Climatic Change (2010) 98:133–154
DOI 10.1007/s10584-009-9642-y

A century of climate and ecosystem change in Western Montana: what do temperature trends portend?

Gregory T. Pederson · Lisa J. Graumlich · Daniel B. Fagre · Todd Kipfer · Clint C. Muhlfeld

Received: 7 February 2008 / Accepted: 29 June 2009 / Published online: 21 August 2009

Abstract The physical science linking human-induced increases in greenhouse gasses to the warming of the global climate system is well established, but the implications of this warming for ecosystem processes and services at regional scales is still poorly understood. Thus, the objectives of this work were to: (1) describe rates of change in temperature averages and extremes for western Montana, a region containing sensitive resources and ecosystems, (2) investigate associations between Montana temperature change to hemispheric and global temperature change, (3) provide climate analysis tools for land and resource managers responsible for researching and maintaining renewable resources, habitat, and threatened/endangered species and (4) integrate our findings into a more general assessment of climate impacts on ecosystem processes and services over the past century. Over 100 years of daily and monthly temperature data collected in western Montana, USA are analyzed for long-term changes in seasonal averages and daily extremes. In particular, variability and trends in temperature above or below ecologically and socially meaningful thresholds within this region (e.g., −17.8°C (0°F), 0°C (32°F), and 32.2°C (90°F)) are assessed. The daily temperature time series reveal extremely cold days (≤ −17.8°C)

G. T. Pederson (✉)
U.S. Geological Survey, Northern Rocky Mountain Science Center,
Montana State University, 229 AJM Johnson Hall, Bozeman, MT 59717, USA
e-mail: gpederson@usgs.gov

G. T. Pederson · L. J. Graumlich
School of Natural Resources,
The University of Arizona, 325 Bioscience East, Tucson, AZ 85721, USA

D. B. Fagre · C. C. Muhlfeld
U.S. Geological Survey, Northern Rocky Mountain Science Center,
Glacier Field Office, Glacier National Park, MT 59936, USA

T. Kipfer
Big Sky Institute, Montana State University,
106 AJM Johnson Hall, Bozeman, MT 59717, USA

terminate on average 20 days earlier and decline in number, whereas extremely hot days (≥32°C) show a three-fold increase in number and a 24-day increase in seasonal window during which they occur. Results show that regionally important thresholds have been exceeded, the most recent of which include the timing and number of the 0°C freeze/thaw temperatures during spring and fall. Finally, we close with a discussion on the implications for Montana's ecosystems. Special attention is given to critical processes that respond non-linearly as temperatures exceed critical thresholds, and have positive feedbacks that amplify the changes.

1 Introduction

The scientific basis for asserting that the global climate system is changing due to human influence has been firmly established through many lines of evidence ranging from observational studies to climate models. General circulation models have quantified and assessed sensitivity of the Earth's climate system to solar and greenhouse gas forcings (e.g. Hansen et al. 2005; Lugina et al. 2005; NRC 2005), and paleoclimatic studies have provided important historical perspectives (e.g. Moberg et al. 2005; Oerlemans 2005; NRC 2006). The physical science basis for detecting and attributing climate change indicates that the recent warming of the climate system is unequivocal, as evidenced from observations of increases in global average air and ocean temperatures (e.g. Hansen et al. 2005; Rayner et al. 2006), widespread melting of perennial snow and glacial ice (Durgerov and Meier 2005), and a rising global average sea level (e.g. Church and White 2006).

The accumulated weight of the scientific evidence for global warming has brought about a profound change in the level of engagement of a wide range of stakeholders in defining potential impacts for ecosystem services and livelihoods. This engagement provides new challenges for the scientific community to develop robust assessments of regional to local trends and trajectories. For example, federal resource managers cite the lack of site-specific information to plan for and manage the effects of climate change as one of the key challenges they face in addressing the impacts of climate change (GAO 2007). More generally, site-specific information is critical to understanding the degree to which regional patterns reflect hemispheric or global temperature rise (Easterling et al. 2000). Accordingly, an analysis of 100+ years of daily and monthly temperature data for western Montana, USA, is presented as a case study with three purposes. First, high-quality, archival climate records are analyzed to assess the nature and significance of local temperature variability and trends. Second, R project (R Development Core Team 2007) software developed to quantify changes in daily temperature extremes is made freely available with modifiable script—allowing for similar analyses to be tailored to, and conducted for, regions and species of interest. Finally, results are used to identify and discuss the sensitivity of ecosystems and economies in Montana to changing temperature based upon a survey of current literature.

Why investigate changes in temperature averages and extremes in western Montana? The region presents a compelling opportunity for a case study because it contains one of the world's last remaining intact temperate ecosystems. At present, the ecosystem still supports the full assemblage of native species known to have historically inhabited the region—since the time of the first biological surveys. The coldwater fisheries support some of the most intact, high-quality habitat remaining for native char and Salmonids. The region also serves as home to the last remaining viable and self-sustaining mega fauna (e.g. American Bison (*Bison bison*)) and predator populations (e.g. Grizzly Bear (*Ursus arctos horribilis*), Gray Wolf (*Canis lupus*)) in the lower 48 United States. Aside from the biological conservation value of western Montana, the mountain ranges serve as critical headwaters for the Columbia, Missouri, and Saskatchewan Rivers. The importance of the hydrological, biological, and natural resources of this region are highlighted by the extent of federally protected lands (Fig. 1), and the designation of core areas (i.e. Glacier–Waterton International Peace Park, and Yellowstone National Park) as United Nations Educational, Scientific, and Cultural Organization (UNESCO) World Heritage sites. Regional warming, and specifically how impacts from global warming are expressed locally, represents one of the largest threats to the biological and natural recourses contained within and around protected areas since the lands were given special protection status.

What climatically defines and sets this region apart from other areas within the lower 48 United States? By the standards of a vast majority of people who live outside the Arctic, western Montana is a "cold" place. Annual average temperatures derived from the nine western Montana station records (Fig. 1, Table 1) show that valley temperatures hover around 5.8°C (42.5°F). This reflects the length of the cool seasons with fall, winter, and spring averaging 6.1°C (43.0°F), −5.0°C (23.0°F), and 5.4°C (41.8°F) respectively. Additionally, the dry continental nature of Montana's climate means localized areas well suited for radiative cooling can experience extreme temperatures exceeding −46°C (−50°F) (Western Regional Climate Center, WRCC 2007). For example, the lowest temperatures ever recorded

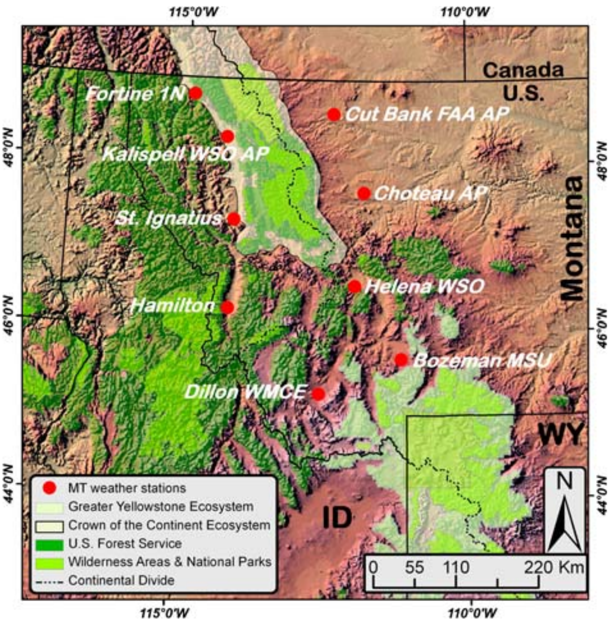

Fig. 1 Map of western Montana showing meteorological stations used in this study, and the extensive, intact ecosystems of the region. National Parks, wilderness areas and other protected and managed federal lands are *highlighted*

Table 1 Location, elevation, and percent of record present for western Montana meteorological stations used in this study

Weather station	Elevation (m)	Latitude	Longitude	Record present (%) (years of record)
Bozeman MSU	1,497.5	45°40′N	111°03′W	99.8 (1892–2006)
Choteau AP	1,172.0	47°49′N	112°12′W	97.3 (1893–2006)
Cut Bank FAA AP	1,169.8	48°36′N	112°23′W	99.0 (1903–2006)
Dillon WMCE	1,593.5	45°13′N	112°39′W	99.5 (1895–2006)
Fortine 1N	914.4	48°47′N	114°54′W	99.5 (1906–2006)
Hamilton	1,080.5	46°15′N	114°10′W	98.6 (1895–2005)
Helena WSO	1,166.8	46°36′N	111°58′W	99.9 (1893–2006)
Kalispell WSO AP	901.3	48°18′N	114°16′W	99.9 (1896–2006)
Saint Ignatius	883.9	47°19′N	114°06′W	98.6 (1896–2006)

in the United States (excluding Alaska) occurred on January 20, 1954 at Rodgers Pass where temperatures fell to −57.0°C (−70.0°F; WRCC 2007). Conversely, summers are defined by warm days and cool nights with valley temperatures averaging 16.9°C (62.3°F). The intermountain regions of western Montana not only have a large climatological difference in cool and warm season temperatures, but also are prone to large and rapid variations in temperature on extremely short time scales (i.e. weather events).

