Long-term temperature and precipitation trends at the Coweeta Hydrologic Laboratory, Otto, North Carolina, USA

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ABSTRACT

Coweeta Hydrologic Laboratory, located in western North Carolina, USA, is a 2,185 ha basin wherein forest climate monitoring and watershed experimentation began in the early 1930s. An extensive climate and hydrologic network has facilitated research for over 75 years. Our objectives in this paper were to describe the monitoring network, present long-term air temperature and precipitation data, and analyze the temporal variation in the long-term temperature and precipitation record. We found that over the period of record: (1) air temperatures have been increasing significantly since the late 1970s, (2) drought severity and frequency have increased with time, and (3) the precipitation distribution has become more extreme over time. We discuss the implications of these trends within the context of regional and global climate change and forest health.

Key words | climate, long-term, precipitation, quantile regression, temperature, time series

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INTRODUCTION

The Coweeta Hydrologic Laboratory is among the oldest, continuously operating, environmental study sites in North America and is located in the eastern deciduous forest of the southern Appalachian Mountains in North Carolina, USA (Figure 1). The laboratory was established in 1934 to determine the fundamental effects of forest management on soil and water resources and to serve as a testing ground for theories in forest hydrology (Swank & Crossley 1988). To facilitate this, a network of climate and precipitation stations was established across the site (Figure 1, Tables 1 and 2). The research program has since expanded its focus to encompass watershed ecosystem science. The original climate and precipitation network continues to facilitate these studies and serves as the foundation of the long-term data record.

Forested ecosystems are inherently complex and require a long-term perspective to evaluate responses to natural disturbances and management. Long-term climate data can be an especially important part of this perspective, particularly when evaluating watershed responses to pulse and press climatic events. Without long-term datasets that encompass a wide range of conditions, quantifying hydrologic and ecologic thresholds can be challenging, and identifying cyclical trends or changes in key climate variables can be impossible (Moran *et al.* 2008). A comprehensive description and analysis of the first 50 years of the climate data recorded at Coweeta was published in 1988 (Swift *et al.* 1988). In that study, few climate trends were evident. For example, no significant trends in maximum or minimum annual temperatures, or changes in the distribution of precipitation were detected. Since then, in the southeastern USA, the last 25 years have been characterized by marked changes in key climate variables, including increases in precipitation (Karl & Knight 1998; Groisman *et al.* 2004) leading to greater streamflow (Groisman *et al.* 2004), increased minimum temperatures (Portmann *et al.* 2009), especially minimum temperatures in the summer months (Groisman *et al.* 2004), and increased cloud cover (Dai *et al.* 2006). In addition, the variability of precipitation has also changed in the southeastern USA, with increases in extreme precipitation events (Groisman *et al.* 2004) including high intensity rainfall as well as extreme droughts (Karl & Knight 1998). The ability to separate actual changes or significant trends in climatic variables from

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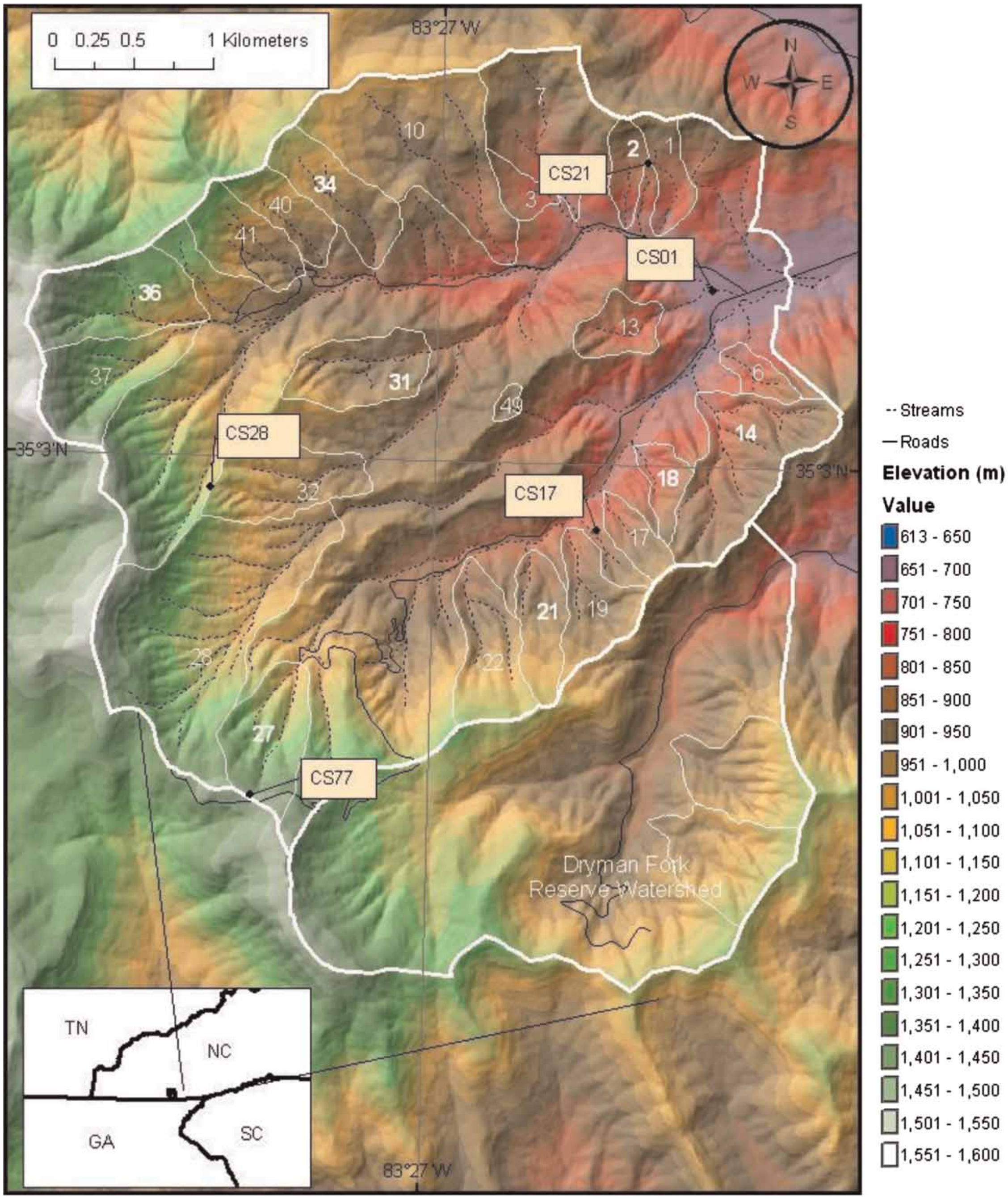

