1,800 Years of abrupt climate change, severe fire, and accelerated erosion, Sierra Nevada, California, USA

Stephen F. Wathen

Received: 26 November 2007 / Accepted: 3 December 2010 / Published online: 12 March 2011
© The Author(s) 2011. This article is published with open access at Springerlink.com

Abstract This paper provides both a detailed history of environmental change in the Sierra Nevada over the past 1,800 years and evidence for climate teleconnections between the Sierra Nevada and Greenland during the late Holocene. A review of Greenland ice core data suggests that the magnitudes of abrupt changes in temperature and precipitation increased beginning c. 3,700 and 3,000 years ago, respectively. Precipitation increased abruptly 1,300 years ago. Comparing paleotemperature data from Cirque Peak, CA with paleoprecipitation data from Pyramid Lake, NV suggests that hot temperatures occurred at the beginnings of most severe droughts in the Sierra Nevada over the past 1,800 years. Severe fires and erosion also occurred at Coburn Lake, CA at the beginning of all severe droughts in the Sierra Nevada over the past 1,800 years. This suggests that abrupt climate change during the late Holocene caused vegetation and mountain slopes in some areas to be out of equilibrium with abruptly changed climates. Finally, the ending of drought conditions in Greenland coincided with the beginning of drought conditions in the Sierra Nevada over the past 1,800 years, perhaps as a result of the rapidly changed locations of the Earth's major precipitation belts during abrupt climate change events.

1 Introduction

Relatively gradual long-term climate change differs from abrupt climate change. The Intergovernmental Panel on Climate Change (IPCC 2007) has concerned itself primarily with gradual climate change that occurs over many decades or longer.

S. F. Wathen (✉)
University of California Davis,
500 Main St., Winters, CA 95694, USA
e-mail: sfwathen@gmail.com, sfwathen@ucdavis.edu

Abrupt climate change (ACC), on the other hand, occurs in a matter of years or a few decades; so fast that societies or ecosystems may not be able to respond quickly enough to these changes and thus may undergo significant alteration or collapse (United States National Research Council Committee on Global Change Research 2002).

Abrupt climate change has probably had a greater impact upon both human societies and natural environments than gradual climate change has had. Severe droughts and extreme temperature events are the most serious abrupt climate change events (ACCEs) to threaten human societies because they affect both agriculture and water supplies (McCabe and Palecki 2006). Indeed, large, abrupt changes in precipitation or temperature have been implicated in the collapse of many early complex human societies (Douglass 1936; Weiss and Bradley 2001; Leroya et al. 2006).

The ACCEs that overturned societies in the past were of a much larger magnitude and/or lasted much longer than the climate events that have affected developed societies in recent decades. For example, in one of the worst demographic catastrophes in human history, 80–90% of Mayans were killed by disease stemming from a sixteenth century megadrought (Acuna-Soto et al. 2005). In another example, abrupt cold temperatures have been implicated in severe declines in agricultural output leading to subsequent periods of mass starvation, rebellion, and dynastic collapse in China over the past 1,000 years (Zhang et al. 2006). These types of severe ACCEs occurred in the past and will occur in the future even if human-caused climate change were not a factor. However, there is concern that current human-caused climate change might trigger severe ACCEs.

Although we know quite a bit about the effects of past ACCEs on human societies, we know less about the effects of ACCEs on natural systems and disturbance regimes. We know from recent experience that extreme droughts and extreme temperature events can kill vegetation, either directly from the drought itself or indirectly through increased insects predation or disease. Dead vegetation can result in accumulated fuels, leading to severe fires and denudation of mountain slopes (Burkett et al. 2005; Shakesby and Doerr 2006). Thus, we can assume that the even more severe droughts or temperature extremes that occurred in the past would have affected vegetation and mountain slopes in similar, or probably more severe, ways.

In this paper, I present a 2,000 year high-resolution climate and disturbance history for the Sierra Nevada based upon two published paleoclimate studies from the Sierra Nevada and my own unpublished charcoal record from Coburn Lake, California. I also present a reinterpretation of published data from both the Sierra Nevada and Greenland to suggest that climates in both locations became moister and more erratic over the past c. 3,000 years. The beginnings of severe droughts in the Sierra Nevada and severe fire events at Coburn Lake, correlate well with peak drought conditions in Greenland and with fire events in eastern Canada over the past 1,800 cal year. Finally, I suggest an “abrupt climate change-severe fire-severe erosion hypothesis” to explain the timing of fires at Coburn Lake (and perhaps elsewhere). All dates used in this article are calibrated to calendar years before AD 1950 (cal year BP).

2 The Coburn Lake study area

The Coburn Lake watershed in California (39° 32' 30"N, 120° 27'Ω) spans 2,280–2,460 m (7,480–8,060 ft) in elevation. The watershed is located just below the crest of the northern Sierra Nevada and adjacent to the western margin of the Great Basin Desert (Fig. 1). The Coburn Lake watershed is small (44 ha) and steep (Fig. 1, lower right), which limits the geographic area from which charcoal can wash into the lake. Coburn Lake is also a relatively deep (13 m) lake for its surface area (1.7 ha). This characteristic made Coburn Lake a good candidate for containing relatively undisturbed bottom sediments (Larsen et al. 1998). Coburn Lake itself, its encircling glacial moraines, and its watershed were created at the end of the Pleistocene from glacial erosion of loosely consolidated Pliocene-aged volcanic rock (Grose et al. 2000).

Fig. 1 Coburn Lake (star at center of figure) is located north of Lake Tahoe, California, just below the east side of the Sierra Nevada crest, and adjacent to the Sierra Valley of the Great Basin Desert. The Truckee River begins at the northern end of Lake Tahoe, passes through Reno, Nevada, runs east and north from Reno, and terminates at Pyramid Lake. The watershed for Pyramid Lake is enclosed within the white dotted line. Insert at left the general location of Coburn Lake. Insert at right a topographic map of the Coburn Lake study area with the watershed of Coburn Lake outlined in solid white. The Sierra Nevada Divide is located at the top of the Coburn Lake watershed, which is in the lower left portion of the map. Berry Creek begins at the northern outlet of Coburn Lake, which is in the upper right portion of the map, and drains north and east into the Sierra Valley

Under current climatic conditions, the Coburn Lake watershed has a high montane Mediterranean climate with cold-snowy winters and cool-dry summers. Vegetation within the heavily-forested watershed is largely dominated by old-growth upper montane red fir trees (*Abies magnifica*); with subalpine mountain hemlock (*Tsuga mertensiana*) codominant on cooler north-facing slopes and western white pines (*Pinus monticola*) codominant on drier slopes and ridge tops.

Emergent vegetation surrounding Coburn Lake may have acted as a partial filter on charcoal and soil sediment traveling overland following fires before being deposited into the lake. Emergent and riparian vegetation is present on the Coburn Lake's flatter and partially filled northern and eastern margins. Conversely, there is relatively little emergent vegetation below slopes on the lake's southern and western margins. However, relatively little of the lake's watershed lies above the lake's southern and western margins.

3 Methods

In the field, I collected two sets of cores from near the center of Coburn Lake. The two sets of cores were located >26 m from each other and also away from steep underwater slopes so as to avoid resampling the same location and sampling slumped sediments, respectively. I used a gravity-activated top corer to collect sediment samples at the water-sediment interface and a modified 5 cm-diameter Livingstone corer to collect 4.36 m of deeper core samples (Wright 1991).