The high inter-seasonal and daily extremes in temperature that define this region and its ecosystems motivated our investigation of changes in seasonal averages and daily extremes (vs. seasonal or annual averages). For many physical processes critical to resource management (e.g. timing of snowmelt, timing and amount of streamflow, and forest fire activity), changes in variability, duration, and timing of extreme events within a season may be just as important (if not more so) than changes in seasonal averages. For example, the timing, duration, and severity of a specific temperature anomaly may cause undesirable biological organisms (i.e. invasive) to thrive, and strain physical resources such as water and its sources (e.g. snow and glaciers). Consecutive days of high temperatures combined with earlier snowmelt and a longer dry season have also resulted in more frequent forest fires in the western U.S. (e.g. Westerling et al. 2006). This point is particularly acute for western Montana forests, as temperatures preceding and during the fire season exert a significant influence on area burned, potentially more than long-term fuel accumulation (Littell et al. 2009; Westerling et al. 2006; McKenzie et al. 2004). The same summertime temperature changes have also been documented to be impacting western Montana's glaciers and perennial snow and ice masses (e.g. Fig. 2; Hall and Fagre 2003; Pederson et al. 2004, 2006; Watson et al. 2008), with recent evidence for a portion of the retreat being driven by wintertime warming (Fountain et al. 2007).

A core objective of this paper is to advance understanding of how western Montana's climate is changing across seasons, the degree to which these changes reflect those observed for the Northern Hemisphere (and globally), and to discuss implications for ecosystems and their services. We also assessed changes in variability and timing of temperature thresholds important to biological and physical systems. Specifically, 100+ years of change in absolute temperature thresholds of −17.8°C (0°F), 0°C (32°F), and 32.2°C (90°F) are investigated due to their importance to the people and ecosystems of western Montana. It should be noted that extremes

Fig. 2 Repeat photographs of Boulder Glacier depicting 97 years of change. The Boulder Glacier resided in Glacier National Park, Montana, and the photos were taken from the summit of Chapman Ridge. Morton Elrod captured the 1910 photo, and Greg Pederson and Daniel Fagre reshot the 2007 image. See the USGS repeat photography webpage (http://www.nrmsc.usgs.gov/repeatphoto/) for more images of glacier change in northwestern Montana

in climate could be quantified in terms of relative and absolute extremes. Relative extremes are expressed in terms of percentiles or statistical distributions, whereas absolute extremes may refer to numerical values that represent the genetic, physiological, or even cultural adaptation of plants or animals to certain temperatures. In this paper absolute extremes are used because of their documented regional importance for physical and biological processes. Further, from the standpoint of science communication, there is much greater potential for immediate understanding of the relevance of changes in absolute rather than relative temperatures. The importance of a particular absolute temperature, however, will vary by region and ecosystem. Recognizing the potential utility of producing these records for different regions and processes of interest, the data resources, methods, and analyses are kept simple, adaptable, and made available to scientists and the general public.

2 Methods

Temperature data were obtained from the nine meteorological stations (out of a potential 21 stations) with the longest, high-quality daily and monthly records positioned within or along the Rocky Mountains of western Montana (Fig. 1, Table 1). The subset of stations maximized the length (100+ years) and completeness (>97%) of daily and monthly measurements, and minimized potential bias from station moves and urban heat island effects. The long-term (1895–2002) monthly and daily data used in analyses were provided by the U.S. Historic Climatology Network (USHCN; Williams et al. 2007c), and recent updates (2002–2006) obtained from the Western Regional Climate Center (WRCC 2007). Northern Hemisphere and Global temperature data were obtained from the Global Historic Climatology Network (Lugina et al. 2005).

Utilizing USHCN *monthly temperature data* ensured records have been corrected for time-of-observation biases, station moves, instrument changes, urban heat island effects, and incompleteness of record (Karl et al. 1986, 1988; and Karl and Williams 1987). Though the USHCN *daily temperature data* represent the best high-resolution, long-term climate records available, and are primarily free of time-of-observation biases, care must be taken when interpreting an individual station record since other types of bias corrections (e.g. station moves) are lacking (see Easterling et al. 1999). The potential influence resulting from problems with a single station record were minimized by producing an average regional climatology through mean-scaling followed by record averaging (see below for details).

Missing data always present a potential problem for analyzing and averaging time series. The U.S. HCN monthly temperature data, however, has missing values interpolated by using a network of surrounding stations, so records are generally free of gaps. No such data interpolation has been performed on daily temperature records; so only stations with records greater than 97% complete (Table 1) were used. This ensured data gaps were minimal (usually restricted to a portion of any particular month), and only portions of regional average time series with data from at least five of the nine meteorological stations were presented in final figures.

Regional temperature time series were constructed using monthly and daily data, and then analyzed for long-term seasonal trends, correspondence with variability and trends in Global and Northern Hemisphere temperature, and investigation of changes in temperature thresholds important to biological and physical systems. Individual station maximum, minimum, and average temperature (T_{max}, T_{min}, and T_{avg} henceforth) records were used to construct regional T_{max}, T_{min}, and T_{avg} records for all seasons by scaling the mean and averaging the records. Mean-scaling was performed by calculating a regional 20th century mean for each temperature variable over each season, and centering each station record on that mean before averaging records together. This method preserves the temperature units in degrees Celsius (vs. dimensionless z-scores), allows for investigation of different rates of change between T_{max} and T_{min}, and provides metric-scaled temperature estimates of seasonal averages. After the seasonal and annual temperature time series were produced, the strength of the relationships between regional, Global, and Hemispheric records was assessed using Pearson product-moment correlation coefficients.

Regional daily temperature data statistics were created following the analysis of Weiss and Overpeck (2005), who documented the decreasing number of days and length of freezing season in the Sonoran Desert. Code was written in the R project software environment (R Development Core Team 2007; http://www.r-project.org/) that tallied and summed the annual number of T_{min} days below −17.8°C (0°F) and 0°C (32°F) over a winter year defined as beginning July 1 and ending June 30.

Concurrently, the program tallies and sums the number of T_{max} days above 32.2°C (90°F) for a summer year beginning January 1 and ending December 31. For each temperature threshold variable, the program also records the first and last summer or winter day the threshold value was met. (The daily temperature analysis code along with documentation is available from the U.S. Geological Survey Northern Rocky Mountain Science Center web site (http://www.nrmsc.usgs.gov/MTclimate/)). After the individual station records were generated, a regional average was produced following the same mean-scaling techniques described above. Principal component analysis (see Timm 2002) was performed on the individual station records to identify common variance and regional patterns of temperature change.

3 Results

3.1 Regional trends in seasonal maximum and minimum temperatures

Globally, instrumental evidence exists for significant decreases in Diurnal Temperature Range (DTR) with a more rapid increase observed in T_{min} relative to T_{max} (Easterling et al. 1997; Vose et al. 2005). Current thinking on the physical explanation for the observed rapid rises in T_{min} includes a combination of increased retention of long-wave radiation due to higher atmospheric CO_2 values, land cover changes, and/or potential increases in cloudiness and atmospheric humidity (Easterling et al. 1997). Though atmospheric CO_2 undoubtedly plays a role, other specific mechanisms such as increases in cloudiness and/or atmospheric humidity have not been shown to be a significant factor in this region. In a previous regional study, Watson et al. (2008) found a significant reduction in DTR due to more rapid increases in T_{min} compared to T_{max} from a network of stations running from northwestern Montana north through Jasper National Park, Alberta, CA. The same relationship is apparent for western Montana; however, changes in T_{max} and T_{min} are different across seasons (Fig. 3, Table 2). Annually and seasonally all linear trends in maximum and minimum temperatures are significant ($p \leq 0.05$). The largest decreases in DTR over the past century were due to a more rapid rise in T_{min} and have occurred in summer (DTR reduction = −0.77°C) and winter (DTR reduction = −0.65°C). Spring T_{max} appears to be rising as fast as T_{min} (DTR = 0.01°C), while conversely DTR over the fall season has increased (DTR increase = 0.21°C) with T_{max} rising more rapidly than T_{min}.

