Hydrology and Management of Forested Wetlands: Proceedings of the International Conference. St. Joseph, MI: American Society of Agricultural and Biological Engineers: 15-25.

Amatya, D.M.; Radecki-Pawlik, A. 2007. Flow dynamics of three experimental forested watersheds in Coastal South Carolina. Acta Scientiarium Polonorum Formatio Cirtumiectus. 1: 3-17.

Amatya, D.M.; Skaggs, R.W.; Gregory, J.D. 1995. Comparison of methods for estimating REF-ET. Journal of Irrigation and Drainage Engineering; 121(6): 427-435.

Amatya, D.M.; Skaggs, R.W.; Gregory, J.D. 1996. Effects of controlled drainage on the hydrology of drained pine plantations in the North Carolina coastal plain. Journal of Hydrology. 181: 211-232.

Amatya, D.M.; Sun, G.; Trettin, C.C.; Skaggs, R.W. 2003. Long-term forest hydrologic monitoring in coastal Carolina. In: Renard, K.G.; McElroy, S.A.; Gburek, W.J. [and others]., eds. Proceedings of First Interagency Conference on Research in the Watersheds. U.S. Department of Agriculture, Agricultural Research Service: 279-285.

Amatya, D.M.; Sun, G.; Skaggs, R.W. [and others]. 2006b. Hydrologic effects of global climate change on a large drained pine forest. In: Hydrology and management of forested wetlands: Proceedings of the International Conference. Williams, T., ed. St. Joseph, MI: American Society of Agricultural and Biological Engineers: 583-594.

Amatya, D.M.; Trettin, C.C. 2007a. Development of watershed hydrologic research at Santee Experimental Forest, coastal South Carolina. In: Furniss, M.J.; Clifton, C.F.; Ronnenberg, K.L., eds. Advancing the fundamental sciences: Proceedings of the Forest Service national earth sciences conference. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture Forest Service, Pacific Northwest Research Station: 180-189.

Amatya, D.M.; Trettin, C.C. 2007b. Annual evapotranspiration of a forested wetland watershed, SC. Paper No. 072222. St. Joseph, MI: American Society of Agricultural and Biological Engineers. 16 p.

Amoah, J., Amatya, D.M.; Nnaji, S. 2012. Quantifying watershed depression storage: determination and application in a hydrologic model. Hydrologic Processes. Published online in wileyonlinelibrary.com DOI: 10.1002/hyp.9364.

Brooks, R.T. 2009. Potential impacts of global climate change on the hydrology and ecology of ephemeral freshwater systems of the forests of the Northeastern United States. Climate Change. 95: 469-483.

Callahan, T.J.; Cook, J.D.; Coleman, M.D. [and others]. 2004. Modeling storm water runoff and soil interflow in a managed forest, upper coastal plain of the Southeast United States. Paper No. 04-2254. St. Joseph, MI: American Society of Agricultural and Biological Engineers: 1-11.

Cui, J.; Li, C.; Sun, G.; Trettin, C. 2005. Linkage of MIKE SHE to Wetland-DNDC for carbon budgeting and anaerobic biogeochemistry simulation. Biogeochemistry. 72: 147-167.

Dai, Z.; Trettin, C.C.; Li, C. [and others]. 2010a. Sensitivity of streamflow and water table depth to potential climatic variability in a coastal forested watershed. Journal of American Water Resources Association. 45: 1036-1048.

Dai, Z.; Li, C.; Trettin, C.C. [and others]. 2010b. Bi-criteria evaluation of MIKE SHE model for a forested watershed on the South Carolina coastal plain. Hydrology and Earth System Sciences. 14: 1033-1046.

Dai, Z.; Trettin, C.C.; Li, C. [and others]. 2011a. Effect of assessment scale on spatial and temporal variations in $CH_4$, $CO_2$ and $N_2O$ fluxes in a forested wetland. Water, Air, and Soil Pollution. 223: 253-265.

Dai, Z.; Trettin, C.C.; Li, C. [and others]. 2011b. Climate variability and its impact on forest hydrology on South Carolina coastal plain of USA. Atmosphere. 2: 330-357.