Fig. 2 Age–depth diagram for Coburn Lake. This figure highlights the locations of 14C AMS dates, a thick layer of Mazama ash at the bottom of the core, and bent strata where older sediments were thrust up and over younger lake sediments

Table 1 Calibrated radiocarbon dates used in this study

Coburn Lake		Lawrence Livermore Center for Accelerator Mass Spectrometry (AMS)				
Depth (cm)	Sample	CAMS #	Material	Calculated	±	Calibrated
July–August/2002						
CalPal 6/3/2005						
CORE A						
41	CCAT:41	97919	Cone scale—big fire, gritty	1460	60	1366
51	CCAT:51	97920	Needle—big fire, clay	1920	40	1867
148	CCA2:8	97989	Needle—below fire, detritus	2210	45	2231
212	CCA2:73	97990	Needle—fire, dark gyttja	4830	100	5540
292	CCA3:22	97991	Wood—magn susc spike	6330	80	7245
392	CCA4:75	97992	Leaf—magn susc spike	6350	80	7280
CORE C						
27	CCC1:2	97921	Needle—above fire	1520	45	1420
55	CCC1:30	97922	Wood—below large fire	1915	35	1860
71	CCC1:45.6	97923	Cone scale—fire, detritus	2200	40	2227
88	CCC1:63	97924	Charred wood—fire, detritus	2925	35	3072
125	CCC1:100.3	97925	Needle—fire, large charcoal	4560	70	5211
145	CCC2:15	97927	Rootlet—below clay, detritus	5455	40	6250
172	CCC2:41.5	97928	Rootlet—clay lens	5920	60	6746
197	CCC2:67	97929	Rootlet—top detritus layer	6285	40	7214
208	CCC2:78	97930	Rootlet—bottom detritus	6540	40	7455
213	CCC2:83	97931	Rootlet—bottom clay layer	6600	35	7500
216	CCC2:85.5	97932	Rootlet—bottom detritus	6750	80	7599
232	CCC2:92.4	97933	Rootlet—bottom clay layer	6640	40	7523
232	CCC2:101.7	97934	Husk—fire, bottom gyttja	5680	60	6474
240	CCC3:3.3	97935	Wood—dark gyttja	6000	45	6826
252	CCC3:14.7	97936	Ford—fire, bottom gyttja	6305	40	7233
265	CCC3:28	97937	Needle—fire, massive clay	6420	60	7346
272	CCC3:35.5	97938	Ford—bottom clay layer	6840	110	7695

Table 1 (continued)

Coburn Lake		Lawrence Livermore Center for Accelerator Mass Spectrometry (AMS)				
Depth (cm)	Sample	CAMS #	Material	Calculated	±	Calibrated
276	CCC3:39	97939	Ford—lenses	6825	50	7658
276 (Dup)	CCC3:39	88405	Ford—lenses	6805	50	7645
330	CCC5A:2	97944	Needle—top segment, silt	6845	40	7670
371	CCC5A:43	97945	Ford—bottom segment	6930	70	7762
385	CCC5B:10–11	97946	Needle—c. bottom silt layer	7030	110	7842
390	CCC5B:16	88403	Needle—brownish gyttja	6910	130	7757
390 (Dup)	CCC5B:16	88404	Needle—brownish gyttja	7020	230	7868
395	CCC5B:20	97947	Needle—fire, lower detritus	7250	90	8066
404	CCC5B:30.2	97948	Ford—clay layer	7410	40	8246
CORE C Dates not used						
133	CCC2:2–4	97926	Cone scale—date off	1850	50	1787
266	CCC3:54.4	97941	Needle—contaminated	5775	50	6572
279	CCC3:42.3	97940	Cone scale—date off	Modern		Deleted
294	CCC4:2	97942	Needle—not needed	6540	35	7453

Accelerator Mass Spectrometry (AMS) dates were derived from plant macrofossils collected from Coburn Lake, California. Calculated dates derived from the Lawrence Livermore Center for Accelerator Mass Spectrometry were transformed to cal year BP (present = AD 1950) using the Cologne CalPal on-line calibration package (Weninger et al. 2004)

Once collected, top core samples were photographed and sub-sampled at 1 cm intervals, unless smaller intervals were necessary to constrain the locations of either stratigraphic boundaries or charcoal visible in the core. Deeper core segments were described in the field, wrapped in cellophane and aluminum foil, and placed in wooden boxes for transit. All samples were kept cool in transit and stored at 4°C once in the laboratory.

In the laboratory, both sets of deeper core segments were split horizontally, sketched, photographed, and described. Sediment layers were visually classified as gyttja (fine organically-rich lake sediments), macro-sized organic detritus, clay, or ash. Deeper core segments were subsampled at 1 cm or smaller intervals for the same reasons given for top core samples.

A radiocarbon-based chronology was developed for Coburn Lake based upon 24 ^{14}C AMS-dated plant macrofossils taken from the primary set of deeper core segments (Fig. 2). To confirm the stratigraphy of the primary set of deeper core segments, the two sets of deeper core segments were compared with each other. The two sets of deeper core segments were cross-correlated using these 24 AMS dates; additional AMS dates from the second set of deeper cores; and shared peaks from various physical parameters: bulk density, magnetic susceptibility and charcoal.

Radiocarbon dates (Table 1) were converted to calibrated year before present (cal year BP, A.D. 1950) using the Cologne CalPal on-line calibration package (Weninger et al. 2004). Layers of organic detritus and clay were not excluded from the age–depth curve because much of the core was made up of non-gyttja material; relying on dates

Fig. 3 Relationships between stratigraphy layers, charcoal peaks, sediment bulk density, and magnetic susceptibility at Coburn Lake. **a** The stratigraphy of Coburn Lake sediments. **b** The number of charcoal particles of $>250\ \mu\text{m}$ in size/ g^3 found within Coburn Lake sediments. The two largest Coburn Lake charcoal peaks with $>1,000$ charcoal particles/ g^3 have been truncated to fit the column size. **c** Bulk density of sediments. **d** Magnetic susceptibility (MS) of sediments

in gyttja alone would produce unrealistic results; and because peaks in charcoal, the focus of this study, were often associated with non-gyttja layers.

Calibrated radiocarbon dates were graphed directly without developing a formal age–depth model because the large number of ^{14}C AMS dates available made this unnecessary, lake deposition appeared to be strongly episodic rather than uniform, and a coherent pattern resulted from using the methods employed.

A thrusting of older sediments over younger sediments was visible in the core and was confirmed by radiocarbon dating (Fig. 2). This overthrusting was probably the result of an earthquake along a nearby known active fault (avalanche scars are visible in the watershed above the lake). This earthquake probably caused slopes above Coburn Lake to slide off and into the lake, in the process shoving existing lake sediments, more or less intact, up and over existing lake sediments located further out into the lake (Wathen, unpublished data). Duplicated sediments caused by this overthrusting were removed from the final chronology used for this paper.

Fig. 4 The distribution of charcoal peaks from Coburn Lake over the past 5,200 years in conjunction with the Pyramid Lake drought record. **a** The northern Sierra Nevada drought record from Pyramid Lake, Nevada is based upon the ratio of *Artemisia* (sagebrush) to *Chenopodiaceae* (shadscale) pollen types (A/C) found in Pyramid Lake sediments. The dashed horizontal lines represent the centers of major charcoal peaks (adapted from Fig. 3, Mensing et al. 2004). **b** The number of charcoal particles of $>250\ \mu\text{m}$ in size/ g^3 found within Coburn Lake sediments. The two largest Coburn Lake charcoal peaks with $>1,000$ charcoal particles/ g^3 were truncated to fit the column size

One cubic centimeter of material was taken from each subsample taken from the primary sets of top and deeper sediment core segments. This material was processed to determine magnetic susceptibility; bulk density; percentages water, carbon, and calcium carbonate; and charcoal abundance. Magnetic susceptibility was measured by placing samples in small (6.6 cm³) non-magnetic plastic boxes and analyzing them in a Bartington MS2 spinner magnetometer. Bulk density was determined by weighing 1 cm³ subsamples and then determining sediment displacement in water. Percentages of water, organic carbon, and calcium carbonate were determined by drying pre-weighed samples in a muffle oven at 40°C, 450°C, and 900°C, respectively, and calculating the mass lost.