Figure 1 | Elevation gradients and main and sub-watersheds (bold and non-bold white lines, respectively) at Coweeta Hydrologic Lab. Numbers denote reference (bold) and experimental (non-bold) watersheds. Climate stations are identified by white text. Inset: location of Coweeta Basin with respect to southeast USA.

natural variability requires long-term records. Hence, these long-term records are critical for detecting historical changes in climate and they can serve as benchmarks for detecting future change. Our objectives were to provide an update of the climate and precipitation network in the Coweeta Basin, summarize the long-term temperature and precipitation data in the Coweeta Basin, and analyze the temporal variation in these two data series.

Table 1 | Location, elevation and description of climate station network

	Climate station				
	CS01	**CS17**	**CS21**	**CS28**	**CS77**
Location (lat/long)	35°03′37.48 83°25′48.36	35°02′43.33 83°26′14.63	35°03′59.63 83°26′09.12	35°02′47.60 83°27′54.05	35°01′49.27 83°27′37.60
Elevation (m)	685	887	817	1,189	1,398
Aspect	Valley floor	N-facing	S-facing	E-facing	NE-facing
SRG[a]	19	96	17	06	77
RRG[a]	06	96			
Date of first record[b]	8/1934	10/1969	7/1974	5/1985	4/1992
Sensors[c] (units)					
Barometric air pressure (kPa)	✓				
Atmospheric CO_2 concentration (ppm)	✓				
Air temperature (°C) and humidity (%, kPa/kPa)[d]	✓	✓	✓	✓	✓
Photosynthetically active radiation (μmol m^{-2} s^{-1})	✓	✓	✓	✓	✓
Pan evaporation (mm)	✓				
Solar radiation (Ly)	✓				
Soil and litter temperature[e] (°C)		✓	✓	✓	✓
Wind speed (m s^{-1}) and direction (°)	✓	✓	✓	✓	✓

[a]SRG denotes Standard Rain Gage, RRG denotes Recording Rain Gage (See Table 2). Climate stations 21, 28 and 77 have only standard rain gages.
[b]Barometer, photosynthetically active radiation, and digital air relative humidity and temperature sensors added at a later date.
[c]See text for make and model numbers and vendor information of sensors.
[d]Humidity and temperature are recorded with both a hygrothermograph instrument and an HMP45c sensor. Both are located adjacent to National Weather Service maximum, minimum and standard thermometers. Air temperature and humidity readings taken in open field setting as well as within forested cover at all climate stations except CS01.
[e]Only in forest setting.

Table 2 | Location, elevation and date of first record of all paired recording and standard rain gages (RRG and SRG, respectively)

Gage or Station	SRG	Location (lat/long)	Elevation (m)	Date of first record	Aspect
RRG06	19	35°03′37.48/83°25′48.36	687	6/4/1936	Valley bottom
RRG05	02	35°03′37.77/83°27′53.98	1,144	6/4/1936	SE-facing
RRG20	20	35°03′53.37/83°26′29.18	740	11/5/1962	Stream bottom
RRG31	31	35°01′57.89/83°28′05.24	1,366	11/1/1958	High elevation gap
RRG40	13	35°03′44.77/83°27′22.18	961	11/10/1942	S-facing
RRG41	41	35°03′19.11/83°25′43.32	776	5/1/1958	N-facing
RRG45	12	35°02′50.19/83°27′31.11	1,001	6/1/1942	Low elevation gap
RRG55	55	35°02′23.59/83°27′19.32	1,035	11/5/1990	N-facing
RRG96	96	35°02′43.33/83°26′14.63	894	11/1/1943	N-facing

SITE DESCRIPTION

The Coweeta Hydrologic Laboratory is located within the Nantahala Mountain Range of western North Carolina, USA, latitude 35°03′ N, longitude 85°25′ W (Figure 1). The Coweeta Hydrologic Lab is 2,185 ha in area and comprised of two adjacent, east-facing basins. The larger of the two basins (1,626 ha), Coweeta Basin, has been the primary focus of watershed experimentation. Within the basin, elevations range from 675 to 1,592 m. Climate is classified as maritime, humid temperate (Trewartha 1954; Critchfield 1966).

Historic vegetation patterns in the basin have been influenced by human activity, primarily through small homestead agriculture, both clear-cut and selective logging, the introduction of chestnut blight (*Cryphonectria parasitica)* (Elliott & Hewitt 1997) and hemlock woolly adelgid (*Adelges tsugae*) (Nuckolls *et al*. 2009), and fire management (Hertzler 1936; Douglass & Hoover 1988). The resulting unmanaged forests are relatively mature (~85 years old) oak-hickory (at lower elevations) and northern hardwood forests (at higher elevations) with an increasing component of fire-intolerant species (Elliott & Swank 2008). Bedrock is comprised of granite-gneiss and mica-schist. Soils are immature Inceptisols and older Ultisols and are relatively high in organic matter and moderately acid with both low cation exchange capacity and base saturation.

METHODS

Climate network

Daily temperature and precipitation data have been recorded at the main climate station (CS01) continuously since 1934 (Table 1). In addition to CS01, there are four climate stations across the basin (Table 1). In the 1980s, measurements at each of these stations were expanded in scope and temporal resolution. Each of these stations now continually measures and records (CR10X, Campbell Scientific, Inc., Logan, UT, USA. The following variables every 5 min: temperature and relative humidity in both an open field and forested setting (HMP45c, Campbell Scientific, Logan, UT, USA), photosynthetically active radiation (LI-190-SB, Campbell Scientific), soil and litter temperature under forest cover (107-L, Campbell Scientific) and wind speed and wind direction at canopy height (014A and 024A, MetOne Instruments, Grants Pass, OR, USA). Barometric air pressure (Vaisala CS106, Campbell Scientific), solar radiation (model 8–48, Eppley Lab, Inc., Newport, RI, USA), atmospheric CO_2 concentration (Licor LI-820, Licor, Lincoln, NE, USA) and pan evaporation are measured only at CS01. Data retrieval from the climate network is via wireless remote access. All data recorded to the CR10X datalogger are transmitted via radio frequency (Freewave Technologies, Inc., FGR-115RC, Boulder, CO) from each of the four climate stations to a computer server in the data processing office.