Danish Hydraulic Institute (DHI). 2005. MIKE SHE technical reference. Version 2005. DHI Water and Environment. Denmark: Danish Hydraulic Institute.

Fissore, C.; Giardina, C.P.; Kolka, R.K.; Trettin, C.C. 2008. Soil organic carbon in forested mineral wetlands at different mean annual temperature. Soil Biology & Biogeochemistry. 41: 458-466.

Flerchinger, G.N.; Cooley, K.R. 2000. A ten-year water balance of a mountainous semi-arid watershed. Journal of Hydrology. 237: 86-99.

Frey, A.E.; Olivera, F.; Irish, J.L. [and others]. 2010. Potential impact of climate change on hurricane flooding inundation, population affected and property damages in Corpus Christi. Journal of the American Water Resources Association. 46: 1049-1059.

Gavilan, P.; Lorite, I.J.; Tornero, S.; Berengena, J. 2006. Regional calibration of Hargreaves equation for estimating reference ET in a semiarid environment. Agricultural Water Management. 81: 257-281.

Graham, D.N.; Butts, M.B. 2005. Chapter 10: Flexible integrated watershed modeling with MIKE SHE. In: Singh, V.P.; Frevert, D.K., eds. Watershed Models. Boca Raton, FL: CRC Press: 245-272.

Hansen, J.E.; Ruedy, R.; Sato, M.; Lo, K. 2010. Global surface temperature change. Reviews of Geophysics. 48: RG4004. 29 p.

Hansen, J.; Sato, M.; Ruedy, R. [and others]. 2006. Global temperature change. In: Proceedings of the National Academy of Science. 103: 14,288-14,293.

Harder, S.V. 2004. Hydrology and water budget of a first order forested coastal plain watershed, South Carolina. Charleston, SC: College of Charleston. 168 p. M.S. thesis.

Harder, S.V.; Amatya, D.; Callahan, T.J.; Trettin, C.C. 2006. Modeling the monthly water balance of a first order coastal forested watershed. In: Williams, T., ed. Hydrology and Management of Forested Wetlands: Proceedings of the International Conference, 8-12 April 2006, New Bern, North Carolina. St. Joseph, MI: American Society of Agricultural and Biological Engineers: 218-230.

Harder, S.V.; Amayta, D.M.; Callahan, T.J. [and others]. 2007. Hydrology and water budget for a forested Atlantic Coastal Plain watershed, South Carolina. Journal of the American Water Resource Assocation. 43: 563-575.

Hargreaves, G.H.; Samani, Z.A. 1985. Reference crop evapotranspiration from temperature. Applied Engineering in Agriculture. 1: 96-99.

Hartig, E.K.; Grozev, O.; Rosenzweig, C. 1997. Climate change, agriculture and wetlands in Eastern Europe: vulnerability, adaptation and policy. Climatic Change. 36: 107-121.

Hawley, N.R. 1949. The old rice plantation in and around the Santee Experimental Forest. Agricultural History. 23: 86–91.

Heath, R.C. 1975. Hydrology of the Albemarle-Pamlico Region of North Carolina. U.S. Geological Survey Water Resources Investigation 9-75. U.S. Geological Survey. 98 p.

Hook, D.D.; Buford, M.A.; Williams, T.M. 1991. Impact of Hurricane Hugo on the South Carolina coastal plain forest. Special Issue No. 8. Journal of Coastal Research: 291-300.

Hook, D.D.; Buford, M.A.; Williams, T.M. 1996. Impact of Hurricane Hugo on the South Carolina coastal plain forest. In: Haymond, J.L.; Hook, D.D.; Harms, W.R., eds. Hurricane Hugo: South Carolina forest land research and management related to the storm. Gen. Tech. Rep. SRS-5. U.S. Department of Agriculture Forest Service, Southern Research Station. 540 p.

Intergovernmental Panel on Climate Change (IPCC). 2001. Climate Change 2001: the scientific basis. Contribution of working group I to the third assessment report of the Intergovernmental Panel on Climate Change. Houghton, J.T.; Ding, Y.; Griggs, D.J. [and others], eds. Cambridge, United Kingdom and New York: Cambridge University Press. 881 p.