Charcoal from Coburn Lake was processed using standard procedures (Whitlock and Laresen 2001). Samples were disaggregated in 5% KOH solution overnight and washed through a series of 250, 125, and 65 µm-sized sieves to concentrate progressively smaller-sized charcoal particles. Charcoal particles of >250 µm-size

Fig. 5 Correlation between the beginnings of severe droughts in the northern Sierra Nevada and Coburn Lake charcoal increases over the past 2,200 years. **a** Northern Sierra Nevada drought record from Pyramid Lake, Nevada based upon the ratio of *Artemisia* (sagebrush) to *Chenopodiaceae* (shadscale) pollen types (A/C) derived from Pyramid Lake sediments (adapted from Fig. 3 in Mensing et al. 2004). The dotted vertical line represents the mean value for the record. **b** The number of charcoal particles of >250 µm in size/g³ found within lake sediments. The two largest Coburn Lake charcoal peaks with >1,000 charcoal particles/g³ were truncated to fit the column size. Dashed horizontal lines represent the centers of charcoal peaks. Dotted vertical line denotes where samples contained >50 particles per cm³ of lake sediment. Arrows denote locations of charcoal increases. Xs denote where the beginnings of droughts are not associated with increases in charcoal

were counted in each cubic centimeter subsample using a 36× dissecting microscope. I also counted 125–250 μm -sized charcoal in a portion of both the primary and secondary set of deeper core segments to test for differences in charcoal patterns. Once complete, the second set of deeper core segments was not processed further.

This study of Coburn Lake was designed to develop a record of local fires within the Coburn Lake watershed during the Holocene. Individual charcoal particles of $>125 \mu\text{m}$ in size, which can be seen with the naked eye, are termed “macrocharcoal.” Macrocharcoal particles of $>125 \mu\text{m}$ in size are heavy enough that it is assumed that they will have traveled only a few hundred meters through the air to their area of deposition (Clark 1988; MacDonald et al. 1991; Clark and Hussey 1996). Smaller particles can and do blow in from greater distances. I chose to focus on

Fig. 6 Environmental history of the Sierra Nevada over the past 2,000 years based upon the integration of three high resolution paleorecords **a** A northern Sierra Nevada drought record from Pyramid Lake, Nevada based upon the ratio (A/C) of *Artemisia* (sagebrush) to *Chenopodiaceae* (shadscale) pollen types. The beginnings of droughts (faint horizontal dashed lines) are numbered from youngest to oldest, from top to bottom. The bold vertical dashed line denotes the median A/C ratio value for the past 2,000 years (adapted from Fig. 5 in Mensing et al. 2004). **b** A southern Sierra Nevada temperature record based upon the analyses of foxtail pine tree-ring chronologies that grew near treeline on Cirque Peak, California. Colder temperature anomalies are to the left and warmer temperature anomalies to the right of zero, the mean from AD 1 to 1980 (adapted from Scuderi 1993). **c** The abundance of charcoal particles of $>250 \mu\text{m}$ in size/ cm^3 within Coburn Lake sediments. The vertical dashed line designates charcoal abundances of >50 particles/ cm^3 . The two largest Coburn Lake charcoal peaks with $>1,000$ charcoal particles/ g^3 were truncated to fit the column size. Bold horizontal dashed lines extend outward from northern Sierra Nevada droughts. Words to the right of Column C denote temperatures or abrupt changes in temperature near treeline on Cirque Peak at the beginning of severe droughts

Fig. 7 Increased precipitation and climate variability in Greenland and the Sierra Nevada over the past 3,700 years. **a** A reconstructed ice accumulation record from the GISP2 ice core as a proxy for precipitation. **b** A reconstructed $\delta^{18}\text{O}$ curve from the GRIP ice core record as a proxy for air temperature (adapted from National Snow and Ice Data Center and World Data Center-A for Paleoclimatology 1997). **c** A northern Sierra Nevada drought record from Pyramid Lake, Nevada based upon the ratio (A/C) of *Artemisia* (sagebrush) to *Chenopodiaceae* (shadscale) pollen (adapted from Fig. 5 in Mensing et al. 2004). Faint horizontal dashed lines represent the onset of droughts. Vertical dotted lines denote the median value over the past 5,000 years. From older to more recent events, vertical arrows (3) and (2) highlight increases in the magnitude of fluctuations in temperature and precipitation that began in Greenland c. 3,700 and 3,000 cal year BP, respectively. Vertical arrow (6) highlights an increase in the frequency of centennial-scale fluctuations in precipitation that occurred in the northern Sierra Nevada sometime between 3,400 and 2,700 cal year BP. Vertical arrow (4) highlights long-term cooling in Greenland that began c. 2,400 cal year BP. Vertical arrow (7) highlights long-term increases in both precipitation and the frequency of abrupt climate change events in the northern Sierra Nevada that began c. 2,000 cal year BP. Vertical arrow (1) highlights the beginning of a long-term shift towards increased precipitation in Greenland c. 1,300 cal year BP. Vertical arrow (5) highlights cooling in Greenland that began c. 2,400 cal year BP

>250 μm -sized charcoal particles as my proxies for past fires because their larger-size would provide even greater assurance of capturing only local fires. From this point forward, I will refer to macrocharcoal particles from Coburn Lake simply as charcoal. Charcoal numbers were not converted to charcoal accumulation rates because the purpose of this study was to investigate individual charcoal peaks in relation to individual ACCEs that occurred over short time intervals.

4 Results

Charcoal peaks from Coburn Lake were typically associated with indicators of erosion. In the Coburn Lake record, distinct layers of organic detritus and clay were interspersed within a matrix of lake-derived organic-rich gyttja. The number of charcoal particles typically peaked in conjunction with peaks in organic detritus, inorganic sediments, high sediment bulk density values, and high magnetic susceptibility values (Fig. 3).

Fig. 8 Correlation between the timing of Coburn Lake charcoal peaks and peak drought conditions in Greenland over the past 2,000 years. **a** The abundance of charcoal particles (>250 μm in size/ cm^3) in Coburn Lake sediments. *Bold horizontal dashed lines* extend outward from major charcoal peaks. Peaks are numbered from oldest to youngest. The two largest Coburn Lake charcoal peaks with >1,000 charcoal particles/ g^3 were truncated to fit the column size. **b** A reconstructed ice accumulation record from the GISP2 ice core serving as a proxy for Greenland precipitation (adapted from National Snow and Ice Data Center and World Data Center-A for Paleoclimatology 1997). The one exception to the overall negative correlation between peak charcoal from Coburn Lake and peak drought conditions in Greenland is noted

Although the charcoal record from Coburn Lake goes back 8,500 years, charcoal peaks (>50 charcoal particles per cm^3) became both more frequent and substantially larger beginning c. 1,800 cal year BP. Over the 3,000 years time period from c. 5,000 to 1,800 cal year BP, only two relatively small, isolated charcoal peaks were deposited (Fig. 4). On the other hand, eight charcoal peaks were deposited beginning 1,800 years ago. The average core subsample from Coburn Lake over the past 8,500 years contained <10 charcoal particles per cm^3 . However, two charcoal peaks deposited since 1,800 cal year BP contained $>1,000$ charcoal particles per cm^3 . These two very large peaks were truncated in order to fit within figure columns in Figs. 3, 4, 5, 6 and 8 of this paper.