Temperature is recorded at CS01 at 0800 EST daily using a National Weather Service (NWS) maximum, minimum and standard thermometer. Daily minimum and maximum temperatures are recorded and then averaged to determine the average minimum or maximum temperature for the month. In addition, air temperature is digitally recorded on a 5 min increment (CR10X, Campbell Scientific). These values are averaged and hourly maximum, minimum and average temperatures are stored. Weekly absolute maximum and minimum temperatures are recorded at all other climate stations with NWS maximum and minimum thermometers.

Total daily precipitation is collected by an 8 in. Standard Rain Gage (NWS). Rainfall volume and intensity are recorded by Recording Rain Gage (Belfort Universal Recording Rain Gage, Belfort Instrument Co., Baltimore, MD, USA). A network of nine Recording Rain Gages and 12 Standard Rain Gages are located throughout the basin (Table 2). (The use of trade or firm names in this publication is for reader information and does not imply endorsement by the US Department of Agriculture of any product or service.)

Statistical models

To describe the climate data, we present means, extremes, deviations from long-term means, and simple Pearson's correlation coefficients (R) among climate variables and time. To test the hypotheses that mean, maximum and minimum annual air temperature (T, °C) has been increasing in the recent part of the record by fitting a time series intervention models to T data, method is described in detail in Ford *et al.* (2005). Candidate models were a simple level, or a mean level plus a linear increase starting at time t. Each potential starting time in the 1975–1988 range, which was the visual range of the temperature increase, was evaluated sequentially (PROC ARIMA, SAS v9.1, SAS Institute, Inc.). We computed Akaike's information criterion (AIC) for each model, which is a statistic used to evaluate the goodness of fit and parsimony of a candidate model, with smaller AIC values indicating a better fitting and more parsimonious model than larger values (Johnson & Omland 2004). We used the differences in the AIC values among candidate models with all starting times ($\Delta_i = \mathrm{AIC}_i - \mathrm{AIC}_{\min}$) to compute a relative weight (w_i) for each model relative to all models fit:

$$w_i = \frac{e^{-0.5\Delta_i}}{\sum_{r=1}^{R} e^{-0.5_i \Delta_r}}, \tag{1}$$

with the sum of all w_i equal to 1. The final model selected was the model with the highest w_i (Burnham & Anderson 2002; Johnson & Omland 2004).

We explored whether the high and low ends of the precipitation distribution were changing over time with quantile regression (Cade & Noon 2003). We analyzed linear trends in all quantiles of precipitation (P, mm) to quantify changes to the distribution of annual and monthly precipitation. We used data from the high- and low-elevation standard rain gages (SRG 19 and 31, Table 2) for the entire period of record. Our model predicted the precipitation amount as a function of year, with elevation as a covariate. All models were fit using PROC QUANTREG in SAS (v9.1, SAS Institute, Inc.). If the bootstrapped 95% confidence interval around the estimated coefficient for the quantile overlapped zero, we interpreted this as no significant time trend. To check whether annual precipitation totals from the two gages were consistent over time, we fit a linear model predicting precipitation from SRG 19 as a function of precipitation from SRG 31, year, and the interaction of year and SRG 31 (PROC GLM).

RESULTS

Temperature

Daily and seasonal temperatures do not fluctuate widely (Figure 2). Temperatures are most variable in the winter months. The warmest year on record occurred in 1999

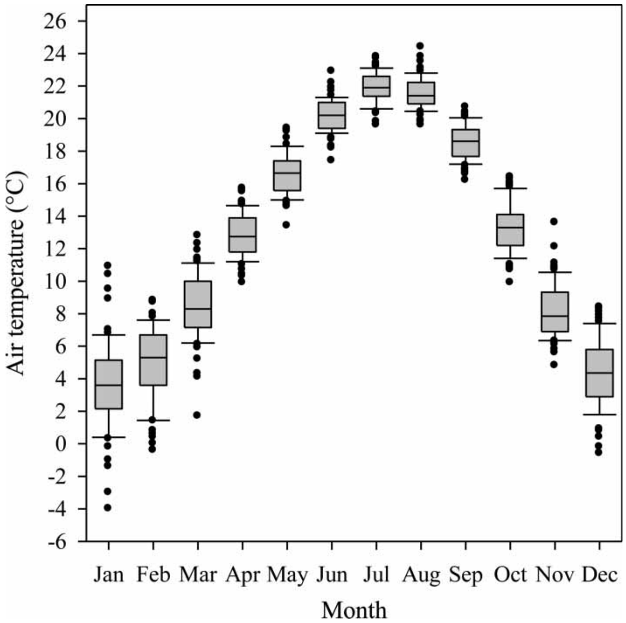

Figure 2 | Monthly mean air temperature at CS01 (see Table 1). Boxes show 75th, 50th, and 25th percentiles. Whiskers show 90th and 10th percentiles. Each outlier (observations outside the 90th and 10th percentiles) is shown.

(average maximum temperature of 21.5 °C). The coldest year on record was 1940 with a minimum of 4.1 °C.