Intergovernmental Panel on Climate Change (IPCC). 2003. Good practice guidance for land use, land-use change and forestry. Penman, J.; Gytarsky, M.; Hiraishi, T. [and others], eds. Kanagawa, Japan: Intergovernmental Panel on Climate Change. 632 p. Chapter 3.

Inubushi, K.; Furukawa, Y.; Hadi, A. [and others]. 2003. Seasonal changes of $CO_2$, $CH_4$, and $N_2O$ fluxes in relation to land-use change in tropical peatlands located in coastal area of South Kalimantan. Chemosphere. 52: 603-608.

Karlsson, M. 2000. Nocturnal air temperature variations between forest and open areas. Journal of Applied Meteorology. 39: 851-862.

Kesik, M.; Bruggemann, N.; Forkel, R. [and others]. 2006. Future scenarios of $N_2O$ and NO emissions from European forest soils. Journal of Geophysical Research. 111: 2018-2022.

Kiese, R.; Li, C.; Hilbert, D.W. [and others]. 2005. Regional application of PnET-DNDC for estimating the $N_2O$ source strength of tropic rainforests in the wet tropics of Australia. Global Change Biology. 11: 128-144.

Kurbatova, J.; Li, C.; Varlagin, A. [and others]. 2008. Modeling carbon dynamics in two adjacent spruce forests with different soil conditions in Russia. Biogeosciences. 5: 969-980.

Lambert, F.H.; Stine, A.R.; Krakauer, N.Y.; Chiang, J.C.H. 2008. How much will precipitation increase with global warming? EOS Transactions, American Geophysical Union. May 20, 2008. 89(21). 193 p.

La Torre Torres, I.B. 2008. Seasonal relationships between precipitation and streamflow patterns related to watershed characterization of two third-order coastal plain watersheds in South Carolina. Charleston, SC: College of Charleston. 220 p. M.S. thesis.

La Torre Torres, I.B.; Amatya, D.M.; Sun, G.; Callahan, T.J. 2011. Seasonal rainfall–runoff relationships in a lowland forested watershed in the Southeastern USA. Hydrology Processes. 25: 2032-2045.

Laughlin, G.P. 1982. Minimum temperature and lapse rate in complex terrain: influencing factors and prediction. Archives for Meteorology Geophysics and Bioclimatology. 30B: 141-152.

Li, C.; Aber, J.; Stang, F. [and others]. 2000. A process-oriented model of $N_2O$ and NO emissions from forest soils. 1. Model development. Journal of Geophysical Research: Atmospheres. 105: 4369-4384.

Li, C.; Cui, J.; Sun, G.; Trettin, C.C. 2004. Modeling impacts of management on carbon sequestration and trace gas emissions in forested wetland ecosystems. Environmental Management (Supplement). 33: S176-186.

Li, C.; Frolking, S.; Frolking, T.A. 1992a. A model of nitrous oxide evolution from soil driven by rainfall events: 1. Model structure and sensitivity. Journal of Geophysical Research. 97: 9759-9776.

Li, C.; Frolking, S.; Frolking, T.A. 1992b. A model of nitrous oxide evolution from soil driven by rainfall events: 2. Model application. Journal of Geophysical Research. 97: 9777-9783.

Long, B.M. 1980. Soil survey of Berkeley County, South Carolina. Harrisburg: PA: U.S. Department of Agriculture. 99 p.

Lu, J.; Sun, G.; Amatya, D.M. [and others]. 2006. Understanding the hydrological response of a coastal plain watershed to forest management and climate change in South Carolina, USA. In: Williams, T., ed. Hydrology and Management of Forested Wetlands: Proceedings of the International Conference, 8-12 April 2006, New Bern, North Carolina. St. Joseph, MI: American Society of Agricultural and Biological Engineers: 231-239.

Lu, J.; Sun, G.; McNulty, S.G.; Amatya, D.M. 2003. Modeling actual evapotranspiration from forested watersheds across the Southern United States. Journal of the American Water Resources Association. 39: 887-896.

Lu, J.; Sun, G.; McNulty, S.G.; Comerford, N. 2009. Sensitivity of pine flatwoods hydrology to climate change and forest management in Florida, USA. Wetlands. 29: 826-836.