The records presented in Fig. 3 exhibit other patterns of variability in seasonal T_{max} and T_{min}, and present evidence of seasonal averages crossing the 0°C solid to liquid phase change (i.e. freeze/thaw) threshold for water. Though freeze/thaw terminology is typically reserved for daily, rather than seasonal, observations of T_{min}/T_{max}, in the interest of keeping discussion simple it will be used interchangeably here. In the spring, summer, and fall interannual variability in T_{max} is greater than T_{min}, but correlation between records is high. During the winter, correlation between records remains high, however, T_{min} exhibits greater absolute interannual variability than T_{max}. Most relevant to water resources (via snow and ice melt) and biological processes, however, are the trend lines for average spring and fall T_{min} that will

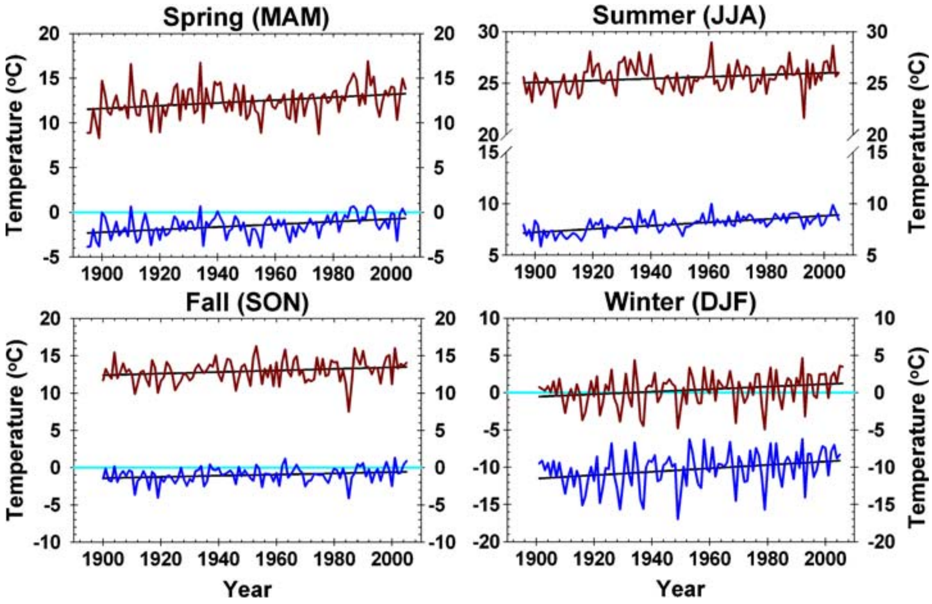

Fig. 3 Seasonal trends in maximum (*red line*) and minimum (*blue line*) temperatures for western Montana. Note change in scale of temperature axis for each season

soon cross the 0°C freeze/thaw threshold if the current trend continues. Though seasonal means are not always the best surrogate for numbers of days above or below specific temperature thresholds, the metrics typically correspond. More importantly, seasonal temperature means do represent the average amount of ambient energy available to do work on a system (e.g. driving phase changes in water), and thus are worth examining in detail. For example, since the 1980s the frequency with which spring and fall T_{min} were above 0°C has increased dramatically (Fig. 3), resulting in a rapid decline in number of days below freezing (discussed further in next section). Winter temperatures show the T_{max} trend-line crossing the 0°C threshold in the 1950s. Specific impacts from further increases of winter T_{max}, however, are unknown since variability is high and has regularly crossed the 0°C threshold in the past.

Table 2 Change in annual and seasonal maximum and minimum temperatures in western Montana

Variable	20th Century Δ (°C)	Δ per decade (°C)	*p*-value
Annual T_{max}	1.13	0.11	0.000
Winter T_{max}	1.77	0.18	0.009
Spring T_{max}	1.58	0.16	0.004
Sumer T_{max}	1.00	0.10	0.015
Fall T_{max}	1.10	0.11	0.027
Annual T_{min}	1.55	0.15	0.000
Winter T_{min}	2.42	0.24	0.002
Spring T_{min}	1.57	0.16	0.000
Summer T_{min}	1.77	0.18	0.000
Fall T_{min}	0.89	0.09	0.010

Overall change and significance of trend was assessed conservatively using ordinary least squares regression

Changes in winter T_{max} may, have substantial impacts on snow depth, snow water equivalent, and cold content of valley snowpacks.

3.2 Trends in daily T_{max}/T_{min} extremes and thresholds

A major concern associated with global warming, and the resultant long-term changes in temperature, are the potential associated changes in frequency and duration of extreme events. Significant changes in number, duration, and variability of the first and last calendar days^{-yr} temperatures were ≥32.2°C (90°F; Fig. 4), ≤0°C (32°F; Fig. 5), and ≤ −17.8°C (0°F; Fig. 5) are documented below. Changes in the number of days^{-yr} ≥32.2°C indicate this region has experienced an approximate three-fold increase in number of extremely hot days^{-yr}. On average, 5 days^{-yr} were ≥32.2°C throughout the early decades of the 20th century. The previous two decades, however, averaged 15 days^{-yr} ≥32.2°C. More conspicuous than the positive trend in days^{-yr} ≥32.2°C, is the increased frequency of years with an extreme number of days ≥32.2°C. The record setting year for number of days ≥32.2°C was 2003 (analysis ends in 2006), at 32 days ≥32.2°C. Other years similar to 2003 in terms of numbers of days ≥32.2°C (i.e. ≥20 days) include, 2001, 2000, 1998, 1988, 1967, 1962, 1961, 1941, 1937, 1932, 1930, and 1919. The number of days^{-yr} the 32.2°C T_{max} threshold was equaled

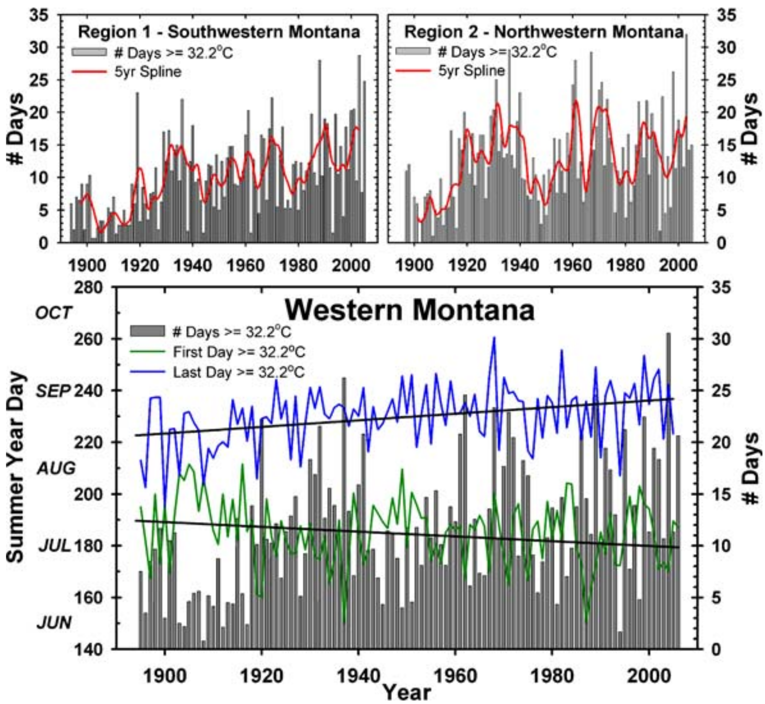

Fig. 4 *Top*: Graphs showing the different rates of change in number of days^{-yr} T_{max} ≥ 32.2°C (*gray bars*) for southwestern (*left*) and northwestern Montana (*right*) from 1895–2006. A 5-year moving average (*red line*) highlights trends and variability in #days^{-yr} ≥ 32.2°C. *Bottom*: Trends in number of days (*gray bars*), and the first (*green line*) and last (*blue line*) day of every summer, that temperature in western Montana equaled or exceeded 32.2°C

