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Climate, Snowpack, and Streamflow of Priest River Experimental Forest, Revisited

Wade T. Tinkham
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Abstract

The climate record of Priest River Experimental Forest has the potential to provide a century-long history of northern Rocky Mountain forest ecosystems. The record, which began in 1911 with the Benton Flat Nursery control weather station, included observations of temperature, precipitation, humidity, and wind. Later, other observations stations were added to the network and observations were expanded to include snow courses and streamflow measurements. The region contains nearly all of the dominant forest types within the northern Rocky Mountains, from the xeric ponderosa pine forest type, to the highly mesic western red cedar type, with mesic Douglas-fir forests in between. Over the last century, the area has experienced an increase in minimum daily temperatures of 2.8 °F, while no discernable trend can be seen in the maximum temperatures. This observed increase in minimum daily temperature is consistent with changes expected from global warming. The total annual precipitation has not changed over the last century, while the March 1st snowpack at the lower elevations within the catchment has declined by over 30%. Although there is no change in total precipitation, there has been a 33% increase in average annual stream runoff. This change in runoff is attributed to both a shift in streamflow timing, due to earlier snowpack melt, and to large changes in tree species composition following the white pine blister rust epidemic in the 1950s. This unique dataset has the potential to inform managers and researchers about the changes regional climatic water balances may undergo as climate continues to shift.

Authors

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Acknowledgments

This synthesis of Priest River Experimental Forest's climate record would not be possible without the effort from dozens of Forest Service personnel who spent countless hours collecting, verifying, and archiving this unique dataset. The length of record has been maintained because of its inherent value in describing the climatic variables of this area; this value has been recognized since the establishment of the Experimental Forest. Scientists from other agencies and institutions outside the Forest Service have also made use of the record and contributed to its value. Gratitude is extended to Dr. Charlie Luce and Johanna Bell for collation and cleaning of early streamflow and meteorological data. The analysis of the data in this report was guided by Dr. John Marshall of the University of Idaho. The authors also wish to thank the following individuals for their thoughtful and constructive suggestions in the preparation of this manuscript: John Abatzoglou, Professor of Meteorology, University of Idaho; Ronald Miller, Science Operations Officer, National Weather Service, Spokane, Washington; Timothy Link, Professor of Hydrology, University of Idaho; William Massman, Atmospheric Scientist, Rocky Mountain Research Station, Fort Collins, Colorado; Larry Bradshaw, Meteorologist, Rocky Mountain Research Station, Missoula, Montana; L. Scott Baggett, Statistician, Rocky Mountain Research Station, Fort Collins, Colorado; Theresa Jain, Research Forester, Rocky Mountain Research Station, Moscow, ID; Brandon Glaza, Hydrologist, Bonners Ferry Ranger District; Bonners Ferry, ID; Abby Lute, Snow and Water Resources Specialist, Natural Resources Conservation Service, Boise, Idaho. And special thanks to Kathleen Graham for the hours spent proofreading this report.

Cover photo: *Priest River Experimental Forest Office/Lab; the control weather station is on the right. (All photos provided by USDA Forest Service unless otherwise noted.)*

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Introduction

For over 100 years Priest River Experimental Forest (PREF), located in the northern Panhandle of Idaho, has served as a test site for researchers investigating timber management, wildfire research, genetic variation within conifer species, forest insect and pathogen vectors, watershed manipulation, and wildlife habitat (Wellner 1976). Over the course of the last century a detailed meteorological record has been collected and maintained by Forest Service personnel and collated within the National Climate Data Center (NCDC). This dataset is accompanied by 73 years of ongoing streamflow measurements dating back to 1939. These datasets have long been used in investigating the role climate plays in controlling the forest composition within PREF, with studies linking weather and climate to fire danger (Larsen and Delavan 1922; Hayes 1941; Barrows 1954; Stockstad and others 1964), climate and forest production (Jemison 1934; Larsen 1930, 1940; Duursma and others 2007), and snowpack accumulation and ablation in watershed management (Stage 1957; Packer 1962; Snyder and others 1975; Haupt 1968).

The climate record was last summarized by Finklin (1983) and included many day-to-day weather observations such as wind speed and cloud cover that have ceased to be collected. This paper does not address the character of wind speed as it is not typically reported to the National Weather Service (NWS) under the National Observer Network. Finklin developed his discussion of wind speed from data collected at the clearcut inflammability station, fire weather observations, the 150-ft weather tower, or the Gisborne lookout. Old photos of the control weather station clearly show at least one, if not more, anemometers in place. Possibly the data was collected and stored in-house and used in fire weather studies. One could surmise that a number of anemometers were installed at the control station to test and calibrate for use at regional fire weather stations. An automated weather station was installed in 2009 to compliment the manual instruments of the control station and has been recording wind speed and direction.