Average annual, maximum and minimum air temperatures at the site have increased significantly relative to the long-term mean (Figure 3). The warming trend is apparent

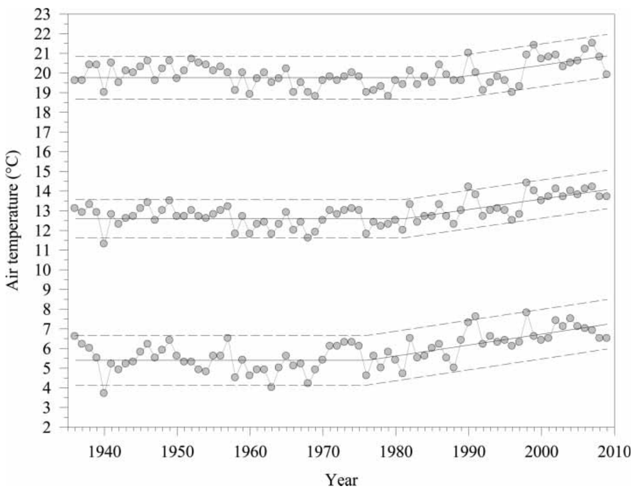

Figure 3 | Long-term average annual, maximum and minimum air temperatures at Coweeta Hydrologic Lab, CS01 (see Table 1). Solid black lines correspond to the modeled mean, with a time series intervention model containing a ramp function at 1981, 1988, and 1976 for average, maximum and minimum data. Dashed lines are the upper and lower 95% confidence intervals about the modeled mean.

in all temperature series (for growing season temperature analysis see Ford *et al.* (2011)), and appeared to begin in the late 1970s to late 1980s. The most parsimonious statistical models indicate a significant increase in average minimum temperatures beginning in 1976 ($w_i = 0.16$), with a rate of increase away from the 5.4 °C long-term mean of 0.5 °C per decade. This same rate of increase occurred in the average annual data series in 1981 ($w_i = 0.13$), and in the annual maximum temperature series in 1988 ($w_i = 0.17$). Average dormant and growing season temperatures also show this trend (data not shown).

Precipitation

Annual precipitation at Coweeta is among the highest in the eastern USA, averaging 1,794 mm (CS01 station, Figure 4(a)). The basin receives frequent, small, low-intensity storms in all seasons, with the wetter months in late winter and early spring. Fall months are drier (Figure 4(b)), but generally have larger, more intense tropical storm activity. Elevation has a strong influence on precipitation amount (Figure 4(b)). For example, precipitation at 1,398 m in elevation is 32% (±6% SD) higher than that at 685 m. Although P increases with elevation at the site, P amounts among the rain gages are highly correlated ($0.96 < R^2 < 0.99$), and this relationship is consistent over time (P vs. time $R = 0.02$; no P by year interaction $Pr = 0.73$, $F_{1.73} = 0.12$).

Annual precipitation totals are also becoming more variable over time, with wetter wet years and drier dry years (Figure 5(a) and (b)). Coweeta experienced the wettest year on record in 2009 with a total of 2,375 mm. Only 2 years prior, in 2007, the driest year on record occurred with 1,212 mm. Low quantiles, ~10–20%, had a significant negative slope over time. Higher quantiles, 65–75%, had a significant positive slope over time. This indicates that the low and high ends of the annual precipitation distribution in the basin changed during the period of record. During the wettest years, not all months were wetter; and similarly, during the driest years, not all months were drier. Our results show that the summer months became drier over time, while the fall months became more wet (Figure 5(c)–(f)). In general, most quantiles describing July precipitation declined over time. In September, only the most extreme part (>85%) of the distribution increased over time due to an increase in high intensity, shorter duration storm events, such as tropical storms, as opposed to an increase in the number of storms per month. For example, the number of storms occurring in September did not increase over time ($R = -0.01$, Figure 6(a)), but the percentage of September storms that fell above the 75th percentile (16.5 mm) appears to increase substantially in the latter part of the record (Figure 6(b)). Other fall months became wetter over time, mainly due to increases in the lower percentile storms (data not shown).

In addition to more intense precipitation, recent climate patterns trend toward more frequent periods of prolonged

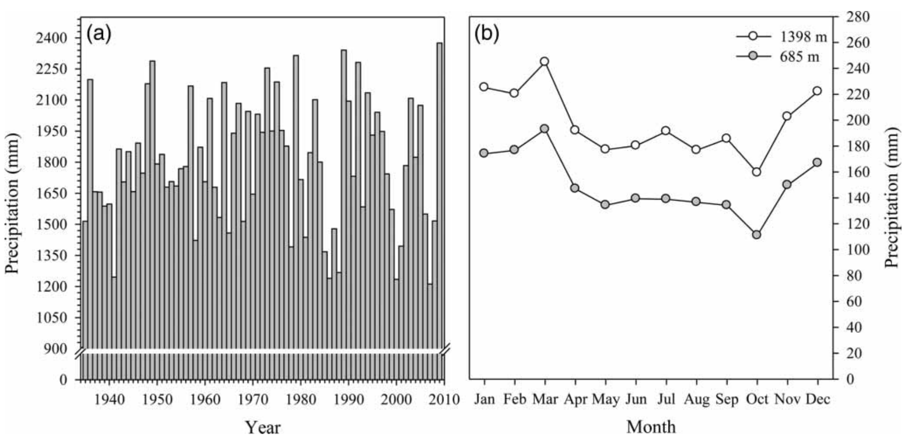

Figure 4 | Total annual precipitation (a) recorded at CS01, and average monthly precipitation (b) at low- and high-elevation stations (see Table 1).