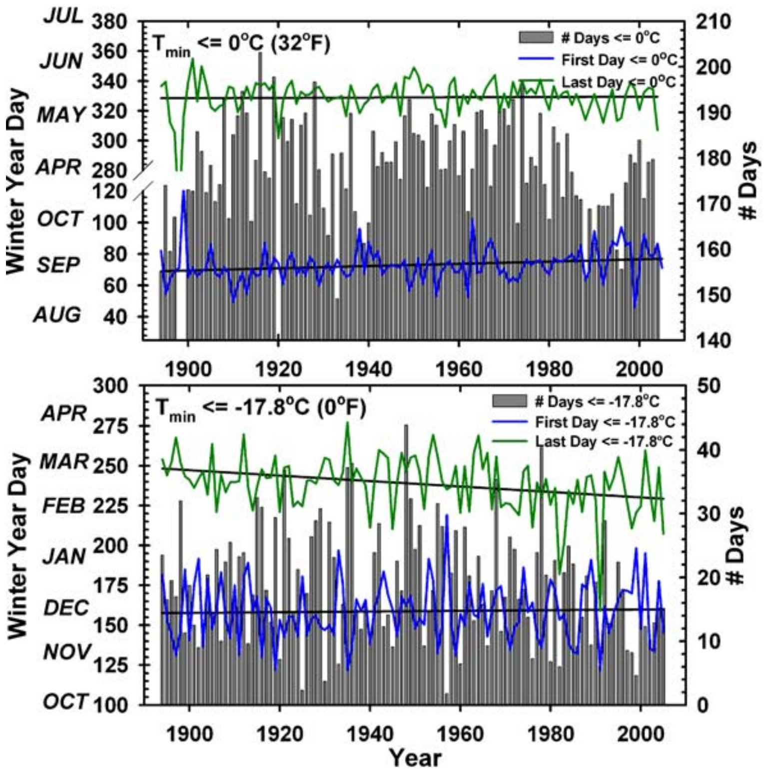

Fig. 5 Average number of frost/freeze days (#days^{-yr} $T_{min} \leq 0.0°C$ (32.0°F)) or extremely cold days (#days^{-yr} $T_{min} \leq -17.8°C$ (0.0°F)) per winter year in Western Montana (*gray bars*). Graphs also depict the first day of fall (*blue line*) and last day of spring (*green line*) temperature equaled or exceeded the defined threshold

or exceeded also exhibits pronounced sub-regional variability. Principal components analysis of individual station data revealed different timing and rates of change for northwestern and southwestern Montana (G. Pederson, unpublished data). Regional averages from stations located in northwestern and southwestern Montana exhibit this relationship (Fig. 4 Top). An extremely rapid early-20th century rise (1917–1942) in average number of days^{-yr} ≥32.2°C, and strong decadal-scale variability is evident for the northwestern region of Montana. The southwestern region, however, exhibits a more linear increase in number of days^{-yr} ≥32.2°C over the period of record (Fig. 4 Top). The rapid 1917–1942 rise in northwestern Montana temperatures was associated with the severe dustbowl and pre-dustbowl droughts of the Pacific Northwest (Pederson et al. 2006; Watson and Luckman 2004), rapid recession of glaciers in Glacier National Park (Carrara 1989; Key et al. 2002; Pederson et al. 2004), as well as increased fire activity (Littell et al. 2009; Pederson et al. 2006).

With a three-fold increase in the average number of days ≥32.2°C, an increase in the seasonal window of time these temperatures can occur is expected. Figure 4 (bottom) shows evidence for the temporal extension of the “hot” summer season with the average first occurrence of temperatures ≥32.2°C in the early-20th century beginning on summer year day (YD) 189 (~July 8), and ending on average by

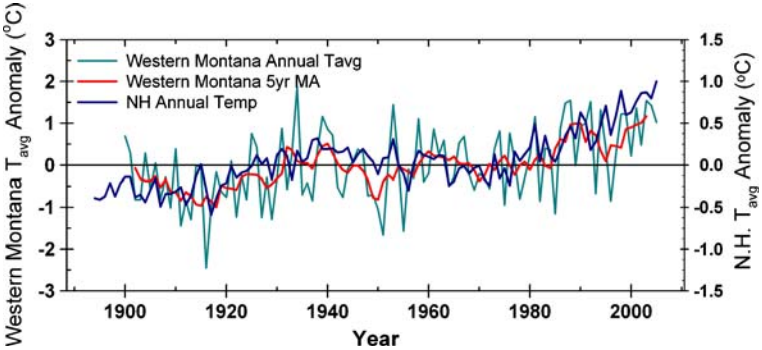

Fig. 6 Comparison of variability and trends in western Montana (*blue-green*) and Northern Hemisphere (*dark blue line*) annual average temperatures. A 5-year moving average (*red line*) highlights the similarity in trends and decadal variability between records

summer YD 223 (~August 11). By the early-21st century, however, the average number of days ≥32.2°C has increased by 24 days, with the first summer YD ≥32.2°C occurring on day 179 (~June 28) and the last "hot" event on summer YD 237 (~August 25).

With a demonstrated increase in number of "hot" days (≥32.2°C) experienced per year across western Montana, it follows logically that a reduction in number of "cold" days per year should be evident. With few exceptions, western Montana meteorological stations have experienced a decrease in annual number of freeze/thaw days ($T_{min} \leq 0$°C), and extremely cold days ($T_{min} \leq -17.8$°C).[1] The average loss of number of days at or below the freeze/thaw threshold ($T_{min} \leq 0$°C) in western Montana is approximately 16 days, declining from an average of ~186 to ~170 days^{-yr} (Fig. 5 top). The sharpest decline in number of freeze/thaw days has occurred within the last 20 years. The decline in number of days ≤0°C corresponds with the increasing number of years that average spring T_{min} has equaled or exceeded 0°C (Fig. 3). Also associated with the decline in average annual number of freeze/thaw days is a narrowing of the annual window over which $T_{min} \leq 0$°C. Figure 5 (top) shows a post-1980s trend towards a later arrival of the first freeze/thaw day in the fall and an earlier termination of freeze/thaw events in the spring.

The regional data document a loss in annual average number of extremely cold days ($T_{min} \leq -17.8$°C). From 1895–1980, western Montana averaged 20 days per year where T_{min} was ≤ −17.8°C, with many "extremely cold" individual years experiencing between 30 to 44 days below −17.8°C (Fig. 5 bottom). Recent decades (1981–2006) have averaged 14 days per year $T_{min} \leq -17.8$°C, with a reduction in frequency of years with high numbers of extremely cold days. For example, the 1992 winter year was the only year with close to a month (29 days) of $T_{min} \leq -17.8$°C.

The onset and end of extremely cold temperatures in the region also exhibits temporal variability. Over the length of record (1895–2006), the onset of extremely cold

[1] In this paper, a freeze/thaw day and an extremely cold day are defined as any 24 hour period where the average regional T_{min} is ≤ 0°C or ≤ −17.8°C respectively. There may be other thresholds of interest, and these can be defined using either T_{avg} or T_{max}, and the R program script.

temperatures ($T_{min} \leq -17.8°C$) is highly variable, exhibits no trends, and typically occurs near winter YD 158 (~December 5; Fig. 5). The last extremely cold day of the winter season, however, has changed significantly, arriving an average of 19 days earlier. During the early-20th century (1900–1910) extremely cold temperatures ($t_{min} \leq -17.8°C$) typically ended on winter YD 248 (~March 5). Over the past decade (1996–2006) the end of winter season's extremely cold events has occurred on average by winter YD 228 (~February 15). The earlier termination of extreme cold events ($t_{min} \leq -17.8°C$) documented here reflects the autumn/spring asymmetry in warming noted below.