The PREF climate record is particularly valuable due to the lack of climate records in this forested region of the United States (Figure 1) and the relatively unique climate of this area. Situated east of the Cascade Mountains and west of the Rocky Mountain crest, the climate is affected by the Pacific Ocean as well as the large land area that weather systems must pass over to reach the site. Climate scientists refer to these effects as “maritime” and “continental,” respectively (Finklin 1983). The balance of maritime and continental influences at PREF shapes a unique climate that is more similar to southeastern British Columbia than the adjacent Rocky Mountains or Cascades. While the Rocky Mountain region generally receives most if its precipitation in January through April, PREF receives the bulk of its annual precipitation in November through January.

Persistent snowpack will form even at low elevations in PREF. However, winter temperatures at PREF are mild relative to locations on the eastern slopes of the Rocky Mountains in Montana due to the moderating effect of maritime climate, making the transition from snow accumulation to snow melt, especially at lower elevations, sensitive to small changes in temperature. These kinds of snowpacks have been termed “at

Figure 1—PREF in relation to neighboring states and Canada.

risk" of transitioning from snow dominated to rain dominated (Nolin and Daly 2006) from climate warming. Previous studies have found trends toward warmer winters have caused snow to melt earlier in the spring, shifting the timing of spring floods to earlier in the year (Stewart and others 2005). Regional annual streamflow has also been shown to have decreased in major rivers across the northwestern United States (Luce and Holden 2009).

Within natural resource management, computer models are often employed to forecast future conditions or to reconstruct previous events. Examples include models of fire frequency and behavior, snow accumulation and ablation, streamflow, species distribution, atmospheric carbon sequestration, and forest productivity. These models are utilized by natural resource managers in making decisions, improving our long-term vision, and in meeting management objectives. Models of this nature serve as a looking glass, helping us view future conditions and allowing us to evaluate management trade-offs. Until recently, climate was often ignored within many of these modeling exercises, with the common assumption that climate would remain static. Advances in climate research over the last 20 years have shifted how we collect, utilize, and think about climatic records. For example, the last time climate was summarized at PREF, the focus was on the 11-year solar cycle (Finklin 1983) and was largely explained by year-to-year variability; long-term climate trends were not widely considered. But if climate continues to change along predicted trajectories, natural resource managers will be challenged with making decisions about a future that is more and more uncertain and in which climate cannot be assumed as static.

This report summarizes the long-term climatic record of PREF, by presenting the annual, decadal, and climate "normal" trends between 1911 and 2013. Climate is traditionally defined as an average set of conditions; a 30-year average will be used within this report to describe the climate normals, which is an interval used by the NWS and other agencies that report long-term climatic data. These data are a useful description of the state of the climate during the recorded period and may provide a reasonable estimate of conditions in the immediate future, even if climate is gradually changing.

Description of the Area

PREF occupies 6,382 acres (2,583 ha) within the Idaho Panhandle National Forest, in northern Idaho (Figure 1), 12.3 miles north of the town of Priest River, Idaho. Within PREF, there are two mountain catchments ranging in elevation from 2,220 to 5,980 ft above sea level (677 to 1,823 m). The landscape is occupied by Canyon Creek and Benton Creek, two first order headwater streams that flow westward until their confluence with the East Fork of the Priest River and the Priest River, respectively. PREF is located at the southern end of the Selkirk Mountains, approximately 120 miles west of the Rocky Mountain crest.

Within a half mile area of the headquarters site, forest types can be found that illustrate the entire range of conditions in the region from the xeric southwestern slopes to the more mesic northeastern slopes with a highly mesic forest system between (Figure 2). Most of the forest types in the northern Rocky Mountains are represented within PREF's boundaries. In the years prior to the 1950s, the forest was dominated by western white pine (*Pinus monticola*), which regenerated following fires dating back to 1860. The mature white pine was nearly eliminated by the white pine blister rust (*Cronartium ribicola*) epidemic that struck the region and peaked in the 1950s (Maloy 1997). Following the blister rust outbreak, PREF was dominated by two major forest types of mixed western larch (*Larix occidentalis*) and Douglas-fir (*Pseudotsuga menziesii*) or nearly pure Douglas-fir (Wellner 1976). By 2000, the basal area on the forest was 35% western redcedar (*Thuja plicata*), 20% Douglas-fir, and 15% western hemlock (*Tsuga heterophylla*) (Duursma and others 2003). Both western redcedar and western hemlock are shade-loving late successional species that established under the canopies of the western larch and Douglas-fir and have since become the dominant species within the forest.