Moriasi, D.; Arnold, J.; Liew, M.W.V. [and others]. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. American Society of Agricultural and Biological Engineers. 50: 885-899.

McCabe, G.J.; Markstrom, S.L. 2007. A monthly water-balance model driven by a graphical user interface. U.S. Geological Survey Open-File Report. 2007-1088. U.S. Geological Survey. 6 p.

Miehle, P.; Livesley, S.J.; Feikema, P.M. [and others]. 2006. Assessing productivity and carbon sequestration capacity of *Eucalyptus globules* plantation using the process model Forest-DNDC: calibration and validation. Ecological Modeling. 192: 83-94.

Miller, R.D.; Johnson, D.D. 2002. The effect of soil moisture tension on carbon dioxide evolution, nitrification, and nitrogen mineralization. Soil Science Society of America Journal. 28: 644-647.

Miwa, M.; Gartner, D.L.; Bunton, C.S. [and others]. 2003. Characterization of headwater stream hydrology in the Southeastern lower coastal plain. Final Report IAG#: DW12945840-01-0. Charleston, SC: U.S. Department of Agriculture Forest Service, Southern Research Station. 33 p.

Monteith, J.L. 1965. Evaporation and environment. In: Proceedings of the 19th Symposium of the Society for Experimental Biology. New York: Cambridge University Press: 205-234.

Morecroft, M.D.; Taylor, M.E.; Oliver, H.E. 1998. Air and soil microclimates of deciduous woodland compared to an open site. Agricultural and Forest Meteorology. 90: 141-156.

Najjar, R.G.; Walker, H.A.; Anderson, P.J. [and others]. 2000. The potential impacts of climate change on the mid-Atlantic coastal region. Climate Research. 14: 219-233.

Nix, L.E.; Hook, D.D.; Williams, J.G.; Blaircom, D.V. 1996. Assessment of hurricane damage to the Santee Experimental Forest and the Francis Marion National Forest with a geographic information system. Gen. Tech. Rep. SRS-5. In: Haymond, J.L.; Hook, D.D.; Harms, W.R., eds. Hurricane Hugo: South Carolina forest land research and management related to the storm: 35-44.

Pacific, V.J.; McGlynn, B.L.; Riveros-Iregui, D.A. [and others]. 2009. Differential soil respiration response to changing hydrologic regimes. Water Resources Research. 45: W07201.

Pietsch, S.A.; Hasenauer, H.; Kucera, J.; Cermak, J. 2003. Modeling effects of hydrological changes on the carbon and nitrogen balance of oak in floodplains. Tree Physiology. 23: 735-746.

Quintana-Gomez, R.A. 1999. Trends of maximum and minimum temperatures in northern South America. Journal of Climate. 12: 2104-2112.

Richter, D.D.; Ralston, C.W.; Harms, W.R. 1983a. Chemical composition and spatial variation of bulk precipitation at a coastal plain watershed in South Carolina. Water Resources Research. 19: 134-140.

Richter, D.D.; Ralston, C.W.; Harms, W.R. 1983b. Prescribed fire: effects on water quality and forest nutrient cycle. Science. 215: 661-663.

Riekerk, H.; Jones, S.A.; Morris, L.A.; Pratt, D.A. 1979. Hydrology and water quality of three small lower coastal plain forested watersheds. In: Proceedings of the Soil and Crop Science Society of Florida. Horner, E.S, ed. Gainesville, FL: Soil and Crop Science Society of Florida. 38: 105-111.

Riveros-Iregui, D.A.; McGlynn, B.L. 2009. Landscape structure control on soil $CO_2$ efflux variability in complex terrain: scaling from point observation to watershed scale fluxes. Journal of Geophysical Research. 114: 1-14.

Sahoo, G.B.; Ray, C.; Carlo, E.H. 2006. Calibration and validation of a physically distributed hydrological model, MIKE SHE, to predict streamflow at high frequency in a flashy mountainous Hawaii stream. Journal of Hydrology. 327: 94-109.