3.3 Global warming vs. regional trends

There is a high degree of regional variability in the expression of climate change because temperature variability at regional scales results from the interaction of local- (e.g. land-use and land cover change) and global-scale forcings (e.g. ocean atmosphere interactions, changing concentrations of greenhouse gasses, volcanic events, solar variability). For western Montana, annual and seasonal temperature variability tracks Global and Northern Hemisphere (NH henceforth) trends on short- (interannual) and long-term (multi-decadal and greater) scales (Figs. 6 and 7). The similarity between the interannual temperature variability implies that on a year-to-year basis, if the NH is warm (or cold), typically western Montana is as well. The similarity between long-term trends (or more generally low-frequency change; highlighted in Figs. 6 and 7 using a 5-year moving average) *suggests* that the same large-scale forcings (e.g. GHG forcings, solar variability, SST patterns,

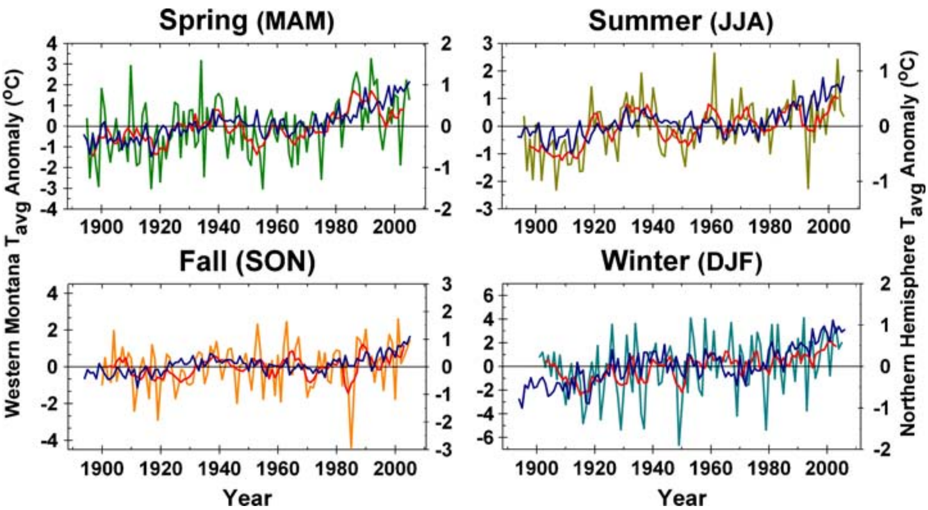

Fig. 7 Comparison between trends in western Montana and Northern Hemisphere (*blue line*) seasonal temperatures. *Red line* displays the western Montana 5-year running mean. Note change in scale of temperature axis for each season, this has implications related to absolute temperature change

Table 3 Correlation between western Montana average annual and seasonal temperatures, and Northern Hemisphere and Global average temperature records

Season	Northern Hemisphere T_{avg} correlation (p-value)	Global T_{avg} correlation (p-value)
Annual	0.581 (0.000)	0.572 (0.000)
Winter (DJF)	0.416 (0.000)	0.401 (0.000)
Spring (MAM)	0.414 (0.000)	0.430 (0.000)
Summer (JJA)	0.465 (0.000)	0.489 (0.000)
Fall (SON)	0.323 (0.001)	0.304 (0.002)

volcanic events) driving global temperature change may drive a substantial portion of the observed low-frequency change in western Montana. Correlations between western Montana, NH, and Global temperatures range from $r = 0.304$ to $r = 0.581$ and are significant ($p \leq 0.005$; Table 3). Similarly, although the relationships between regional and Global temperatures appear robust, at the scale of an individual station the strength of the relationship varies (Fig. 8). The intermediate strengths of the correlations indicate the importance of local- to regional-scale climate forcings as compared to global-scale climate forcings (see Section 4), but also imply results should be interpreted cautiously since the high number of observations functionally results in lower correlation thresholds for a statistically significant finding. Also, correlation analysis assumes a linear relationship between variables; meaning if non-linear relationships between variables exist an overall lower correlation coefficient will be produced.

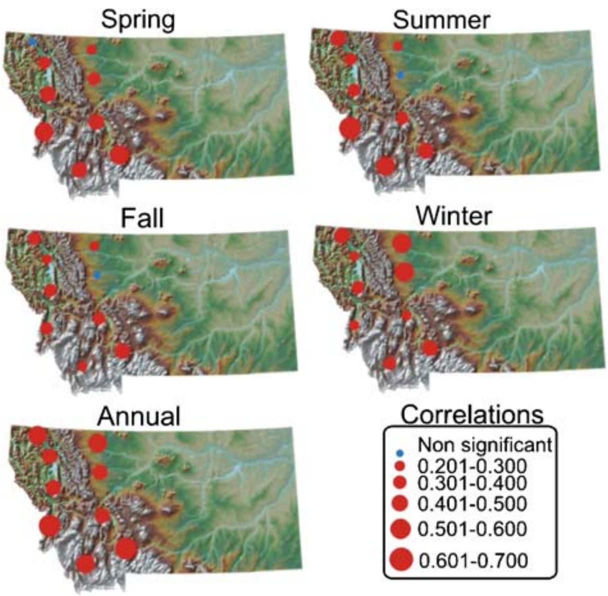

Fig. 8 Correlations between average annual and seasonal temperature records for the Northern Hemisphere and the nine individual Montana stations. Correlations are calculated between the unsmoothed time series and significant values are base on p-value ≤ 0.05

4 Discussion

4.1 Significance and representativeness of climatic trends

The long-term climatic trends in western Montana are consistent with other studies of mountains in the temperate zone (e.g. Nogués-Bravo et al. 2007; Diaz and Eischeid 2007; Mote 2003). Significant trends in daily and seasonal temperature resemble the more rapid warming occurring at high latitudes and across heavily forested regions (Dang et al. 2007). Western Montana has thus far experienced a +1.33°C (1900–2006) rise in annual average temperatures (Fig. 6), which is 1.8 times greater than the +0.74°C (1900–2005) rise in Global temperatures (Lugina et al. 2005).

Any discussion of local- to regional-scale changes in climate, however, warrants further discussion of signal-to-noise ratios, and specifically the increasing amount of unexplainable variability (or "noise") that is encountered at increasingly smaller spatial scales. For example, temperature records from a given meteorological station reflect a mix of local- (e.g. microtopography, orography, development, instrument changes, station moves), regional- (e.g. land-use and land-cover changes, concentration of tropospheric aerosols), and global-scale climate forcings (e.g. ocean atmosphere interactions, changing concentrations of greenhouse gasses, volcanic events, solar variability) whereby the contribution to observed variance in climate from any particular forcing is non-stationary through time. This relationship is reflected by the variable correlation strengths shown for annual and seasonal average temperature records from individual Montana meteorological stations as compared to averages for the Northern Hemisphere (Fig. 8).

Regional climatologies reduce noise associated with local forcings thereby providing a more representative picture of temperature trends and variability at scales comparable to broader climate system changes, yet relevant to regional ecosystems. The fact that western Montana tracks global and hemispheric patterns of temperature change (Figs. 6 and 7) suggests that global-scale forcings dominate, or at least are not strongly counteracted by, local- to regional-scale climate forcings. While this relationship is suggestive that knowledge of global or hemispheric temperature change might provide some predictive relationship of western Montana temperatures, we caution against such simplistic explanations. Using an ensemble of global climate models Williams et al. (2007b) predict the Northern Rockies and consequently western Montana will likely see the rise of a no-analog climate system configuration (see Figure 3 in Williams et al. 2007b). What this means for the future correspondence between western Montana's temperature in relation to global trends and variability is unclear. Similarly, the relationship between global temperature trends (and variability) and trends shown for western Montana do not constitute a formal test of attribution—and should not be interpreted as such.

4.2 Evidence for tipping points and thresholds in climate impacts

The rapid rise in temperature has had a substantial impact on regional resources and ecosystems, in part due to the crossing of critical daily and seasonal temperature thresholds documented here (Figs. 3, 4 and 5). In the discussion below, we describe the most sensitive elements of Montana's ecosystems and economies as those systems that (1) have critical processes that change rates as temperatures exceed critical thresholds, and (2) have positive feedbacks that amplify the changes.

4.2.1 Alpine glaciers are retreating

Perhaps the most iconic impact of climate change in Montana is the retreat of alpine glaciers within Glacier National Park, Montana ([Key et al. 2002; Hall and Fagre 2003; Pederson et al. 2004], cf. Boulder Glacier repeat photographs; Fig. 2). The dramatic recession of glaciers has resulted in part from the accelerated rate of ablation (i.e. melting) that occurs with increasing average temperatures over the critical spring and summer ablation season. Increases in ablation season average temperatures coupled with spring and fall average $T_{\min}$ crossing the freeze/thaw threshold implies both an intensification of available energy to melt ice, and a potential lengthening of season over which melt occurs. The analysis of daily data presented here shows a reduction in extreme cold events and frost/freeze events, and an intensification of daily high-temperature events with a lengthening of ablation season (Figs. 4 and 5).