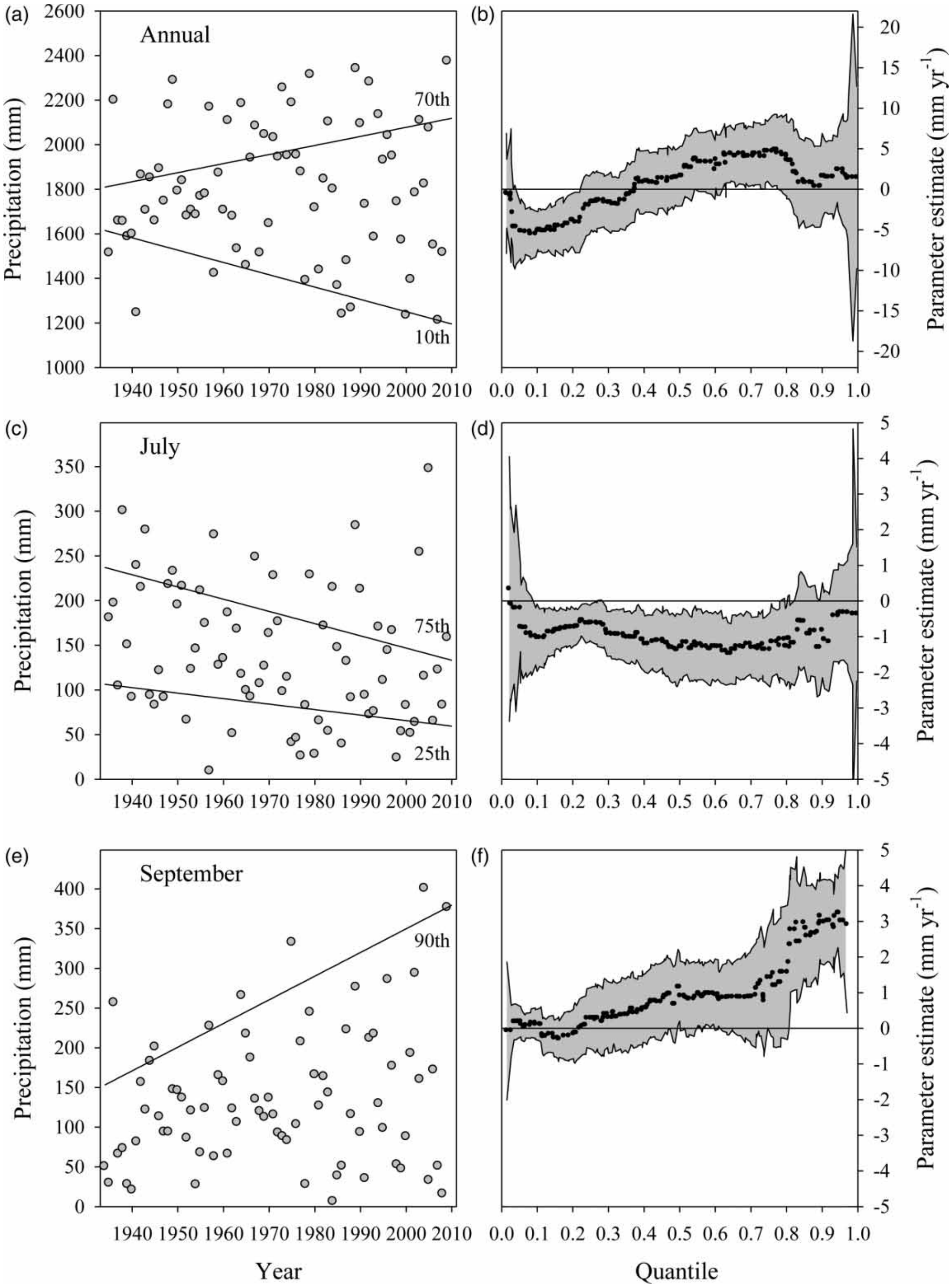

Figure 5 | Annual (a), July (c) and September (e) total precipitation from CS01 (see Table 1). Lines show the modeled *q*th quantile as a function of time. Slopes of all lines shown are significantly different than zero. Panels on right show the modeled estimates (symbols) of the quantile slope conditional on year, for annual (b), July (d) and September (f) precipitation totals. Bootstrapped upper and lower 95% confidence intervals also shown for parameter estimates (grey area).

drought (Figure 7) as inferred by comparing annual totals against the long-term mean. In addition, drought severity (accumulated deficit in precipitation over time) is increasing with time ($R = -0.35$, $t_{0.05,37} = -2.29$, $Pr = 0.01$). Beginning with a severe drought in 1985, a 1,600 mm deficit in rainfall accumulated through 2008.

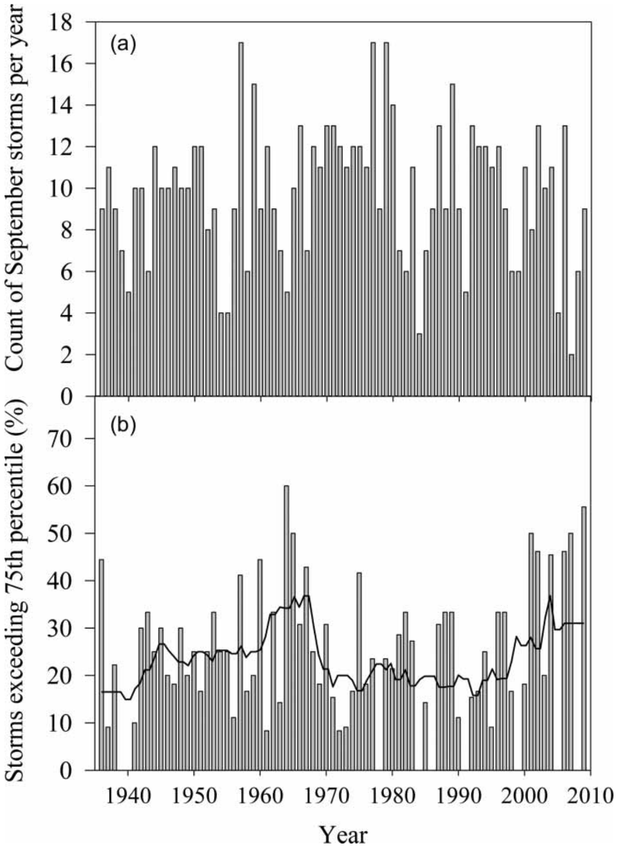

Figure 6 | (a) Number of precipitation events in September for each year in the long-term record, and (b) the percentage of those events that fall above the 75th percentile (16.5 mm). Solid line in (b) is a 10 yr moving average.

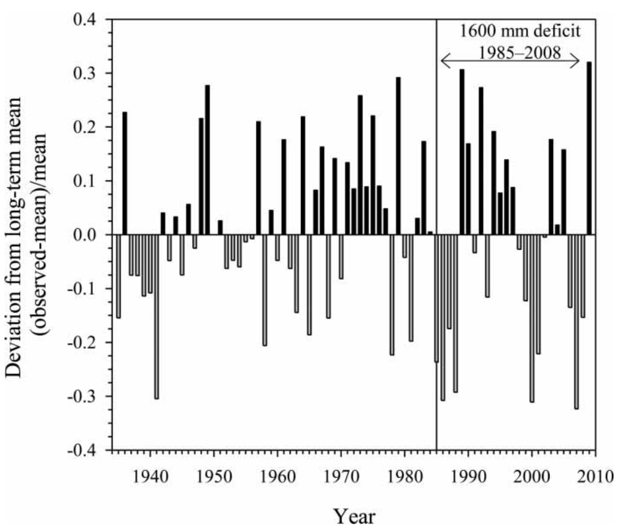

Figure 7 | Deviation of annual precipitation amounts from the long-term mean recorded at CS01 (see Table 1).