Saucier J.R.; Clark III., A. 1985. Tables for estimating total tree and product weight and volume of major southern tree species groups. Southwide Energy Committee. Washington, DC: American Pulpwood Association, Inc. 57 p.

Scavia, D.; Field, J.C.; Boesch, D.F. [and others]. 2002. Climate change impacts on U.S. coastal and marine ecosystems. Estuaries. 25: 149-164.

Schroth, G. 1995. Tree root characteristics as criteria for species selection and systems design in agroforestry. Agroforestry Systems. 30: 125-143.

Sepaskhah, A.R.; Razzaghi, F. 2009. Evaluation of the adjusted Thornthwaite and Hargreaves-Samani methods for estimation of daily evapotranspiration in a semi-arid region of Iran. Archive of Agronomy and Soil Science. 55: 51-66.

Smith, H.R. 2012. In land of cypress and pine: an environmental history of the Santee Experimental Forest, 1683-1937. Gen. Tech. Rep. SRS-155. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. 17 p.

Smith, J.E.; Heath, L.S.; Jenkins, J.C. 2003. Forest volume-to-biomass models and estimates of mass for live and standing dead trees of U.S. forests. Gen. Tech. Rep. NE-298. Newtown Square, PA: U.S. Department of Agriculture Forest Service, Northeastern Research Station. 57 p.

Smith, P.; Fang, C.; Dawson, J.J.C.; Moncrieff, J.B. 2008. Impact of global warming on soil organic carbon. Advances in Agronomy. 97: 1-43.

Stang, F.; Butterbach-Bahl, K.; Papen, H. 2000. A process-oriented model of $N_2O$ and NO emissions from forest soils. 2. Sensitivity analysis and validation. Journal of Geophysical Research. 105: 4385-4398.

Sulzman, E.W.; Brant, J.B.; Bowden, R.D.; Lajtha, K. 2005. Contribution of aboveground litter, belowground litter, and rhizosphere respiration to total soil $CO_2$ efflux in an old growth coniferous forest. Biogeochemistry 73: 231-256.

Sun, G.; Amatya, D.M.; McNulty, S.G. [and others]. 2000. Climate change impacts on the hydrology and productivity of a pine plantation. Journal of the American Water Resources Association. 36: 367-374.

Sun, G.; Callahan, T.J.; Pyzoha, J.E.; Trettin, C.C. 2006. Modeling the climatic and geomorphologic controls on the hydrology of a Carolina bay wetland in South Carolina, USA. Wetlands. 26: 567-580.

Trenberth, K.E.; Jones, P.D.; Ambenje, P. [and others]. 2007. Observations: surface and atmospheric climate change. In: Solomon, S.; Qin, D.; Manning, M. [and others], eds. Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York: Cambridge University Press.

Trettin, C.C.; Jurgensen, M.F. 2003. Carbon cycling in wetland forest soils. In: Kimble, J.; Birdsie, R.; Lal, R., eds. Carbon sequestration in U.S. forests. Boca Raton, FL: CRC Press LLC: 311-331.

Trettin, C.C.; Laiho, R.; Minkkinen, K.; Laine, J. 2006. Influence of climate change factors on carbon dynamics in northern forested peatlands. Canadian Journal Soil Science. 86: 269-280.

Trettin, C.C., D.M. Amatya, C. Kaufman, [and others]. 2009. Recognizing change in hydrologic functions and pathways due to historical agricultural use – implications to hydrologic assessments and modeling. In: Webb, R.M.T.; Semmens, D.J., eds. Planning for an uncertain future—monitoring, integration, and adaptation. Proceedings of the Third Interagency Conference on Research in the Watersheds: U.S. Geological Survey Scientific Investigations Report 2009-5049: 273-277.

Turner, K.M. 1991. Annual evapotranspiration of native vegetation in a Mediterranean-type climate. Water Resources Bulletin. 27: 1-6.

Ward, R.C. 1972. Checks on the water balance of a small catchment. Nordic Hydrology. 3: 44-63.

Wentz, F.J.; Ricciardulli, L.; Hilburn, K.; Mears, C. 2007. How much more rain will global warming bring? Science. 317: 233-235.