The melting of alpine glaciers and perennial snow and ice masses, however, is not a simple linear response to an outside climatic forcing. The initial response of alpine glaciers to regional warming (i.e. glacier retreat) entrains a number of local climatic positive feedbacks that amplify the physical response of the system. This is especially true when average temperatures begin crossing important physical thresholds, such as the 0°C freeze/thaw isotherm. For example, as ice retreats and exposes more of the surrounding bedrock and cirque walls, approximately 50% more long-wave radiation is reemitted due to greatly reduced surface albedo resulting in more sensible heating of the local environment. Thus, the area around the glacier warms non-linearly and increases melt rates along the glacial margins, thereby accelerating the retreat process.

4.2.2 Fire and mortality is transforming forests

The increasing number of hot days (days$^{-yr} \geq 32.2°$C) and the loss of frost/freeze (days$^{-yr} \leq 0°$C) coincides with a number of observed changes in forest ecosystems. First, the overall warming of the mountainous areas of western Montana during the winter and spring, and the average loss of 16 days of temperatures ≤0°C matches the observed 5 to >20 day advance in the center-of-mass timing (CT) in streamflow for Montana (Stewart et al. 2005), and a 30% reduction in April 1 snow water equivalent across the Pacific Northwest since 1950 (Mote 2003). Though changes in temperature records from western Montana have not explicitly been linked to changes in snowpack and streamflow timing here, Stewart et al. (2005) documents changes in temperature as a significant driver in CT with the effects of larger synoptic controls (i.e. the Pacific Decadal Oscillation) removed (see Figure 11; Stewart et al. 2005). Also, a recent detection and attribution study from Barnett et al. (2008) ascribes a majority (>60%) of the observed changes in Western U.S. snowpack (and hence streamflow) from 1950–1999 to anthropogenic causes.

The earlier melt-out of mountain snowpacks combined with the increasing number of days and length of season over which hot days occur has been shown by Westerling et al. (2006) to have resulted in significant increases in fire frequency and area burned both regionally and throughout the Western U.S. since the 1970s. This study, however, lacks the long-term perspective provided by other fire/climate research (e.g. Littell et al. 2009; McKenzie et al. 2004), which provide a more nuanced perspective. The forests of western Montana, and the northern Rockies have been found to have a fire regime strongly controlled by temperature and precipitation (i.e. water balance [Littell et al. 2009]), thus making the forests of western Montana highly vulnerable to increased temperatures (Westerling et al. 2006). Increased temperatures, however, are not the sole cause of frequent and large forest fire activity. Both an ignition source (e.g. lightning, human activity) and a mechanism for rapid spread (i.e. wind generated by storm fronts or the fires themselves) are a necessity for widespread regional fire activity (McKenzie et al. 2004), and it is unclear how these variables may be changing. The potential increased vulnerability to fire, however, is important since forest fires play an important role in species structure and composition (Bond et al. 2005), and changes in fire frequency are expected to play a role in driving biome shifts (Scholze et al. 2006). The recent decades of increasingly large fires (Westerling et al. 2006) may signal Montana's forested ecosystems are currently in the process of change.

Insect outbreaks are another component of temperature-driven changes to western forests. Increases in temperature affect bark beetle species in different ways. Warmer temperatures—such as the winter and spring warming and loss of extreme cold days in western Montana—may alter outbreak frequency/duration, reduce winterkills, speed up life cycles, modify herbivory and damage rates, and lead to range expansion or contraction (Carroll et al. 2003; Logan and Powell 2001; Logan et al. 2003). From western Montana through interior British Columbia the mountain pine beetle (*Dendroctonus ponderosae*) has expanded its range to higher elevations, and farther east then previously documented, causing widespread tree mortality (Logan and Powell 2001). For example, the hardest hit areas of the recent outbreak lie within interior British Columbia with the Mountain Pine Beetle affecting 9,243,408 ha (22,840,959 acres) of lodgepole pine (*Pinus contorta*) as of September 2006 (B.C. Ministry of Forests 2007).

With the Mountain Pine Beetles expansion to higher elevations, novel species/host associations have occurred with the beetle infesting and killing whitebark pine (*Pinus albicalus*). This is disconcerting since whitebark pine is considered a 'keystone' species due to its provision of food for more then seventeen animal species (Arno and Hoff 1990; and Tomback et al. 2001). With whitebark pine already considered to be "functionally extinct over a third of its range" due to blister rust, a changing fire regime, and now infestation from the mountain pine beetle there is serious cause for concern regarding the future functional response of this subalpine ecosystem (Tomback et al. 2001). Additionally, modeling efforts investigating the influence of bioclimatic variables on the functional niche of whitebark pine within the Greater Yellowstone Ecosystem suggest the potential for a complete loss of whitebark pine due to projected changes in temperature and precipitation alone (Schrag et al. 2008; Bartlein et al. 1997).

4.2.3 Rapid changes in freshwater fisheries

Rapid ecosystem change may already be impacting the aquatic ecosystems of our highest and coldest watersheds. Globally, over the last four decades the world has witnessed the disappearance of over 7,000 km^2 of mountain glaciers (Dyurgerov 2003). The Greater Yellowstone and the Crown of the Continent Ecosystems (which encompasses Glacier National Park) have lost 42% and 66% of their glacial and perennial snow and ice cover respectively since 1900 (Fountain et al. 2007). Within Glacier National Park the loss of glaciers has been most dramatic. Since the termination of the Little Ice Age (ca. 1850 AD) glaciers and perennial snow/ice masses have been reduced in number from approximately 150 to 26, which corresponds to an 83% loss in total ice mass. With the loss of glaciers has come the loss of watersheds containing glaciers: 23 first-order watersheds historically contained glaciers at the source of their headwaters, today only 14 watersheds contain glaciers or perennial snow and ice.

The influence of glaciers on aquatic ecosystems ranges from providing base flows during the hot, dry summers to moderating stream temperatures. In these remnant cold-water fisheries regulation of stream temperature is of key importance in controlling the distribution and abundance of invertebrates (Hauer et al. 1998) and fish (Keleher and Rahel 1996; Dunham et al. 2003). Salmonids are often considered a keystone species for aquatic and terrestrial ecosystems, and may be an especially important indicator of ecosystem health in the face of climate change. Salmonids provide an excellent early warning indicator of climate warming because their body temperature is dependent on the temperature of their surroundings, and they have a characteristically narrow range of thermal tolerance. Almost all of the native inland cutthroat (*Oncorhynchus clarkii* spp.) species, grayling (*Thymallus arcticus*) and bull trout (*Salvelinus confluentus*) have been proposed for listing under the Endangered Species Act and a number are currently listed as "threatened". Trout, grayling, and char historically inhabited a variety of freshwater habitats, but have declined due to habitat degradation, fragmentation, introductions of nonnative species, and elevated water temperature. Many native salmonid populations are restricted to small, fragmented headwater habitats, which are increasingly vulnerable to wildfires and subsequent flooding. The bull trout (*Salvelinus confluentus*), for example, is a native char to northwestern North America that requires cold, connected and complex habitats for growth, survival, and long-term population persistence. A warming climate, and changes to seasonal and daily temperature extremes during the season of greatest stress (i.e. summer; see Figs. 4 and 7), may negatively impact existing trout populations by increasing water temperatures beyond critical physiological thresholds. Bull trout have among the lowest mean tolerance for high water temperatures of North American salmonids (Selong et al. 2001). Using theoretical modeling and empirical air temperature data, Rieman et al. (2007) estimated that warming temperatures over the distributional range of bull trout could result in the losses of 18–92% of thermally suitable natal habitat area and 27–99% of large (>10,000-ha) habitat patches (Rieman et al. 2007).

Global warming may ultimately be the greatest threat to the persistence of native fishes because it will exacerbate current negative effects of invasive aquatic species and habitat degradation while increasing water temperatures to unsuitable thresholds (Williams et al. 2007a). In conjunction with losing the cooling effect of glaciers and perennial snow and ice, stream temperature will be affected most by changes in maximum summer temperatures and minimum winter temperatures (Keleher and Rahel 1996). Using an upper temperature threshold of 22°C (71.6°F) as a constraining variable for a guild of cold water fish (brook trout, cutthroat trout, and brown trout), Keleher and Rahel (1996) predicted that the length of streams occupied in Wyoming would decrease 7.5–43.3% for increases in temperature from 1 to 5°C. Changes in temperature of this magnitude may not only decrease existing habitat by increasing air and water temperatures, but will likely further fragment available suitable habitat, increase the risk of catastrophic fire, change the timing and quantity of water from snowpack, increase winter flooding in some areas, and provide habitat conditions that favor introduced species, putting many native salmonids at high risk of extinction in the western United States (Williams et al. 2007a).