DISCUSSION

Climate change

The increased mean annual air temperature (i.e. 0.5 °C per decade) observed since the early 1980s at Coweeta is consistent with other global and regional observations. In the observed climate records, globally, the 20 warmest years have all occurred since 1981 (Peterson & Baringer 2009). Across the USA, a significant warming trend in air temperature also began in the late 1970s to early 1980s (Groisman *et al*. 2004; Peterson & Baringer 2009). This warming trend is predicted to continue; ensemble atmosphere-ocean general circulation models (AOGCMs) predict that by the early 21st century (2030), southeastern US air temperatures will increase at a rate of 0.5 °C per decade (IPCC 2007). Causes for the increases in air temperature include both natural (i.e. surface solar radiation) and anthropogenic (e.g. ozone and CO_2 concentrations) sources, and potential interactions of sources (IPCC 2007). For example, as aerosols increase, surface solar radiation is reduced (i.e. global dimming), which decreases surface temperatures (Wild 2009). One explanation of the lack of significant warming in the 1950–1980 period, followed by the rapid warming in the last 25 years, is that the lower surface solar radiation in the former period masked the warming trend, while the higher surface solar radiation in the latter period apparently accelerated warming (Wild 2009). Although cause and effect is difficult to establish, the timing of increased surface solar radiation is coincident with the passage and implementation of the 1977 Clean Air Act (CAA) and the 1990 CAA Amendments in the USA, which have been quite effective at reducing anthropogenic aerosols (Streets *et al*. 2006). Similar to our hypothesis here, over Europe a 60% reduction in aerosols has been linked to the 1 °C increase in surface temperature since the 1980s due to impacts on shortwave and long-wave forcing (Philipona *et al*. 2009).

Precipitation is increasing in the southeast, similar to what we observed in the Coweeta Basin (Karl & Knight 1998; Groisman *et al*. 2004). These increases in precipitation have translated to increases in streamflow according to long-term US Geological Survey streamflow data (Karl & Knight

1998; Lins & Slack 1999; IPCC 2007). Recent trends in eastern US precipitation, and specifically those in the Coweeta Basin, have been linked to regular patterns in the North Atlantic Oscillation (Riedel 2006a, b). A trend in drier summers since the 1980s has occurred for the southeast (Groisman *et al.* 2004; Angert *et al.* 2005). Simultaneously, a trend in wetter fall months has also occurred (Groisman *et al.* 2004). Our findings in the Coweeta Basin are consistent with both of these larger-scale regional patterns. Whether the trend of increasing precipitation will continue for the region in a warmer, higher-CO_2 scenario is uncertain. Most AOGCMs do not agree on the predicted change in direction of future precipitation for the southern Appalachians and southeast USA, e.g. wetter vs. drier (IPCC 2007).

Many regions of the USA have experienced an increased frequency of precipitation extremes, droughts and floods over the last 50 years (Easterling *et al.* 2000; Groisman *et al.* 2004; Huntington 2006; IPCC 2007). As the climate warms in most AOGCMs, the frequency of extreme precipitation events increases across the globe, resulting in an intensification of the hydrologic cycle (Huntington 2006). For example, the upper 99th percentile of the precipitation distribution is predicted to increase by 25% with a doubling of CO_2 concentration (Allen & Ingram 2002). The lower end of the precipitation distribution is also predicted to change. Forecasts of the drought extent over the next 75 years show that the proportion of land mass experiencing drought will double from 15 to 30% (Burke *et al.* 2006). For example, with a doubling in the peak CO_2 concentration, dry season precipitation is expected to decline irreversibly on average by 15% on most land masses (Solomon *et al.* 2009). The timing and spatial distribution of extreme precipitation events are among the most uncertain aspects of future climate scenarios, however (Karl *et al.* 1995; Allen & Ingram 2002). Our results show that the extremes of the annual precipitation distribution are increasing in magnitude, with recent increases in the frequency of drought, and wetter wet years and drier dry years. We have observed the most extreme precipitation changes in the fall months, with increases in intense rainfall in September in particular. This is partly associated with precipitation generated from tropical storm events. However, a wetter fall season is also being observed due to an increase in the low percentile rain events in November (Ford *et al.* 2011).

Effects on forest function and health

Observed changes in temperature and precipitation distributions that have occurred both locally and regionally have significantly affected forest function and health. The eastern USA has experienced an earlier onset in spring due to rising temperatures (Czikowsky & Fitzjarrald 2004), which has increased spring forest evapotranspiration (Czikowsky & Fitzjarrald 2004) and growth (Nemani *et al.* 2003; McMahon *et al.* 2010). However, the increase in spring growth has been largely offset by drier summers in the southeast (Angert *et al.* 2005), and areas with observed sustained increases in forest growth over time have been those in the northeast (McMahon *et al.* 2010) and at the highest elevations (Salzer *et al.* 2009), where temperatures are more limiting than water, and the tropics (Nemani *et al.* 2003), where radiation is the primary limiting factor.

Whether forest productivity is experiencing recent increases concomitant with temperature increase in the Coweeta Basin has not yet been reported. The effects of extreme events, most notably drought, have had a more dramatic effect on forest health and forest species composition than the trends in temperature. Native insect outbreaks, e.g. southern pine beetle (*Dendroctonus frontalis*), are triggered by drought. The successive droughts in the 1980s and late 1990s caused widespread southern pine beetle infestations in Coweeta watersheds, and throughout the southern Appalachians. As a result of these outbreaks, a decrease in pitch pine (*Pinus rigida*) stands and increased canopy gap area due to dead or dying snags (Clinton *et al.* 1993; Vose & Swank 1994; Kloeppel *et al.* 2003) occurred. The growth of eastern white pine (*Pinus strobus*) has also been significantly reduced by drought (Vose & Swank 1994; McNulty & Swank 1995).