Except where silvicultural studies and harvests have taken place, the forest has largely escaped fire or major harvest disturbances over the last century. This lack of disturbance has allowed the western redcedar and western hemlock to become increasingly dominant over time. This is particularly true of the Benton Creek watershed (Figure 3), which has undergone limited cutting and no significant wildfires since the 1860s. The upper watershed above the Benton gauging dam had a narrow "transect" clearcut by a Civilian Conservation Corps crew in 1940 (Figure 3, LiDAR and NAIP images). The Upper Benton harvest covered about 95 acres (38 ha) and was situated below the Benton Spring snowcourse; cut in 1965 to 1966, it was broadcast burned in 1968. The other harvest was the Lower Benton clearcut, which harvested about 110 acres (45 ha) on the north and south slopes of lower Benton Creek near the gauging dam. Logging was completed in 1968 on the Lower Benton harvest and logging slash was burned in 1969. There has been additional stand thinning and harvesting, but they have been mostly reserved to the Canyon Creek drainage or kept small enough to not influence water flow in Benton Creek at the bottom of the valley.

Figure 2—Two extremes of the forested environment found in PREF. The top photo is the highly mesic western redcedar/western hemlock association within the Benton Creek riparian zone. Below is a stand of ponderosa pine (*Pinus ponderosa*) on a dry xeric southwesterly slope above Benton Creek.