4.3 Ecosystem services and economic impacts

Montana's ecotourism- and agriculture-based economy will likely experience a mixture of positive and negative impacts as a consequence of future climate change. A potential positive impact for ecotourism may arise from weather conditions more amenable to people at the start and end of the traditional summer tourist season—thereby increasing overall tourism numbers and length of visitation season. Conversely, the premiere ski resort industry is likely to see a reduction in profits due to a shortening season over which a high quantity and quality of snowpack is available for skiers (Breiling and Charmanza 1999). With a reduction in snowpack, and increased stream temperatures over the spring and summer, fishing guides may expect increasingly more frequent closures of streams and rivers due to reduced flows and increased thermal stress on aquatic species.

Montana's agricultural system has always had a tenuous relationship with Montana's climate. The predominance of dry-land farming coupled with the region's tendency to experience sustained drought conditions (Pederson et al. 2006) led to the harsh human conditions and massive number of farm foreclosures during the dustbowl and pre-dustbowl droughts of the 1920s and 30s (Murphy 2003; Pederson et al. 2006). In spite of this, western Montana's highly productive and high-quality valley grasslands have always served as valuable land for livestock production. With changes in timing of specific chilling periods, which is likely happening as shown by decreases in winter season cold temperatures (Fig. 5), it is expected that crop yields will decline and more xeric conditions will prevail reducing pasture quality (Slingo et al. 2005) and threatening Montana's livestock industry. Economic models, coupled with climate change predictions show agricultural regions in Montana that will be hardest hit are those with the least resources and ability to adapt (Antle et al. 2004), which mirrors expectations of global societal and agricultural impacts (Tol et al. 2004).

5 Conclusions

Regional analysis of trends in western Montana temperatures reveals changes that track both interannual and multi-decadal variability exhibited in global and NH temperature records. In all cases, however, the rise in extremes and seasonal averages has been two to three times greater than that of the global average. Importantly, we see substantial changes in extreme conditions, with both a loss of extremely cold days as well as an increase in extremely hot days. Important thresholds are being exceeded, in particular the 0°C seasonal frost/freeze value for average T_{min} over the spring and fall. Evidence for major ecosystem changes within the region is associated with these changes in seasonal average temperatures, and the changing frequency of daily temperature extremes and thresholds associated with physical and biological processes. A take-home message of this analysis and review of impacts is that there is danger in assuming that long-term trends in temperature will be associated with equally paced or simple linear changes in ecosystems and their services. The processes by which ecosystem changes take place are often complicated by synergistic and non-linear relationships between variables (e.g. Nogués-Bravo et al. 2007; Scheffer et al. 2001), many of which are still unknown. Thus, more intensive research on local and regional climate interactions with coupled socio-ecosystems should be completed through the integration of observational studies of past climate-socio-ecosystem relationships. The software provided herein is intended to assist with the often-daunting task of extracting meaningful climate metrics. In conjunction with these efforts, capacity to monitor for new system trajectories, or sudden shifts, in our biophysical systems should be increased for long-term planning and/or rapid mitigation measures. Regardless of future efforts in carbon mitigation and sequestration, over the course of this next century we are committed to a warming climate. Only through increased monitoring, research, and generation of spatially explicit patterns of expected change, can we expect citizens and resource managers to engage in well-informed decision-making.

Acknowledgements We would like to thank Chris Caruso for his early and helpful contribution to this manuscript, and we wish him well in his work and on his travels through Mozambique. We would also like to that Jeremy Weiss, Jonathan Overpeck, and Steve Running for providing the inspiration to conduct this research for this region. In addition, we are thankful for the insightful comments on this manuscript from Jeremy Littell, and three anonymous reviewers. Their time and efforts greatly improved the writing quality and figures. Ali Macalady provided both valuable insights along with important additions to the R program for daily temperature analysis. Additional thanks are due to all the people, institutions, and agencies that have done the important work of making high-quality climate data and analysis software freely available. This work was supported by and is a product of the U.S. Geological Survey's Western Mountain Initiative and the Global Change Program.

References

Antle JM, Capalbo SM, Elliot ET, Paustian KH (2004) Adaptation, spatial heterogeneity, and vulnerability of agricultural systems to climate change and CO_2 fertilization: an integrated assessment approach. Clim Change 64(3):289–315

Arno SF, Hoff RJ (1990) Whitebark pine (*Pinus albicaulis* Engelm.). In: Burns RM, Honkala BH (eds) Silvics of North America, agriculture handbook 654. US Department of Agriculture Forest Service, Washington, DC, pp 530–554

B.C. Ministry of Forests (2007) 2006 Aerial overview survey summary. Forest practices branch, Forest health conditions. URL http://www.for.gov.bc.ca/hfp/health/overview/2006table.htm. Cited 22 January 2008

Barnett TP, Pierce DW, Hidalgo HG, Bonfils C, Santer BD, Das T, Bala G, Wood AW, Nozawa T, Mirin AA, Cayan DR, Dettinger MD (2008) Human-induced changes in the hydrology of the western United States. Sci Express 319(5866):1080–1083

Bartlein PJ, Whitlock C, Shafer SL (1997) Future climate in the Yellowstone National Park region and its potential impact on vegetation. Conserv Biol 11:782–792

Bond WJ, Woodward FI, Midgley GF (2005) The global distribution of ecosystems in a world without fire. New Phytol 165:525–538
Breiling M, Charmanza P (1999) The impact of global warming on winter tourism and skiing: a regionalized model for Austrian snow conditions. Reg Environ Change 1(1):4–14
Carroll AL, Taylor SW, Régniére J, Safranyik L (2003) Effects of climate change on range expansion by the mountain pine beetle in British Columbia. In: Shore TL, Brooks JE, Stone JE (eds) Mountain pine beetle symposium: challenges and solutions. October 30–31, 2003, Kelowna, British Columbia. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Information Report BC-X-399, Victoria, BC, 298 pp
Carrara PE (1989) Late quaternary glacial and vegetative history of the Glacier National Park region, Montana. US Geol Surv Bull 1902:64
Church JA, White NJ (2006) A 20th century acceleration in global sea-level rise. Geophys Res Lett 33:L01602. doi:10.1029/2005GL024826
Dang H, Gillett NP, Weaver AJ, Zwiers FW (2007) Climate change detection over different land surface vegetation classes. Int J Climatol 27:211–220. doi:10.1002/joc.1397
Diaz HF, Eischeid JK (2007) Disappearing "alpine tundra" Koppen climatic type in the western United States. Geophys Res Lett 34:L18707. doi:10.1029/2007GL031253
Dunham, Rieman JB, Chandler G (2003) Influences of temperature and environmental variables on the distribution of bull trout within streams at the southern margin of its range. North Am J Fish Manage 23:894–904
Durgerov M, Meier MF (2005) Glaciers and the changing Earth system: a 2004 snapshot. Occasional Paper 58. Institute of Arctic and Alpine Research, University of Colorado, Boulder, CO, 118 pp
Dyurgerov M (2003) Mountain and subpolar glaciers show an increase in sensitivity to climate warming and intensification of the water cycle. J Hydrol 282:164–176
Easterling DR, Horton B, Jones PD, Peterson TC, Karl TR, Parker DE, Salinger MJ, Razuvayev V, Plummer N, Jamason P, Folland CK (1997) Maximum and minimum temperature trends for the globe. Science 277:364–367
Easterling DR, Karl TR, Lawrimore JR, Del Greco SA (1999) United States historical climatology network daily temperature, precipitation, and snow data for 1871–1997. ORNL/CDIAC-118, NDP-070. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge
Easterling DR, Meehl GR, Parmesan C, Changnon SA, Karl TR, Mearns LO (2000) Climate extremes: observations, modeling, and impacts. Science 289:2068–2074
Fountain A, Hoffman M, Jackson K, Basagic H, Nylen T, Percy D (2007) Digital outlines and topography of the glaciers of the American West. USGS Open File Report 2006-1340, 23 pp
GAO: U.S. Government Accountability Office (2007) Climate change: agencies should develop guidance for addressing the effects on federal lands and water resources. US Government Open File Report GAO-07-863, 184 pp. http://www.gao.gov/cgi-bin/getrpt?GAO-07-863. Cited 2 December 2008
Hall MP, Fagre DB (2003) Modeled climate-induced glacier change in Glacier National Park, 1850–2100. Bioscience 53(2):131–140. doi:10.1002/(SICI)1099-1085(19970630)11:8<903::AID-HYP511>3.0.CO;2-7
Hansen J, Nazarenko L, Ruedy R, Sato Mki, Willis J, Del Genio A, Koch D, Lacis A, Lo K, Menon S, Novakov T, Perlwitz Ju, Russell G, Schmidt GA, Tausnev N (2005) Earth's energy imbalance: confirmation and implications. Science 308:1431–1435. doi:10.1126/science.1110252
Hauer RF, Baron JS, Campbell DH, Fausch KD, Hostetler SW, Leavesley GH, Leavitt PR, McKnight DM, Stanford JA (1998) Assessment of climate change and freshwater ecosystems of the Rocky Mountains, USA and Canada. Hydrol Process 11(8):903–924
Karl TR, Diaz HF, Kukla G (1988) Urbanization: its detection and effect in the United States climate record. J Climate 1:1099–1123
Karl TR, Williams CN Jr (1987) An approach to adjusting climatological time series for discontinuous inhomogeneities. J Clim Appl Meteor 26:1744–1763
Karl TR, Williams CN Jr, Young PJ, Wendland WM (1986) A model to estimate the time of observation bias associated with monthly mean maximum, minimum and mean temperatures for the United States. J Clim Appl Meteor 25:145–160
Keleher CJ, Rahel FJ (1996) Thermal limits to salmonid distributions in the Rocky Mountain region and potential habitat loss due to global warming: a geographic information system (GIS) approach. Trans Am Fish Soc 125:1–13
Key CH, Fagre DB, Menicke RK (2002) Glacier retreat in Glacier National Park, Montana. In: Williams RS Jr, Ferrigno JG (eds) Satellite image atlas of glaciers of the world, glaciers of North