I was able to match the two sets of cores using AMS dates as well as peaks in bulk density, magnetic susceptibility and charcoal. This outcome increased my confidence that the stratigraphic interpretation and the AMS dates associated with the primary set of cores were robust. I found little difference between the charcoal patterns developed using 125–250 versus >250 μm -sized charcoal.

5 Discussion

5.1 Correlating charcoal peaks with abrupt climate change events

Researchers have mostly used sediment charcoal from lakes to study the relationships between past climates and past fire frequencies over large time scales, spanning several hundreds to several thousands of years (Long et al. 1998). In the typical lake, it is assumed that charcoal deposition takes place relatively uniformly and continuously through time. In the typical lake, such large amounts of charcoal are deposited through time that it is often difficult to delineate charcoal peaks from high levels of background charcoal.

A standard methodology has been used with success to analyze these typical charcoal records (e.g., Cwynar 1977; Gajewski et al. 1985; Clark 1990; Whitlock and Anderson 2003). Using this standard methodology, a line of demarcation is computed between what are to be considered charcoal peaks and what will be considered background charcoal. What are considered charcoal peaks are assumed to represent individual severe fire events from which fire frequencies can be derived.

The record from Coburn Lake, California is not a typical charcoal record because deposition of charcoal into Coburn Lake was strongly episodic, and because there is apparently little background charcoal present in the record (Fig. 4). Long periods of time, spanning thousands of years, produced little or no charcoal; while much shorter periods of time, in particular over the past 1,800 years, produced very large amounts of charcoal. The charcoal record from Coburn Lake has more in common with charcoal records from mountain debris flows (Meyer et al. 1992; Pierce et al. 2004) than with typical lake charcoal records. Therefore, I elected to compare charcoal peaks from Coburn Lake with ACCEs rather than with millennial-scale climate changes because of the episodic nature of the Coburn Lake charcoal record, the absence of background charcoal, the large number of radiocarbon dates available to date individual charcoal peaks, and the pursuit of a different question – what caused the peaked distribution of charcoal into Coburn Lake?

Correlating charcoal peaks with ACCEs challenges the conventional wisdom for many within the sediment charcoal community that individual charcoal peaks do not represent individual short-term climate events. This conventional wisdom is based on the fact that individual charcoal peaks are not well correlated with individual ACCEs in most charcoal records. If a few charcoal peaks are correlated with known ACCEs, most are not. Therefore, those few that are correlated are suspected of being correlated purely by chance. Exceptions are studies by Meyer et al. (1992) and Pierce et al. (2004) in which individual charcoal lenses from within discontinuous hillside debris flow deposits were analyzed in relation to short-term climate changes.

Some researchers were also hesitant early on to acknowledge that climate events in California and Greenland could be correlated with each other unless the mechanisms for those climate teleconnections, still unsatisfactorily understood at this point, could be explained to them. Though robust and insightful, the results of this study may thus be somewhat controversial.

5.2 The nature of the fires represented by charcoal peaks from Coburn Lake

The presence of distinct charcoal peaks in the Coburn Lake charcoal record in conjunction with proxies for increased erosion (organic detritus, inorganic sediments, high sediment bulk density values, and high magnetic susceptibility values) suggests that these charcoal peaks resulted from stand-replacing fires followed by severe soil erosion.

5.3 Correlations between Coburn Lake charcoal peaks and a drought record from Pyramid Lake, Nevada

Pyramid Lake (40° 0' N, 119° 30' W) is located within the Great Basin desert c. 84 km east of Coburn Lake (Fig. 1). A published 7,500 years drought record derived from Pyramid Lake (Mensing et al. 2004) was used as the paleoprecipitation record for Coburn Lake because Pyramid Lake receives almost all of its water as runoff from the northern Sierra Nevada via the Truckee River (Benson et al. 2002). Thus the Pyramid Lake precipitation record has been interpreted as a record of precipitation for the northern Sierra Nevada near where Coburn Lake is located (Fig. 1). Sediments from Pyramid Lake also have a greater temporal resolution than do sediments from Coburn Lake; with past deposition rates of 0.12–0.23 cm year⁻¹ (Benson et al. 2002) vs. 0.02–0.06 cm year⁻¹, respectively.

Severe fires at Coburn Lake appear to have started at the beginning of severe droughts in the northern Sierra Nevada. A striking degree of synchronicity was observed between charcoal peaks from Coburn Lake and the onset of droughts in the northern Sierra Nevada over the past 2,200 years (Fig. 5). Over this time period, charcoal peaks or increases in charcoal from Coburn Lake were tightly correlated with the beginnings of 12 of 12 severe droughts in the northern Sierra Nevada (Pearson product moment correlation coefficient, $r = 0.999$).

Although deposition of charcoal was highly correlated with the beginnings of severe droughts in the northern Sierra Nevada, the amount of charcoal that was deposited into Coburn Lake does not seem to have been proportional to the magnitude of precipitation declines at those times.

5.4 Correlations between the Pyramid Lake drought record and the Cirque Peak, California temperature record

Cirque Peak is located at 3,937 m in elevation, just below the crest of the southern Sierra Nevada, and 12 km south–southeast of Mount Whitney. Temperatures appear to have changed often and abruptly below Cirque Peak over the past 2,000 years (Scuderi 1993). A visual comparison of the Cirque Peak temperature record vis-à-vis the Pyramid Lake precipitation record (Mensing et al. 2004) suggests that abrupt changes in precipitation in the northern Sierra Nevada usually coincided with abrupt changes in temperature in the southern Sierra Nevada (Fig. 6).

However, abrupt changes in temperature in the Scuderi record were more common than abrupt changes in precipitation in the Mensing et al. record. Therefore not every abrupt temperature change coincided with an abrupt change in precipitation. On the other hand, most abrupt changes in precipitation did coincide with extreme changes in temperature over the past 2,000 years.

Severe fires at Coburn Lake typically occurred at the beginnings of severe droughts and during times of high temperature over the past 1,800 years in the Sierra Nevada. As a rule, hot temperatures occurred at the beginnings of severe droughts, while cold temperatures or abrupt changes in temperature occurred at the beginnings of pluvials. With the exception of the severe drought that began c. 1,600 cal year BP, the beginnings of all severe droughts over the past 1,800 years were associated with hot temperatures.

5.5 Evidence for increases in moisture and the frequency of abrupt climate change events during the late Holocene

Both Greenland and the Sierra Nevada became cooler during the Late Holocene. In Greenland, the size of fluctuations in temperature increased markedly c. 3,700 cal year BP, long-term cooling began c. 2,400 cal year BP, and cooling accelerated again c. 1,000 cal year BP (National Snow and Ice Data Center and World Data Center-A for Paleoclimatology 1997) (Fig. 7). In the Sierra Nevada, Clark (2000) noted that cooling began by 3,400 cal year BP.

During the Late Holocene, both Greenland and the Sierra Nevada experienced increased precipitation as well as larger fluctuations in precipitation (Fig. 7). In Greenland, the size or magnitude of fluctuations in precipitation increased markedly c. 3,000 cal year BP. Precipitation then increased conspicuously c. 1,300 cal year BP (National Snow and Ice Data Center and World Data Center-A for Paleoclimatology 1997).