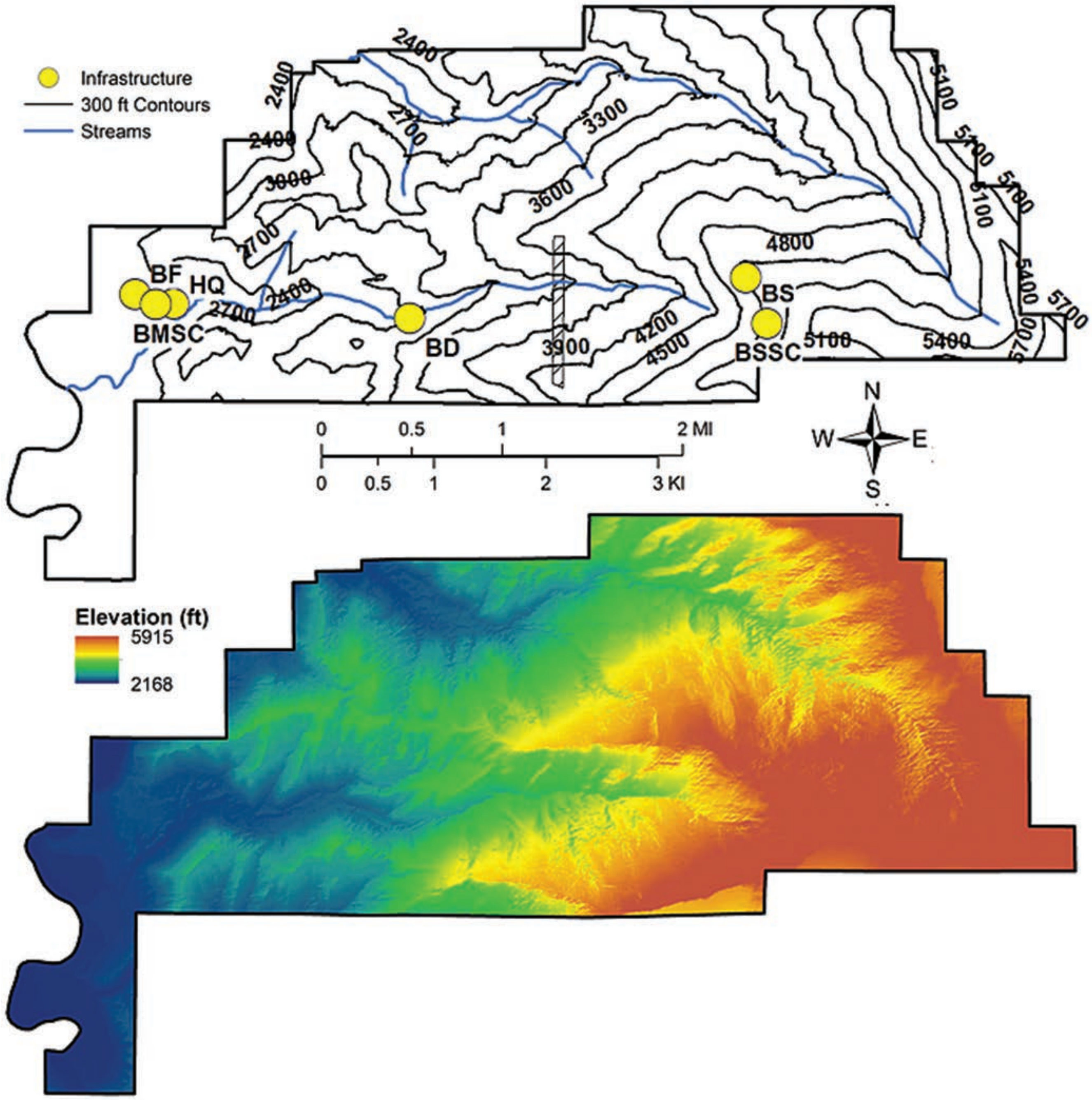

Figure 3—Maps of PREF, including topographic contours at 300 ft intervals (Top) and LiDAR-derived digital elevation maps (Bottom). Locations of infrastructure sites are also overlaid, including climate stations and snow courses. Marked sites include the control weather station next to headquarters (HQ), the low-elevation Benton Meadow (BMSC) snowcourse, the Benton Flat (BF) nursery, the Benton Dam (BD) streamflow and rain gauges, and the Benton Spring (BS) rain gauge, the Benton Spring high elevation snowcourse (BSSC), and the hashed polygon is the 1940 “transect” harvest.

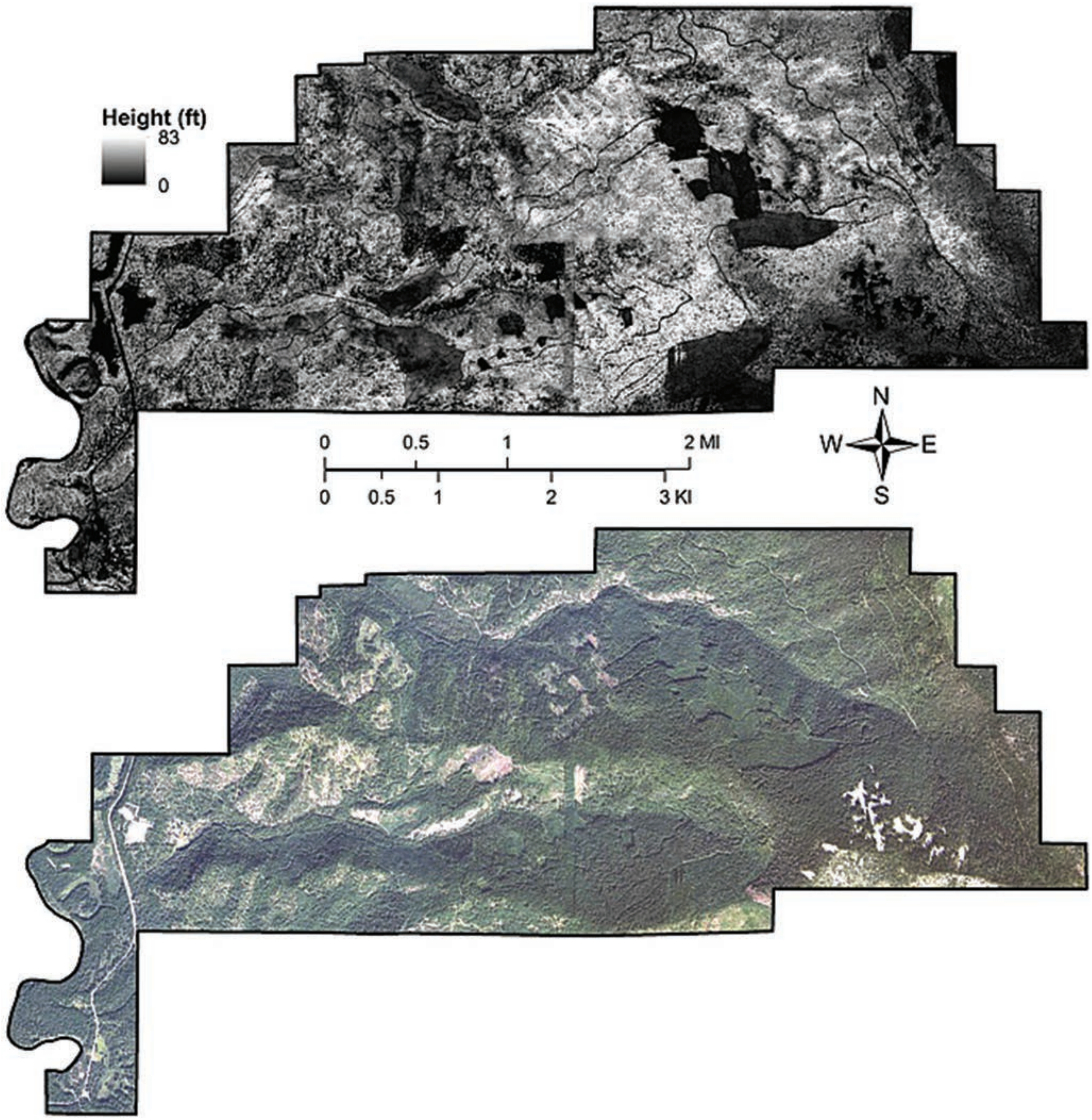

Figure 3 Continued—Maps of PREF, including LiDAR-derived canopy height model (Top; collected in 2002) and National Agriculture Imagery Program (NAIP) 0.5 m aerial photograph collected in 2013 (Bottom). The “transect” timber harvest from 1940 is still visible in both the canopy height model and aerial photograph.