Deciduous hardwood ecosystems have also been impacted by droughts. For example, accelerated mortality of oaks in the red oak group (especially *Quercus coccinea*) occurred during the successive droughts in the 1980s and late 1990s, and interestingly, larger trees were more vulnerable than smaller trees (Clinton *et al.* 1993). The earliest reports of drought in the area in the 1920s also noted that oak mortality was higher than other deciduous tree species (Hursh & Haasis 1931). Growth rate data for oaks in the 1980–1990 period showed comparable growth rates during wet and dry periods, suggesting either deep rooting and access to stored water in the deep soils at Coweeta (Kloeppel *et al.* 2003), or highly conservative gas exchange in both wet and dry periods (Bush *et al.* 2008; Ford *et al.* 2010).

SUMMARY AND CONCLUSIONS

Analysis of 75 years of climate data at the Coweeta Hydrologic Laboratory has revealed a significant increase in air temperatures since the late 1970s, an increase in drought severity and frequency, and a more extreme precipitation distribution. Cause and effect are difficult to establish, but these patterns are consistent with observations throughout the southeastern USA that suggest linkages between reduced aerosols and temperature patterns, and linkages between the North Atlantic Oscillation and increased precipitation variability. Similar patterns are predicted with AOGCMs under climate change and this recent variability in the observed record may be providing a glimpse of future climatic conditions in the southern Appalachian. Based on observed ecosystem responses to climate variability over the past 20 years, we anticipate significant impacts on ecosystem structure and function.

Climate change during the 21st century is predicted to include novel climates – combinations of seasonal temperature and precipitation that have no historical or modern counterpart (Williams *et al.* 2007). In the USA, the southeastern region is predicted to be the most susceptible to novel climates (Williams & Jackson 2007; Williams *et al.* 2007). Detecting ecosystem change, including ecological 'surprises', will require long-term data from monitoring networks and studies (Lindenmayer *et al.* 2010), such as those presented here from the Coweeta Hydrologic Laboratory.

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REFERENCES

Allen, M. R. & Ingram, W. J. 2002 Constraints on future changes in climate and the hydrologic cycle. *Nature* **419**, 224–232.

Angert, A., Biraud, S., Bonfils, C., Henning, C. C., Buermann, W., Pinzon, J., Tucker, C. J. & Fung, I. 2005 Drier summers cancel out the CO_2 uptake enhancement induced by warmer springs. *Proc. Natl. Acad. Sci.* **102**, 10823–10827.

Burke, E. J., Brown, S. J. & Christidis, N. 2006 Modeling the recent evolution of global drought and projections for the twenty-first century with the Hadley Centre Climate Model. *J. Hydrometeorol.* **7**, 1113–1125.

Burnham, K. P. & Anderson, D. R. 2002 *Model Selection and Multimodel Inference: A Practical Information-Theoretic Approach*. Springer-Verlag, New York.

Bush, S. E., Pataki, D. E., Hultine, K. R., West, A. G., Sperry, J. S. & Ehleringer, J. 2008 Wood anatomy constrains stomatal responses to atmospheric vapor pressure deficit in irrigated, urban trees. *Oecologia* **156**, 13–20.

Cade, B. S. & Noon, B. R. 2003 A gentle introduction to quantile regression for ecologists. *Front. Ecol. Environ.* **1**, 412–420.

Clinton, B. D., Boring, L. R. & Swank, W. T. 1993 Canopy gap characteristics and drought influences in oak forests of the Coweeta Basin. *Ecology* **74**, 1551–1558.

Critchfield, H. J. 1966 *General Climatology*. Prentice Hall, Englewood Cliffs, New Jersey, USA.

Czikowsky, M. J. & Fitzjarrald, D. R. 2004 Evidence of seasonal changes in evapotranspiration in eastern US hydrological records. *J. Hydrometeorol.* **5**, 974–988.

Dai, A., Karl, T. R., Sun, B. & Trenberth, K. E. 2006 Recent trends in cloudiness over the United States, a tale of monitoring inadequacies. *Bull. Am. Meteorol. Soc.* **87**, 597–606.

Douglass, J. E. & Hoover, M. D. 1988 Introduction and site description. In: *Ecological Studies, Vol. 66: Forest Hydrology and Ecology at Coweeta* (W. T. Swank & D. A. Crossley, eds). Springer-Verlag, New York, pp. 17–31.

Easterling, D. R., Meehl, G. A., Parmesan, C., Changnon, S. A., Karl, T. R. & Mearns, L. O. 2000 Climate extremes: observations, modeling, and impacts. *Science* **289**, 2068–2074.

Elliott, K. J. & Hewitt, D. 1997 Forest species diversity in upper elevation hardwood forests in the southern Appalachian Mountains. *Castanea* **62**, 32–42.

Elliott, K. J. & Swank, W. T. 2008 Long-term changes in forest composition and diversity following early logging (1919–1923) and the decline of American chestnut (*Castanea dentata*). *Plant Ecol.* **197**, 155–172.

Ford, C. R., Goranson, C. E., Mitchell, R. J., Will, R. E. & Teskey, R. O. 2005 Modeling canopy transpiration using time series analysis: a case study illustrating the effect of soil moisture deficit on *Pinus taeda*. *Agric. Forest Meteorol.* **130**, 163–175.

Ford, C. R., Hubbard, R. M. & Vose, J. M. 2010 Quantifying structural and physiological controls on canopy transpiration of planted pine and hardwood stand species in the southern Appalachians. *Ecohydrology* **4**, 183–195.

Ford, C. R., Laseter, S. H., Swank, W. T. & Vose, J. M. 2011 Can forest management be used to sustain water-based ecosystem services in the face of climate change? *Ecol. Appl.* **21**, 2049–2067.

Groisman, P. Y., Knight, R. W., Karl, T. R., Easterling, D. R., Sun, B. & Lawrimore, J. H. 2004 Contemporary changes of the hydrological cycle over the contiguous United States: trends derived from *in situ* observations. *J. Hydrometeorol.* **5**, 64–85.

Hertzler, R. A. 1936 *History of the Coweeta Experimental Forest*. Unpublished report on file at Coweeta Hydrologic Laboratory.