In the northern Sierra Nevada, the number of abrupt changes in precipitation increased sometime between 3,400 and 2,700 cal year BP. Unfortunately, an unintentional gap in the record exists between the two long core sections taken from Pyramid Lake that covers this time period. Therefore the timing cannot be further constrained. Moser et al. (2004), however, noted that the climate of Sierra Nevada became wetter and more variable c. 3,000 years ago.

Both precipitation and the number of abrupt changes in precipitation increased markedly in the northern Sierra Nevada beginning c. 2,000 cal year BP (Mensing et al. 2004).

5.6 Possible impacts of both increased available moisture and the increased frequency of abrupt climate change events upon the Coburn Lake watershed

Increased precipitation, cooler temperatures, and an increase in the frequency of ACCEs could explain the increase in severe fires at Coburn Lake over the past 1,800 cal year BP. Increased precipitation and cooler temperatures would have meant higher moisture availability to plants nearly everywhere during the Late Holocene. However, the effects of higher moisture availability on plant composition, fire frequency, and fire severity would have varied with plant community type. At upper montane Coburn Lake, an increase in precipitation and a decrease in temperatures would likely have resulted in more precipitation coming as snow in the winter. Increased snow packs would likely have resulted in more soil moisture being available to plants during the beginning of California's typically dry summers. An increase in available soil moisture could have resulted in a change in the dominance of plants towards those better adapted to cooler, moister conditions. Indeed, the dominant tree growing around Coburn Lake today, red fir, dominates in the Sierra Nevada where the winter snow pack is the deepest (Barbour et al. 1991).

Increased soil moisture and changes in vegetation would have altered fire regimes at Coburn Lake as well as vegetation composition. Light fuels, like grasses, may have increased in the understory resulting in more frequent low-severity fires in forest understories. On the other hand, moister and cooler conditions would have allowed heavy fuels, which would have increased with the increased growth of trees and which are slower to dry out than lighter fuels, to accumulate between fires. This situation would have resulted in the occurrence of infrequent but severe, standing-replacing fires of the type I hypothesize are represented in the Coburn Lake charcoal record. Indeed, low-severity fires have occurred very frequently and high intensity fires have occurred very rarely in the red fir forests surrounding Coburn Lake over the past 300 years based on dendrochronological studies (Steve Wathen, unpublished data).

The abrupt beginning of severe droughts and hot temperatures during the late Holocene could have stressed and killed dominant vegetation better adapted to earlier cooler and moister conditions. Dead trees would have added to already heavy fuel loads and high temperatures would have allowed heavy fuels greater opportunities to dry out and catch fire. Heavy fuels catching fire would have meant more fires getting into tree overstories causing severe stand-replacing fires. This scenario is hypothesized to explain why the charcoal record from Coburn Lake correlates so closely with the beginning of severe drought conditions in the northern Sierra Nevada during the late Holocene.

5.7 An “abrupt climate change-severe fire-severe erosion hypothesis”

Evidence for a correspondence between the timing of severe fires at Coburn Lake and the onset of ACCE in the Sierra Nevada suggests a more general hypothesis. An “Abrupt climate change-severe fire-severe erosion hypothesis” postulates that the abrupt onset of severe droughts and temperature extremes during the Holocene would have caused vegetation and mountain slopes in some areas to be out of balance with new abruptly-changed climates. Vegetation-climate imbalances would have resulted in the widespread die-off of vegetation adapted to moister and cooler

climatic conditions, with diseases and insect infestations acting as the direct causal agents for the death of drought-stressed trees. Eventually the accumulation of dead and drying biomass would have dried and caught fire resulting in severe stand-replacing fires. This would have been followed by accelerated erosion of slopes recently denuded of vegetation. Vegetation and soils would have changed until vegetation and soils were once again in quasi-equilibrium with new climates.

Evidence from studies at different temporal scales and from different locations supports the abrupt climate change-severe fire-severe erosion hypothesis. In conjunction with increasing available moisture plus an increase in the number and/or the intensity of ACCEs, charcoal peaks at Coburn Lake became larger, more frequent, and more closely correlated with the beginning of severe droughts and associated temperature extremes over the past 1,800 years. Results from other long-term paleoecological studies also support the abrupt climate change-severe fire-severe erosion hypothesis. Stand-replacing fires and transitory spikes in charcoal were found to follow changes in climate in Washington (Cwynar 1987), Yellowstone National Park (Meyer et al. 1995), New York (Clark et al. 1996), Minnesota (Whitlock and Bartlein 1997), and Idaho (Pierce et al. 2004) during the Holocene. Both Meyer et al. (1995) and Pierce et al. (2004) reported increased charcoal deposition beginning c. 3,000 years ago. Charcoal records from adjacent lakes in eastern British Columbia became more synchronized with climate events as climates became more variable beginning c. 2,500 cal year BP (Gavin et al. 2006). Miller et al. (2001) found that a shift to drier and hotter conditions over the period c. 2,500 to 1,300 cal year BP in central Nevada led to massive mountain slope erosion over the past c. 1,900 years, with channel entrenchment occurring in the downslope sediment deposits that resulted from this erosion.

In eastern Canadian boreal forests, Carcaillet et al. (2001) found large increases in both fire frequency and the deposition of charcoal into lakes beginning 2,200–2,000 cal year BP. The authors noted that Jack pine (*Pinus banksiana*) began a sustained increase in dominance 2,000 cal year BP; and that both Jack pine and green alder (*Alnus viridis*), both fire-adapted early pioneer species, increased in dominance beginning 1,300 cal year BP coincident with an abrupt increase in precipitation in Greenland. Carcaillet et al. (2001) concluded that increases in fire incidence, charcoal deposition, and the number of pioneer species in eastern Canada resulted from the onset of more unstable climate conditions beginning c. 2,000 cal year BP.

Studies limited to the past few centuries also support the abrupt climate change-severe fire-severe erosion hypothesis. Widespread fires in the American West have occurred during or following extreme droughts in the northern Sierra Nevada (Taylor 2000), eastern Washington (Hessl et al. 2004) and the American Southwest (Swetnam and Betancourt 1998). Severe erosion has also followed severe drought conditions over the past 400 years (McAuliffe et al. 2006).

Experiences with droughts and fires that have occurred recently also support the abrupt climate change-severe fire-severe erosion hypothesis. Even relatively brief droughts of <10 years in duration have caused severe tree mortality followed by severe fires (Burkett et al. 2005) and severe soil erosion (Reinhardt et al. 2001; Shakesby and Doerr 2006). In the central Sierra Nevada, higher tree mortality followed a series of years with below normal precipitation and snow pack (Guarin and Taylor 2005). Drought-killed forests in the American Southwest have been burning and are now being replaced by new vegetation better adapted to newer, drier

climate conditions (Breshears et al. 2005). Recent modeling suggests that very large fires should be expected during periods of climate transition (Pueyo 2007). Given these responses to the onset of relatively mild droughts occurring today, it seems appropriate to assume that the onset of more severe droughts, lasting for decades or centuries, coupled with extremely high temperatures, as occurred in the Holocene, would have had even more severe impacts upon ecosystems and natural landscapes.

The Coburn Lake charcoal record is unusual in that all charcoal peaks or increases in charcoal occurred at the beginning of severe droughts and only at the beginning of severe droughts over the past 1,800 cal year BP. The size and configuration of the Coburn Lake watershed, as described above in Section 2: The Coburn Lake Study Area, may explain why Coburn Lake was so unusually sensitive to recording only ACCE-linked fires. Emergent vegetation around Coburn Lake may have filtered out charcoal except following the largest events.