Forest Infrastructure and Data Collection

Data presented in this document from sites within PREF include the control weather station, Benton dam raingauge, Benton Spring raingauge, Benton Meadow and Benton Spring snow surveys, and discharge from Benton gauging dam. Included is a brief discussion of the fire weather observations and the National Atmospheric Deposition Program.

Control Weather Station

Recording of the PREF climate record began in 1911. The NWS assisted with the weather station installation, provided instruments, and the protocols for observations and reporting. PREF is a member of the National Observation Network, station ID #107386. The original control weather station was established in November 1911 at a site that is now the Benton Flat nursery (Figure 4). In 1916, the instruments were moved 1,500 ft (460 m) east at a constant elevation to their present location next to the Headquarters Building at latitude 48.3512 N and longitude -116.8355 W (Figure 5). The station is now located on a slight rise overlooking the Benton Creek floodplain at 2,380 ft (726 m) above sea level. While the two sites that the weather station has occupied were both clearings of similar topography, the forest edge had already moved “much closer” by 1983 and the trees have continued to grow since. (This forest encroachment will be discussed in more detail later in this report.)

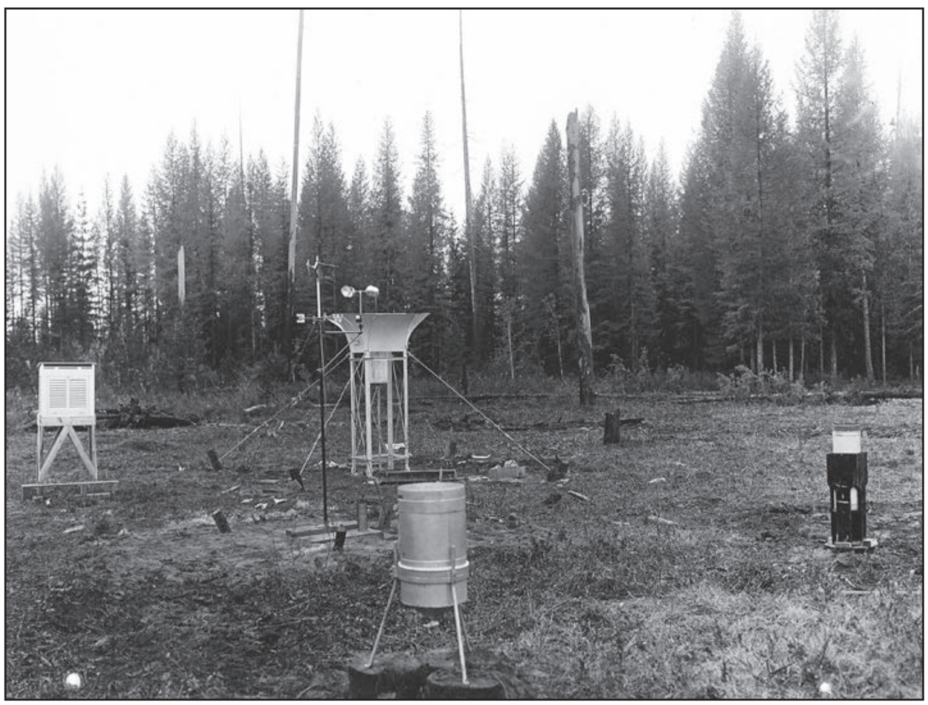

Figure 4—The control weather station was originally installed in 1911 in what is now the Benton Flat nursery. In 1916 it was moved to its present location about 1,500 ft east and adjacent to the Office/Lab. In this view of the nursery site, from L. to R. is an instrument shelter housing the minimum and maximum thermometers, anemometers, snow catch instrument, and in the foreground and right, a tipping bucket and rain storage canisters.

Figure 5—An overview of the Headquarters site at the Experimental Forest, 1936. The control weather station is located at the center of the photo (A). The area left of the weather station, between the driveways, is the site of the Benton Meadow snowcourse and the present sample points 1-5. Note the lack of overstory trees within the snowcourse site and weather station.

Temperatures at the weather station are influenced by nighttime inversions, which deliver cool air from upslope into the valley, especially on clear, still summer nights. The top of this layer of cool air occurs "a few hundred feet below the 3,800-ft elevation" in the summertime (Finklin 1983). Minimum temperatures averaged 4.8 °F (2.7 °C) cooler in the valley bottoms (2,700 ft; 823 m) than in the warmer air above (3,800 ft; 1,159 m) (Hayes 1941). During the daytime, the inversion disappears and the normal cooling with elevation returns, with an observed daytime temperature lapse rate of 4.0 °F/1,000 ft (2.2 °C/305 m) of elevation (Finklin 1983).