Wilson, L.; Amatya, D.; Callahan, T.; Trettin, C. 2006. Hurricane impact on streamflow and nutrient exports for a first-order forested watershed of the lower coastal plain, South Carolina. Second Interagency Conference on Research in the Watersheds. Otto, NC: U.S. Department of Agriculture Forest Service, Coweeta Hydrologic Laboratory: 169-180.

Wolock, D.M.; McCabe, G.J. 1999. Estimates of runoff using water-balance and atmospheric general circulation models. Journal of the American Water Resources Association. 35: 1341-1350.

Xu, M.; Qi, Y. 2001. Soil-surface $CO_2$ eflux and its spatial and temporal variations in a young ponderosa pine plantation in northern California. Global Change Biology. 7: 667-677.

Xu, C-Y; Singh, V. 2005. Evaluation of three complementary relationship evapotranspiration models by water balance approach to estimate actual regional evapotranspiration in different climatic regions. Journal of Hydrology. 308: 105-121.

Yan, J.; Smith, K. 1994. Simulation of integrated surface water and ground water systems–model formulation. Water Resources Bulletin. 30: 1-12.

Young, C.E., Jr. 1966. Water balance on a forested watershed in the flatwoods. In: Proceedings, Association of Southern Agricultural Workers 63rd Annual Convention. Jackson, MS, Feb. 7-9 1966. American Society of Agronomy, Madison, WI.

Young, C.E., Jr.; Klaiwitter, R.A. 1968. Hydrology of wetland forest watersheds. In: Proc of CUCOH Hydrol. Conference. Clemson, SC: Clemson University, March 28-29, 1968: 29-38.

Young, C.E., Jr.; Klawitter, R.A. 1968. Hydrology of wetland forest watersheds. Proceedings, Hydrology in Water Resources Management, WRRI Report. Clemson, SC: Clemson University. 4: 29-38.

Young, C.E., Jr.; Klaiwitter, R.A.; Henderson, J.E. 1972. Hydrologic model of a wetland forest. Journal Soil and Water Conservation. 27: 122-124.

Zhai, P.M.; Ren, F.M. 1999. On change of China's maximum and minimum temperatures in 1951–1990. Acta Meteorology Sinapore. 13: 278–290.

Zhang, Y.; Li, C.; Trettin, C.C. [and others]. 2002. An integrated model of soil, hydrology and vegetation for carbon dynamics in wetland ecosystems. Global Biogeochemical Cycles. 16: 1-17.

Zhang, X.; Zwiers, F.W.; Hegerl, G.C. [and others]. 2007. Detection of human influence on twentieth-century precipitation trends. Nature. 448: 461-465.

**Zhaohua Dai; Trettin, Carl C.; Amatya, Devendra M**. 2013. Effects of climate variability on forest hydrology and carbon sequestration on the Santee Experimental Forest in coastal South Carolina. Gen. Tech. Rep. SRS–172. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. 32 p.

Long-term weather and hydrology data from the Santee Experimental Forest were used to assess trends in air temperature, precipitation, and the water balance in gauged watersheds over a 63-year period. Since 1946, the mean annual air temperature has increased at a rate of 0.19 °C per decade, a rate higher than the global mean for the same period. Total annual precipitation has not changed significantly over the period of 1946–2008; however, large storm events (>50 mm precipitation) have increased 21 percent over the 63-year period. Annual stream discharge has varied from 5.5 percent of annual precipitation in dry years to 44.7 percent in wet years. In 1989, much of the forest was destroyed by Hurricane Hugo, a disturbance that, in turn, influenced streamflow. The water balance was estimated using the hydrologic model MIKE SHE; the long-term simulations showed that average annual flow was about 24 percent of annual precipitation and that mean annual evapotranspiration was approximately 76 percent over the 63-year period. The carbon balance on the 500-ha watershed was evaluated using Forest-DNDC. The model performance efficiency was 0.67 for soil $CO_2$ efflux, 0.70 for soil temperature, 0.40 for soil moisture, and 0.86 for wood biomass dynamics, demonstrating that this model was applicable for predicting carbon dynamics for this complex forest mosaic.

**Keywords:** Carbon cycling, climate change, Forest-DNDC, forest hydrology, long-term weather data, streamflow.