Abrupt climate change-linked fires probably affected other ecosystems at the beginning of severe droughts and high temperatures during the late Holocene as well. However, ACC-linked fires may not be evident in charcoal records from other sites due to differences in geomorphology, vegetation, and fire regimes between sites; and different ecosystems would have reacted differently to increases in available moisture and ACCES. If ACC-linked fires did occur at other sites, ACC-linked charcoal peaks may be hard to distinguish from the abundance of charcoal that has typically accumulated from non-ACCE-linked fires.

5.8 Peak fluvial conditions in the Sierra Nevada coincided with peak drought conditions in Greenland

Evidence from Coburn and Pyramid Lake suggests synchronization between climate events that occurred in the Sierra Nevada and climate events that occurred in eastern Canada and Greenland. Figure 8 displays the timing of peak drought conditions in Greenland in relationship to the timing of charcoal peaks from Coburn Lake. Charcoal peaks from Coburn Lake, associated with the beginnings of drought conditions in the Sierra Nevada, were highly correlated with peak drought conditions in Greenland (Pearson product moment correlation coefficient, $r = 0.998$). Only one of eight charcoal peaks from Coburn was not closely associated with one of the eight instances of precipitation minima in Greenland over the past 1,800 years. This one charcoal peak occurred at 1,430 cal year BP, c. 115 years after peak drought conditions had occurred in Greenland (Fig. 8, Col A). On average, the timing of peak charcoal deposits into Coburn Lake and the occurrence of peak drought conditions in Greenland differed by only 34 years.

A remarkable degree of synchronicity also appears to exist between the timing of the start of droughts in the Sierra Nevada and the timing of severe fires in an eastern Canadian boreal forest. Carcaillet et al. (2001) studied charcoal deposited into Lac Francis over the past c. 7,650+ years. Though Carcaillet et al. did not specifically study individual charcoal peaks in relation to ACCES, an analysis of their published data suggests that Lac Francis, like Coburn Lake, might also have been an unusually good recorder of ACC-caused fires (Fig. 9).

To compare the two data sets, I first determined the 11 largest charcoal peaks deposited into Lac Francis over the past 2,800 years (Fig. 7 in Carcaillet et al. 2001). I did this by comparing the size of each charcoal peak relative to the size of adjacent

Fig. 9 Correlation between the timing of the beginning of droughts in the northern Sierra Nevada (Mensing et al. 2004) and the deposition of charcoal peaks into Lac Francis, Quebec. The timing of the starting dates for 11 severe droughts in northern Sierra Nevada over the past c. 3,000 years as compared with timing for the deposition of the 11 largest charcoal peaks from Lac Francis over the past 3,000 years (adapted from Carcaillet et al. 2001). Vertical numbers above charcoal peaks represent the timing of charcoal peaks from Lac Francis relative to (:) the timing of the onset of droughts in the northern Sierra Nevada

charcoal peaks. Then I compared the timing of these 11 largest charcoal peaks relative to the timing of the beginnings of severe droughts in the northern Sierra Nevada (Fig. 5 in Mensing et al. 2004).

Similarities between the two records were remarkably high despite the great distance between the two study sites, differences in vegetation (subalpine forest at Coburn Lake versus boreal forest at Lac Francis), and differences in their respective climate regimes. Beginnings of drought conditions in the Sierra Nevada were highly correlated in time with the occurrence of the largest charcoal peaks deposited into Lac Francis over the past 2,800 years (Pearson product moment correlation coefficient = 0.999; Fig. 9). Indeed, the average number of years of difference between the onset of severe droughts in the northern Sierra Nevada and the timing of deposition of large charcoal peaks into Lac Francis (± 23 years) was below the levels of uncertainty involved in dating the lake sediments originally. In addition, charcoal deposition into Lac Francis rose significantly during the Late Holocene, just as it had at Coburn Lake.

Other studies have recognized climate teleconnections between California and the North Atlantic region. In sediments from the Santa Barbara Ocean Basin off southern California, Behl and Kennett (1996) found evidence for 19 of 20 warm interstadial periods (Dansgaard–Oeschger events) previously reported from Greenland ice cores and North Atlantic Ocean sediment cores. Pisias et al. (2001) also suggested correlations between coastal upwelling, temperature, and vegetation along the coast of Oregon and Dansgaard–Oeschger cycles reported from Greenland. Dean (2007) studied ocean sediments from the margins of Alta and Baja California covering the past 60,000 years and suggested climate teleconnections between California, the Cariaco Basin off Venezuela, and Greenland. Benson et al. (1997, 1998) and Lin et al. (1998) reported teleconnections between three lakes located in the Great Basin east of the Sierra Nevada Range (Owens, Mono, and Searles Lakes) and Greenland.

This synchronicity between climate and disturbance events in the Sierra Nevada and disturbance and climate events at Lac Francis and in Greenland, respectively, suggests there were shared climate teleconnections between at least high elevation sites in the northern Sierra Nevada and high latitude sites in eastern Canada (50° N latitude) and Greenland (75° N latitude) in the past. However, shared climate teleconnections between the northwestern Pacific and the North Atlantic do not require that events that occurred in one region (e.g. the North Atlantic) directly caused events in the other (e.g. the Sierra Nevada), rather that both regions were affected by at least some of the same climate drivers.

One possible explanation for these climate teleconnections proposed here is that the Earth's major precipitation zones (the northern Polar Front, the Polar Jet Stream, the Subtropical High Pressure Arid Zone, and the Intertropical Convergence Zone) all moved rapidly northward during some ACCEs. Movement of the Polar Front and associated storms northward would have taken precipitation away from the northern Sierra Nevada and towards Greenland, thus ending drought conditions in Greenland. At the same time, movement of the dry subtropical high-pressure desert belt northward would have brought drought conditions to the northern Sierra Nevada.

Evidence exists for the Polar Front moving in response to cold and warm events. Eynaud et al. (2009) described abrupt shifts in the Polar Front caused by cold Heinrich Events in the North Atlantic Ocean at the end of the last glacial period. Geirsdóttir et al. (2009) suggested that the Iceland Ice Sheet broke up catastrophically c. 15,000 years ago as the Polar Front migrated northward due to warming.

What is interesting, and perhaps suggestive in terms of ongoing man-caused global climate change, is how fast changes from wetter to drier and from hot to cold conditions appear to have occurred in the Sierra Nevada and Greenland during past periods of ACC. Modeling from the IPCC Assessment Report 4 (IPCC 2007) suggests that the subtropical dry zones of the world will both dry and expand poleward in the future due to greenhouse warming. Seager et al. (2007) noted that recent severe droughts experienced in the southwestern United States may have been associated with a northward shift of storm tracks and expansion of the subtropical high into the mid-latitudes. Though ongoing warming due to the gradual buildup of greenhouse gases might suggest to us that changes in climate will occur slowly over time, the paleoclimate record shows us that a transition to a megadrought or extreme temperatures can be very abrupt indeed, with tragic consequences for many.

6 Conclusions

Combining three paleorecords from the Sierra Nevada resulted in a detailed history of environmental change in the Sierra Nevada over the past 2,000 years. Comparing a published record of paleoprecipitation for the northern Sierra Nevada, derived from Pyramid Lake, Nevada, with a published record of paleotemperature for the southern Sierra Nevada, derived from Cirque Peak, California, suggests that precipitation and temperature in the Sierra Nevada changed abruptly over the past 2,000 years and often changed in concert with each other. Hot temperatures appear to have occurred at the beginning of most severe droughts over that time period.