As a cooperative venture with the National Weather Service (NWS), daily observations of minimum and maximum temperature, liquid precipitation, and snow depth are collected at 1700 hours (Figures 6,7, and 8). Finklin (1983) described and manually tabulated the written records and data collected from magnetic tapes. The NWS provides and calibrates the thermometers, rain canisters, and dipsticks. Temperature is observed with NWS minimum and maximum thermometers (°F) mounted on a Townsend support within a Hazen instrument shelter. Precipitation is measured at the control weather station with an NWS 8-inch storage canister and dipstick graduated in inches, tenths, and hundredths. During the summer months, the secondary canister is placed within the 8-inch canister and an 8-inch funnel placed over both.

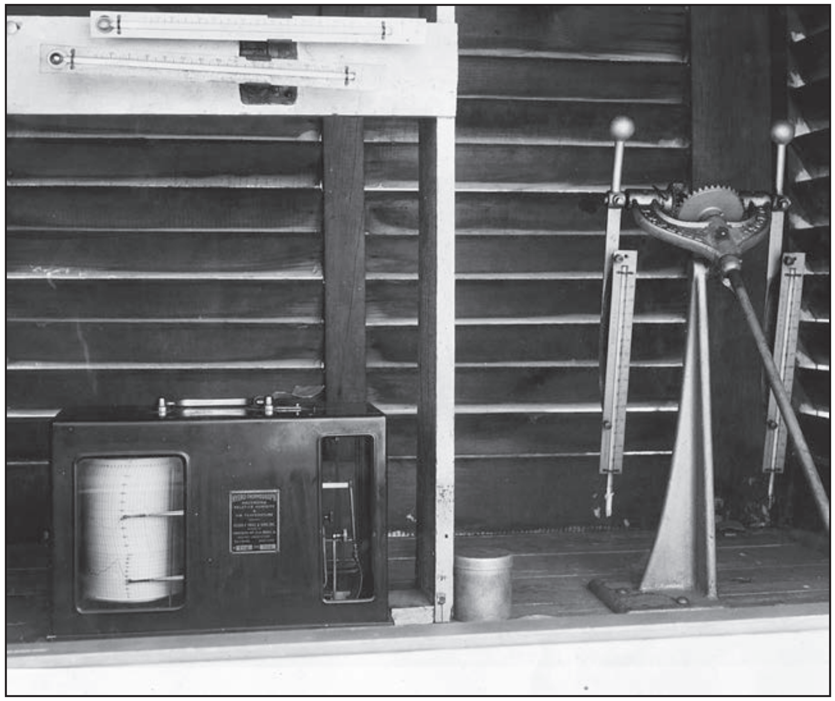

Figure 6—(Top) Interior view of the Hazen instrument shelter (installed 1932, still in service) at the control weather station. At the upper left are the National Weather Service minimum and maximum thermometers; below is a hygrothermograph that records temperature and humidity. To the right is a whirling psychrometer, used to accurately determine humidity and calibrate the hygrothermograph; the use of both of these instruments has been discontinued. (Bottom) H. T. Gisborne comparing rain gauges at the control weather station, 1936. The small, inexpensive canister on the right was developed at PREF for use at Forest Service facilities throughout the region. The gauge in the center is an electronic tipping bucket and the canister on the left is a standard Weather Service rain gauge.

Figure 7—A view of the control weather station, 1932. In the center foreground is the Hazen instrument shelter, housing the minimum and maximum thermometers, hygrothermograph, and whirling psychrometer. To the left is a Cotton type shelter for housing comparative tests of instruments. Behind the weather station is the western larch “weather tree.” Instruments were mounted at the top of the larch to record wind speed, temperature, and humidity at an elevation above the surrounding forest canopy. This data was used for fire weather studies. Climbing spikes in the tree enabled scientists to reach the top and maintain the instruments. The man at the top of the "weather tree" is George Jemison, who started his career at PREF as a seasonal assistant and later went on to become the director of the Northern Rocky Mountain and Pacific Southwest Research Stations. He finished his career as Deputy Chief of the Forest Service for Research.

Figure 8—Present day control weather station, from left, the Hazen instrument shelter, manual and tipping bucket rain gauges, and an automated weather station. The automated weather station was installed in 2009 and provides hourly and daily measurements of temperature, humidity, solar radiation, wind speed and direction, and accumulating snow depth.