Huntington, T. G. 2006 Evidence for intensification of the global water cycle: review and synthesis. *J. Hydrol.* **319**, 83–95.

Hursh, C. R. & Haasis, F. W. 1931 Effects of 1925 summer drought on southern Appalachian hardwoods. *Ecology* **12**, 380–386.

IPCC 2007 Contribution of working groups I, II and III to the fourth assessment report of the Intergovernmental panel on climate change. In: *Climate Change 2007: Synthesis Report*, Core Writing Team (R. K. Pachuari & A. Reisinger, eds). Geneva, Switzerland, pp. 104.

Johnson, J. B. & Omland, K. S. 2004 Model selection in ecology and evolution. *Trends Ecol. Evol.* **19**, 101–108.

Karl, T. R. & Knight, R. W. 1998 Secular trends of precipitation amount, frequency, and intensity in the USA. *Bull. Am. Meteorol. Soc.* **79**, 231–241.

Karl, T. R., Knight, R. W. & Plummer, N. 1995 Trends in high-frequency climate variability in the twentieth century. *Nature* **377**, 217–220.

Kloeppel, B. D., Clinton, B. D., Vose, J. M. & Cooper, A. R. 2003 Drought impacts on tree growth and mortality of southern Appalachian forests. In: *Climate Variability and Ecosystem Response at Long-term Ecological Research Sites* (D. Greenland, D. G. Goodin & R. C. Smith, eds). Oxford University Press, New York, NY, pp. 43–55.

Lindenmayer, D. B., Likens, G. E., Krebs, C. J. & Hobbs, R. J. 2010 Improved probability of detection of ecological 'surprises'. *Proc. Natl. Acad. Sci.* 107, 21957–21962.

Lins, H. & Slack, J. R. 1999 Streamflow trends in the United States. *Geophys. Res. Lett.* **26**, 227–230.

McMahon, S. M., Parker, G. G. & Miller, D. R. 2010 Evidence for a recent increase in forest growth. *Proc. Natl. Acad. Sci.* **107**, 3611–3615.

McNulty, S. G. & Swank, W. T. 1995 Wood $\delta^{13}C$ as a measure of annual basal area growth and soil water stress in a *Pinus strobus* forest. *Ecology* **76**, 1581–1586.

Moran, M. S., Peters, D. P. C., McClaran, M. P., Nichols, M. H. & Adams, M. B. 2008 Long-term data collection at USDA experimental sites for studies of ecohydrology. *Ecohydrology* **1**, 377–393.

Nemani, R. R., Keeling, C. D., Hashimoto, H., Jolly, W. M., Piper, S. C., Tucker, C. J., Myneni, R. B. & Running, S. W. 2003 Climate-driven increases in global terrestrial net primary production from 1982 to 1999. *Science* **300**, 1560–1563.

Nuckolls, A., Wurzburger, N., Ford, C. R., Hendrick, R. L., Vose, J. M. & Kloeppel, B. D. 2009 Hemlock declines rapidly with hemlock woolly adelgid infestation: impacts on the carbon cycle of Southern Appalachian forests. *Ecosystems* **12**, 179–190.

Peterson, T. C. & Baringer, M. O. 2009 State of the climate in 2008. *Bull. Am. Meteorol. Soc.* **90**, S1–S196.

Philipona, R., Behrens, K. & Ruckstuhl, C. 2009 How declining aerosols and rising greenhouse gases forced rapid warming in Europe since the 1980s. *Geophys. Res. Lett.* **36**, L02806.

Portmann, R. W., Solomon, S. & Hegerl, G. C. 2009 Spatial and seasonal patterns in climate change, temperatures, and precipitation across the United States. *Proc. Natl. Acad. Sci.* **106**, 7324–7329.

Riedel, M.S. 2006a North Atlantic oscillation influences on climate variability in the Southern Appalachians. *8th Interdisciplinary Solutions for Watershed Sustainability*. Joint Federal Interagency, Reno, NV.

Riedel, M.S. 2006b Atmospheric/oceanic influence on climate in the Southern Appalachians. In: *Proceedings of the Secondary Interagency Conference on Research in the Watersheds*. USDA SRS, Otto, NC, pp. 7.

Salzer, M. W., Hughes, M. K., Bunn, A. G. & Kipfmueller, K. F. 2009 Recent unprecedented tree-ring growth in bristlecone pine at the highest elevations and possible causes. *Proc. Natl. Acad. Sci.* **106**, 20348–20353.

Solomon, S., Plattner, G., Knutti, R. & Friedlingstein, P. 2009 Irreversible climate change due to carbon dioxide emissions. *Proc. Natl. Acad. Sci.* **106**, 1704–1709.

Streets, D. G., Wu, Y. & Chin, M. 2006 Two-decadal aerosol trends as a likely explanation of the global dimming/brightening transition. *Geophys. Res. Lett.* **33**, L15806.

Swank, W. T. & Crossley, D. A. 1988 Introduction and site description. In: *Ecological Studies, Vol. 66: Forest Hydrology and Ecology at Coweeta* (W. T. Swank & D. A. Crossley, eds). Springer-Verlag, New York, pp. 3–16.

Swift, L. W., Cunningham, G. B. & Douglass, J. E. 1988 Climate and hydrology. In: *Ecological Studies, Vol. 66: Forest Hydrology and Ecology at Coweeta* (W. T. Swank & D. A. Crossley, eds). Springer-Verlag, New York, pp. 35–55.

Trewartha, G. T. 1954 *An Introduction to Climate*. Mc-Graw Hill, New York, USA.

Vose, J. M. & Swank, W.T. 1994 Effects of long-term drought on the hydrology and growth of a white-pine plantation in the southern Appalachians. *For. Ecol. Manage.* **64**, 25–39.

Wild, M. 2009 Global dimming and brightening: a review. *J. Geophys. Res.* **114**, D00D16.

Williams, J. W. & Jackson, S. T. 2007 Novel climates, no-analog communities, and ecological surprises. *Front. Ecol. Environ.* **5**, 475–482.

Williams, J. W., Jackson, S. T. & Kutzbach, J. E. 2007 Projected distributions of novel and disappearing climates by 2100 AD. *Proc. Natl. Acad. Sci.* **104**, 5738–5742.

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