Charcoal from Coburn Lake, California displayed an unusually peaked distribution. Charcoal peaks were deposited at the beginnings of every severe drought in the northern Sierra Nevada over the past 1,800 years. Most of the charcoal peaks were also associated with proxies suggesting erosion after stand-replacing fires. These results suggest that stand-replacing fires at Coburn Lake occurred at the beginning of severe droughts coupled with hot temperatures over the past 1,800 years, and that these stand-replacing fires were often followed by severe erosion.

From this evidence, I propose a generalized “abrupt climate change-severe fire-severe erosion hypothesis.” This hypothesis suggests that abrupt climate change during the late Holocene caused vegetation and mountain slopes in some areas to be out of balance with abruptly changed climates. These imbalances severely stressed vegetation adapted to preceding moister climates, resulting in increased insect or disease infestation followed by widespread forest die-off, stand-replacing fires, and accelerated soil erosion.

A review of the Greenland ice core data suggests that the climates in Greenland became more variable, cooler, and wetter during the past 3,700 to 3,000 years than in preceding millennia. The magnitude of abrupt changes in temperature increased c. 3,700 years ago; while the magnitude of abrupt changes in precipitation increased 3,000 years ago. Temperatures began to decline in Greenland c. 2,400 years ago and precipitation underwent a major increase c. 1,300 years ago.

Climates became wetter and more variable in the northern Sierra Nevada during the latest Holocene as well. Precipitation began exhibiting more extreme changes in precipitation sometime between 3,400 and 2,800 years ago and then precipitation increased substantially c. 2,000 years ago. More extreme changes in precipitation as well as a general increase in available moisture may explain both an increase in the number of severe fires at Coburn Lake and a close correlation between those fires and abrupt climate events over the past 1,800 years.

Synchronicity between climate events in the Sierra Nevada and Greenland also increased during the latest Holocene. Charcoal peaks from Coburn Lake and the beginnings of severe droughts in the northern Sierra Nevada were significantly correlated with the beginning of the end of severe drought conditions in Greenland. As moisture was increasing in Greenland, severe droughts were beginning in the northern Sierra Nevada.

A possible mechanism to explain this relationship is that the general locations of the Earth’s major precipitation belts shifted rapidly northward during abrupt climate change events during the late Holocene, sending the storm-laden Polar Front northward over Greenland and the arid northern subtropical high pressure zone northward over northern California.

Acknowledgements Results from Coburn Lake were first presented in May and August of 2005 by the author (Wathen 2005). Thank you to all those people who reviewed versions of this paper since then. In particular, I would like to thank my advisor Dr. Michael Barbour at UC Davis for his support, Dr. Jennifer Richards at Florida International University for her editing of this manuscript, and Tom Brown at the Livermore CAM Laboratory for his generosity in ^{14}C AMS dating. Thanks also to those individuals at the University of California Davis who helped me process and count charcoal; the Geological Society of America and the University of California Davis for funding; and Christopher Carcaillet et al., Scott Mensing et al., Louis Scuderi, and the National Geophysical Data Center for generously sharing their data.

Open Access This article is distributed under the terms of the Creative Commons Attribution Noncommercial License which permits any noncommercial use, distribution, and reproduction in any medium, provided the original author(s) and source are credited.

References

- Acuna-Soto R, Stahle DW, Therrell MD, Chavez SG, Cleaveland MK (2005) Drought, epidemic disease, and the fall of classic period cultures in Mesoamerica (AD 750–950): hemorrhagic fevers as a cause of massive population loss. *Med Hypotheses* 65:405–409
- Barbour MG, Berg NH, Kittel TGF, Kunz ME (1991) Snowpack and the distribution of a major vegetation ecotone in the Sierra Nevada of California. *J Biogeogr* 18:141–149
- Behl RJ, Kennett JP (1996) Brief interstadial events in the Santa Barbara basin, NE Pacific, during the past 60 kyr. *Nature* 379:243–246
- Benson L, Burdett J, Lund S, Kashgarian M, Mensing S (1997) Nearly synchronous climate changes in the Northern Hemisphere during the last glacial termination. *Nature* 388:263–265
- Benson LV, Lund SP, Burdett JW, Kashgarian M, Rose TP, Smoot JP, Schwartz M (1998) Correlation of late-Pleistocene lake-level oscillations in Mono Lake, California, with North Atlantic climate events. *Quat Res* 49:1–10
- Benson L, Kashgarian M, Rye R, Lund S, Paillet F, Smoot J, Kester C, Mensing S, Meko D, Lindström S (2002) Holocene multidecadal and multicentennial droughts affecting Northern California and Nevada Pyramid Lake, Nevada. *Quat Sci Rev* 21:659–682
- Breshears DD, Cobb NS, Rich PM, Price KP, Allen CD, Balice RG, Romme WH, Kastens JH, Floyd ML, Belnap J, Anderson JJ, Myers OB, Meyer CW (2005) Regional vegetation die-off in response to global-change-type drought. *PNAS* 102:15144–15148
- Burkett VR, Wilcox DA, Stottlemeyer R, Barrowa W, Fagre D, Baron J, Price J, Nielsen JL, Allen CD, Peterson DL, Ruggerone G, Doyle T (2005) Nonlinear dynamics in ecosystem response to climatic change: case studies and policy implications. *Ecol Complex* 2:357B394
- Carcaillat C, Bergeron Y, Richard PJH, Frechette B, Gauthier S, Prairie YT (2001) Change of fire frequency in the Eastern Canadian boreal forests during the Holocene: does vegetation composition or climate trigger the fire regime? *J Ecol* 89:930–946
- Clark JS (1988) Particle motion and the theory of charcoal analysis: source area, transport, deposition, and sampling. *Quat Res* 30:67–80
- Clark JS (1990) Fire and climate change during the last 750 yr in Northwestern Minnesota, USA. *Ecol Monogr* 60:135–160
- Clark DH (2000) Revised glacial chronology for the Sierra Nevada, California: late-Wisconsin through present. In Geological Society of America Annual Meeting. Geological Society of America, Reno, NV
- Clark JS, Hussey TC (1996) Estimating the mass flux of charcoal from sedimentary records: effects of particle size, morphology, and orientation. *The Holocene* 6:129–144
- Clark JS, Royall PD, Chumbley C (1996) The role of fire during climate change in an eastern deciduous forest at Devil's Bathtub, New York. *Ecology* 77:2148–2166
- Cwynar LC (1977) Recent history of fire and vegetation from laminated sediment of greenleaf lake, Algonquin Park, Ontario. *Can J Bot* 56:10–21
- Cwynar LC (1987) Fire and the forest history of the north cascade range. *Ecology* 68:791–802
- Dean WE (2007) Sediment geochemical records of productivity and oxygen depletion along the margin of western North America during the past 60,000 years: teleconnections with Greenland Ice and the Cariaco Basin. *Quat Sci Rev* 26(1–2):98–114
- Douglass AE (1936) The central pueblo chronology. *Tree-Ring Bull* 2:29–34
- Eynaud F, de Abreu L, Voelker A, Schönfeld J, Salgueiro E, Turon J, Penaud A, Toucanne S, Naughton F, Sánchez G, Fernanda M, Malaizé B, Cacho I (2009) Position of the polar front along the Western Iberian margin during key cold episodes of the last 45 ka. *Geochem Geophys Geosyst* 10(7):Q07U05
- Gajewski K, Winkler MG, Swain AM (1985) Vegetation and fire history from three lakes with varved sediments in Northwestern Wisconsin (USA). *Rev Palaeobot Palynol* 44:277–292
- Gavin DG, Hu FS, Lertzman K, Corbett P (2006) Weak climatic control of stand-scale fire history during the late Holocene. *Ecology* 87:1722–1732
- Geirsdóttir A, Gifford H, Miller G, Axford Y, Ólafsdóttir S (2009) Holocene and latest Pleistocene climate and glacier fluctuations in Iceland. *Quat Sci Rev* 28(21–22):2107–2118