For winter operation, the 8-inch canister stands alone; any 24-hour amount of frozen precipitation is moved to the office to thaw while a spare canister is substituted at the weather station. The thawed precipitation is poured into a secondary canister from which all measurements are taken. Snow fall is measured on the ground as both a daily sum and total snowpack accumulation. An NWS dipstick, graduated in inches and tenths is used to determine depth of snow. Daily snow accumulation is measured on a sheet of plywood painted white, which is then cleared of the snow and laid on top of the existing snowpack. Total snowpack is measured daily with a permanent staff gage. Thanks to the efforts of Arnold Finklin and others, we were able to gather the climate data from NCDC records (http://www.ncdc.noaa.gov/oa/ncdc.html). The most up-to-date climatic data is available at the Moscow Forestry Sciences Lab, Moscow Idaho.

Benton Dam Rain Gauge

Benton Dam and rain gauge are located one mile east of the headquarters site (Figure 3).This record was condensed from a dataset provided by the NCDC, which listed the hourly and daily precipitation for Benton Dam from July 1948 to May 1977. Daily totals were culled from this dataset to produce monthly and water year totals. From 1948 to 1977, PREF staff transcribed strip chart data to National Oceanic and Atmospheric Administration Form 79-Id and submitted to the NWS; since 1977, PREF staff continued to record the strip chart data and archived the data at PREF and the Moscow Forestry Sciences Laboratory (FSL). These data were collected by a Friez dual traverse recording rain gauge (Figure 9), with the strip charts analyzed by PREF personnel to determine hourly, daily, and monthly totals. The record now extends to 2009; however, problems with the rain gauge and unsuccessful efforts to replace it put a temporary hold on the data collection. This was remedied when an electronic tipping bucket rain gauge was installed in 2010.

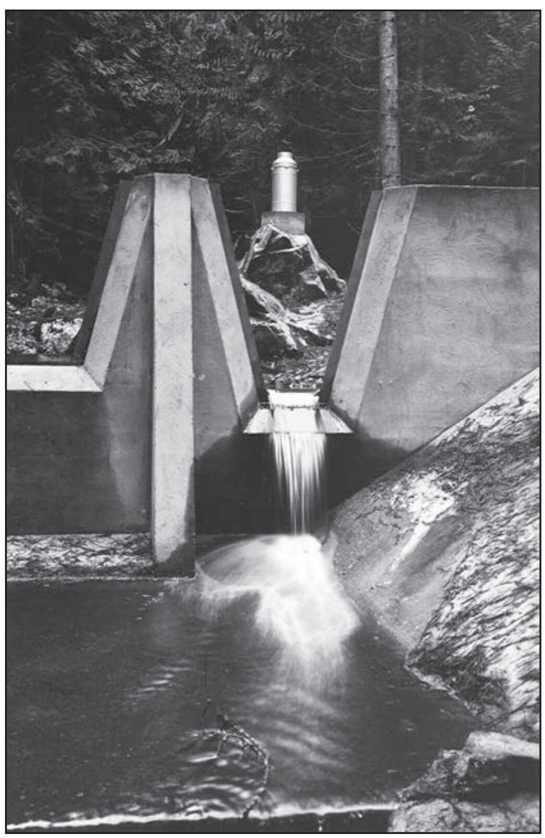

Figure 9—Benton Creek gauging dam in 1948. Behind the deep v-notched weir is the Friez dual traverse recording rain gauge. It operates on a 7-day chart and clock, from which hourly, daily, and monthly totals of precipitation were derived.

Benton Spring Rain Gauge

The earliest continuous collection of monthly data at this site began in December 1960 (Figure 3). The station is equipped with a 10-ft tall tower with an Alter wind shield, protecting an 8-inch diameter, 42-inch tall rain storage canister. The rain gauge is located in a small clearing at 4,775 ft (1,456 m) in elevation, above Forest Road 597-B between sample points 1 and 2 of the Benton Spring snowcourse (Figure 10). Measurements are taken on or about the first of the month with a NWS 36-inch dipstick, graduated in inches and tenths; these data are archived at the Moscow FSL.

In his earlier summary, Finklin (1983) noted difficulties with accurately estimating winter precipitation with the Benton Spring rain gauge and estimated that the measured mean annual precipitation of 37 inches (950 mm) should be increased to 42 inches (1,070 mm), a 13% increase over the raw value. The correction was based on snow accumulation observations from snow surveys on adjacent peaks and justified based on the observation that the gauge was located near trees that may have intercepted or redistributed snow above the gauge. A photograph in Finklin's report (Finklin 1983, Figure 4B) shows trees immediately behind the gauge. The data presented here for Benton Spring are not corrected, but the possibility that they have underestimated real precipitation should be kept in mind.

Figure 10—The Benton Spring rain gauge, March 31, 2014, in about 48 inches of snow. The Alter wind shield surrounding the canister reduces the effect of wind on the catch of precipitation.