America—Glaciers of the Western United States. United States Government Printing Office, Washington DC, pp J365–J381
Littell JS, McKenzie D, Peterson DL, Westerling AL (2009) Climate and wildfire area burned in Western U.S. ecoprovinces, 1916–2003. Ecol Appl 19(4):1003–1021
Logan JA, Powell JA (2001) Ghost forests, global warming and the mountain pine beetle (Coleoptera: Scolytidae). Am Entomol 47(3):160–172
Logan JA, Régniére J, Powell JA (2003) Assessing the impacts of global warming on forest pest dynamics. Front Ecol Environ 1:130–137
Lugina KM, Groisman PYa, Vinnikov KYa, Koknaeva VV, Speranskaya NA (2005) Monthly surface air temperature time series area-averaged over the 30-degree latitudinal belts of the globe, 1881–2005. In: Trends online: a compendium of data on global change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S. http://cdiac.ornl.gov/trends/temp/lugina/data.html. Cited 22 January 2008
McKenzie D, Gedalof Z, Peterson DL, Mote P (2004) Climatic change, wildfire, and conservation. Conserv Biol 18:890–902
Moberg A, Sonechkin DM, Holmgren K, Datsenko NM, Karlen W (2005) Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. Nature 433:613–617
Mote PW (2003) Trends in snow water equivalent in the Pacific Northwest and their climatic causes. Geophys Res Lett 30:1601. doi:10.1029/2003GL017258
Murphy M (2003) Hope in hard times: new deal photographs of Montana, 1936–1942. Montana Historical Society, Helena, 256 pp
Nogués-Bravo D, Arújo MB, Errea MP, Martinez-Rica JP (2007) Exposure of global mountain systems to climate warming during the 21st Century. Glob Environ Change 17:420–428. doi:10.1016/j.gloenvcha.2006.11.007
NRC (2005) Radiative forcing of climate change: expanding the concept and addressing uncertainties. The National Academies Press, Washington, D.C., 208 pp
NRC (2006) Surface temperature reconstructions for the last 2,000 years. The National Academies Press, Washington, D.C., 145 pp
Oerlemans J (2005) Extracting a climate signal from 169 glacier records. Science 308:675–677
Pederson GT, Fagre DB, Gray ST, Graumlich LJ (2004) Decadal-scale climate drivers for glacial dynamics in Glacier National Park, Montana, USA. Geophys Res Lett 31:L12203. doi:10.1029/2004GL019770
Pederson GT, Gray ST, Fagre DB, Graumlich LJ (2006) Long-duration drought variability and impacts on ecosystem services: a case study from Glacier National Park, Montana. Earth Interact 10:1–28
R Development Core Team (2007) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. ISBN 3-900051-07-0, URL http://www.R-project.org/. Cited 22 January 2008
Rayner NA, Brohan P, Parker DE, Folland CK, Kennedy JJ, Vanicek M, Ansell TJ, Tett SFB (2006) Improved analyses of changes and uncertainties in sea surface temperature measured in situ since the mid-nineteenth century: the HadSST2 dataset. J Climate 19:446–469
Rieman BE, Isaak D, Adams S, Horan D, Nagel D, Luce C, Myers D (2007) Anticipated climate warming effects on bull trout habitats and populations across the interior Columbia River basin. Trans Am Fish Soc 136:1552–1565
Scheffer M, Carpenter S, Foley JA, Folke C, Walker B (2001) Catastrophic shifts in ecosystems. Nature 413:591–596
Scholze M, Knorr W, Arnell NW, Prentice IC (2006) A climate-change risk analysis for world ecosystems. PNAS 103(35):13116–13120
Schrag AM, Bunn AG, Graumlich LJ (2008) Influence of bioclimatic variables on tree-line conifer distribution in the Greater Yellowstone Ecosystem: implications for species of conservation concern. J Biogeogr 35(4):698–710
Selong JH, McMahon TE, Zale AV, Barrows FT (2001) Effect of temperature on growth and survival of bull trout, with application of an improved method for determining thermal tolerances in fishes. Trans Am Fish Soc 130:1026–1037
Slingo JM, Challinor AJ, Hoskins BJ, Wheeler TR (2005) Introduction: food crops in a changing climate. Philos Trans R Soc B Biol Sci 360:1983–1989
Stewart IT, Cayan DR, Dettinger MD (2005) Changes toward earlier streamflow timing across western North America. J Climate 18:1136–1155

Timm NH (2002) Applied multivariate analysis. Springer, New York, 693 pp, ISBN: 978-0-387-95347-2

Tol RSJ, Downing TE, Kuik OJ, Smith JB (2004) Distributional aspects of climate change impacts. Glob Environ Change 14:259–272

Tomback DF, Arno SF, Keane RE (2001) The compelling case for management intervention. In: Tomback DF, Arno SF, Keane RE (eds) Whitebark pine communities: ecology and restoration. Island, Washington DC, pp 3–25

Vose RS, Easterling DR, Gleason B (2005) Maximum and minimum temperature trends for the globe: an update through 2004. Geophys Res Lett 32:L23822. doi:10.1029/2005GL024379

Watson E, Luckman BH (2004) Tree-ring based reconstructions of precipitation for the southern Canadian Cordillera. Clim Change 65:209–241

Watson E, Pederson GT, Luckman BH, Fagre DB (2008) Glacier mass balance in the northern U.S. and Canadian Rockies: paleo-perspectives and 20th century change. In: Orlove B, Luckman BH, Wiegandt E (eds) Darkening peaks. University of California Press, Berkley, pp 139–151

Weiss JL, Overpeck JT (2005) Is the Sonoran desert losing its cool? Glob Chang Biol 11:2065–2077. doi:110.1111/j.1365-2486.2005.01020.x

Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW (2006) Warming and early spring increase Western U.S. forest wildfire activity. Science 313(5789):940–943. doi:10.1126/science.1128834

Western Regional Climate Center (2007) Climate of Montana. http://www.wrcc.dri.edu/narratives/MONTANA.htm. Cited 22 January 2008

Williams JE, Haak AL, Neville HM, Colyer WT, Gillespie NG (2007a) Climate change and western trout: strategies for restoring resistance and resilience in native populations. In: Carline RF, LoSapio C (eds) Wild Trout IX: Sustaining wild trout in a changing world. Wild Trout Symposium, Bozeman, Montana, pp 236–246

Williams JW, Jackson ST, Kutzbach JE (2007b) Projected distributions of novel and disappearing climates by 2100 AD. PNAS 104(14):5738–5742. doi:10.1073/pnas.0606292104

Williams CN Jr, Menne MJ, Vose RS, Easterling DR (2007c) United States historical climatology network monthly temperature and precipitation data. ORNL/CDIAC-118, NDP-019. Available on-line (monthly, http://cdiac.ornl.gov/epubs/ndp/ushcn/usa_monthly.html; daily, http://cdiac.ornl.gov/epubs/ndp/ushcn/usa.html) from the Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee. Cited 22 January 2008