- Grose TLT, Moar RR, Saucedo GJ, Little JD (2000) Geologic map of the Sierraville 15' Quadrangle, Sierra and Plumas Counties, California. California Division of Mines and Geology, Sacramento
- Guarin A, Taylor AH (2005) Drought triggered tree mortality in mixed conifer forests in Yosemite National Park, California, USA. *For Ecol Manage* 218:229–244
- Hessl AE, McKenzie D, Schellhaas R (2004) Drought and pacific decadal oscillation linked to fire occurrence in the Inland Pacific Northwest. *Ecol Appl* 14:425–442
- IPCC (2007) The Physical Science Basis. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) *Climate change 2007: Fourth assessment report of the international panel on climate change*. Cambridge University Press, Cambridge, p 1007
- Larsen CPS, Pienitz R, Smol JP, Moser KA, Cumming BF, Blais JM, MacDonald GM, Hall RI (1998) Relations between lake morphometry and the presence of laminated lake sediments: a re-examination of Larsen and Macdonald (1993). *Quat Sci Rev* 17:711–717
- Leroya SAG, Jousseb H, Cremaschic M (2006) Dark nature: responses of humans and ecosystems to rapid environmental changes. *Quat Int* 151:1–2
- Lin JC, Broecker WS, Hemming SR, Hajdas I, Anderson RF, Smith GI, Kelley M, Bonani G (1998) A reassessment of U-Th and C-14 ages for late-glacial high-frequency hydrological events at Searles Lake, California. *Quat Res* 49:11–23
- Long CJ, Whitlock C, Bartlein PJ, Millspaugh SH (1998) A 9000-year fire history from the Oregon Coast Range, based on a high-resolution charcoal study. *Can J For Res* 28:774–787
- MacDonald GM, Larsen CPS, Szeicz JM, Moser KA (1991) The reconstruction of boreal forest-fire history from lake sediments- a comparison of charcoal, pollen, sedimentological, and geochemical indexes. *Quat Sci Rev* 10:53–71
- McAuliffe JR, Scuderi LA, McFadden LD (2006) Tree-ring record of hillslope erosion and valley floor dynamics: landscape responses to climate variation during the last 400yr in the Colorado Plateau, Northeastern Arizona. *Glob Planet Change* 50:184–201
- McCabe GJ, Palecki MA (2006) Multidecadal climate variability of global lands and oceans. *Inter J Climatol* 26:849–865
- Mensing SA, Benson LV, Kashgarian M, Lund S (2004) A holocene pollen record of persistent droughts from pyramid Lake, Nevada, USA. *Quat Res* 62:29–38
- Meyer GA, Wells SF, Balling RC, Jull AJT (1992) Response of alluvial systems to fire and climate change in Yellowstone National Park. *Nature* 357:147–150
- Meyer GA, Wells SG, Jull AJT (1995) Fire and alluvial chronology in Yellowstone National Park: climatic and intrinsic controls on Holocene geomorphic processes. *Geol Soc Am Bull* 107:1211B1230
- Miller J, Germanoski D, Waltman K, Tausch R, Chambers J (2001) Influence of late Holocene hillslope processes and landforms on modern channel dynamics in upland watersheds of Central Nevada. *Geomorphol* 38:373–391
- Moser KA, MacDonald GM, Bloom AM, Potito A, Porinchu DF (2004) A Holocene record of climate change from the Sierra Nevada, CA, USA: a paleolimnological perspective of California drought. In *AGU Fall Meeting, San Francisco, CA, PP43A-0600*
- National Snow and Ice Data Center and World Data Center-A for Paleoclimatology (1997) *The Greenland Summit Ice Cores CD-ROM*. University of Colorado and National Geophysical Data Center, Boulder, Colorado
- Pierce JL, Meyer GA, Jull JT (2004) Fire-induced erosion and millennial-scale climate change in Northern Ponderosa pine forests. *Nature* 432:87–90.
- Pisias NG, Mix AC, Heusser L (2001) Millennial scale climate variability of the northeast Pacific Ocean and northwest North America based on radiolaria and pollen. *Quat Sci Rev* 20:1561–1576
- Pueyo S (2007) Self-organized criticality and the response of wildland fires to climate change. *Clim Change* 82:131–161
- Reinhardt ED, Keane RE, Brown JK (2001) Modeling fire effects. *Inter J Wild Fire* 10:373–380
- Scuderi LA (1993) A 2000-year tree ring record of annual temperatures in the Sierra Nevada mountains. *Science* 259:1433–1437
- Seager R, Graham N, Celine Herweijer C, Gordon AL, Kushnir Y, Cook E (2007) Blueprints for Medieval Hydroclimate. *Quat Sci Rev* 26(19–21):2322–2336
- Shakesby RA, Doerr SH (2006) Wildfire as a hydrological and geomorphological agent. *Earth-Sci Rev* 74:269–307
- Swetnam TW, Betancourt JL (1998) Mesoscale disturbance and ecological response to decadal climatic variability in the American Southwest. *J Clim* 11:3128–3147

- Taylor AH (2000) Fire regimes and forest changes in mid and upper montane forests of the southern Cascades, Lassen Volcanic National Park, California, U.S.A. *J Biogeogr* 27:87–104
- United States National Research Council Committee on Global Change Research (2002) Abrupt climate change: inevitable surprises. In: Alley RB, Marotzke J, Nordhaus WD, Overpeck JT, Peteet DM, Pielke RA Jr, Pierrehumbert RT, Rhines PB, Stocker TF, Talley LD, Wallace JM (eds) National Academy Press, Washington
- Wathen SF (2005) The use of high magnitude spikes in sedimentary charcoal and magnetic susceptibility to detect abrupt climate change and subsequent geomorphological and ecological readjustment. 90th Annual Meeting of the Ecological Society of America, Montreal, Canada, August 10
- Weiss H, Bradley RS (2001) What drives societal collapse? *Science* 291:609–610
- Weninger B, Jöris O, Danzeglocke U (2004) Cologne radiocarbon, calibration, and paleoclimate research package (Calpal): Online Quickcal 2004 Version 1.2
- Whitlock C, Anderson RS (2003) Fire history reconstructions based on sediment records from Lakes and Wetlands. In: Veblen TT, Baker WL, Montenegro G, Swetnam TW (eds) Fire and climatic change in temperate forests of the Americas. Springer, New York, pp 3–31
- Whitlock C, Bartlein PJ (1997) Vegetation and climate change in Northwest America during the past 125 Kyr. *Nature* 388:57–61
- Whitlock C, Larsen C (2001) Charcoal as a fire proxy. In: Smol JP, Birks HJB, Last WM (eds) Tracking environmental change using lake sediments: volume 3 terrestrial, algal, and siliceous indicators. Kluwer, Dordrecht, pp 75–97
- Wright HEJ (1991) Coring tips. *J Paleolimnol* 6:37–50
- Zhang DD, Jin CY, Lin GCS, He YQ, Wang JJ, Lee HF (2006) Climatic change, wars and dynastic cycles in China over the last millennium. *Clim Change* 76:459–477