Figure 11—Top photo is a view of the snow tube in use. The tubes are graduated in inches for measuring the depth of the snowpack and length of the snow core. The soil plug at the cutting tip indicates the entire depth of snow was recovered; the plug is removed and depth and core length adjusted. The weight of the core determines the water content of the snow. The bottom photo is taken at Benton Spring snowcourse, station 4, looking northwesterly over the Priest River valley.

Snow Courses

Two manual snow courses are maintained in cooperation with the Natural Resources Conservation Service (NRCS) (Figure 3). The low elevation site, Benton Meadow (2,330 ft or 710 m) is located just to the west of the control weather station on rolling, old forest ground. The Benton Spring snowcourse (Figure 11) runs between 4,770 and 4,870 ft (1,454 and 1,485 m) along Forest Road 597-B and occupies a west-southwesterly aspect.

Both snow courses were established in January 1937 and have continuous measurements to the present. A schedule of measurements, as prescribed by the NRCS, begins on or about the 1st of January (±2 days) and continues monthly until the 1st of May or melt-out, whichever comes first. The snowpack is measured for depth and snow water equivalent with a scale and standard snow survey tubes (Figure 11). NRCS protocols are followed for all sampling and measurement calculations, as described in USDA Agricultural Handbook 169.

Benton Dam Streamflow

Streamflow has been monitored on Benton Creek since 1939, by a concrete dam supporting a compound Cipolleti Weir with steel edged crests (Figure 12), located at latitude 48.3504 N, longitude -116.8100 W, and 2,660 ft (411 m) in elevation. The dam was designed with a concrete barrier down to the underlying bedrock to block any flow of water below the surface, forcing all flow through the notch of the weir, where it can be measured. The weir has two notches—the reference weir is a deep, narrow notch for low flows and a higher, wider notch to monitor high flows (Figure 12). A Boyden hook gauge, located in the stilling well, is used to determine the water level above the weirs and calibrate the recording instruments.

Figure 12—A recent view of Benton gauging dam when the recording rain gauge (right) was still in use. Note the development of the vegetation and the stilling rack placed at the head of the weir pool. The rack slows the current entering the pool and provides a calm surface for more accurate water level measurements.

At this point in the watershed, Benton Creek is a first-order perennial headwater stream. The creek drains a watershed of 950 acres (384 ha) above the dam, reaching east to a ridge that forms the top of Gisborne Mountain, at approximately 5,500 ft (1,675 m) (Figures 13 and 14). The weir was constructed in 1938 because Harry T. Gisborne, then Fire Research Investigator for the research station, "was concerned because not one "Little Water" was being gauged or studied in the entire northern Rocky Mountains" (Wellner 1976). Early streamflow research at PREF was pioneered by Stage (1957), who explored the first 44 years of temperature and precipitation data and 16 years of streamflow data. Stage was able to create an early climatic water budget and also demonstrate the linkage between precipitation timing and streamflow discharge.

Streamflow data collection has been performed with a number of different devices ranging from mechanical strip charts to electronic water level sensors connected to electronic data loggers. The data were collated into a single time series and integrated to daily and monthly time steps by Link and Wei (2010) and included (1) a summary of paper records, (2) digitized hydrographs, and (3) data from digital recorders. In many instances, data gaps occurred in one record, but were filled using data from other recorders. Where overlapping records were available, strong agreement was seen between observations. Nonetheless, several gaps remain in the datasets. Significant portions (greater than 1 month) of the following years are missing: 1961, 1962, 1970 to 1975, 1986 to 1988, and 1990.

Additional Data Collections

Throughout PREF's history, several additional datasets have been collected in conjunction with the century-long climate record. One of the earliest mandated research projects by PREF scientists was undertaken in 1916 and attempted to improve detection and control of forest fires, emphasizing fire rate of spread, interactions with weather, and site conditions. These observations would ultimately lead to PREF being the first fire weather observation station within the U.S. Weather Bureau. These stations (Figure 15) were charged with recording and relaying daily relative humidity, wind, and lightning activity for the months of May through October for regional radio broadcasts. These observations were collected from two sites in and around PREF from 1922 until 1978 when they were discontinued. This undertaking was spearheaded by Harry T. Gisborne, who was hired in 1922 as the first full time fire scientist in the Northern Rocky Mountain Research Station and continued his career in fire studies until his death in 1949. Gisborne's efforts resulted in advances in firefighting techniques, improved understanding of conditions that promote fires, and the study and use of climatology in wildfire applications throughout the United States. Among the substantial fire related research accomplishments was the creation of the Model 1 Fire Danger Meter in 1932. This breakthrough made it possible to estimate a fire's rate of spread and what actions would be needed to fight it based on physical observations of weather and fuels (Brown and Davis 1939). A detailed review of the fire weather data collection can be found in Finklin (1983). The fire research pioneered at PREF cleared the way and proved the need of a dedicated fire research facility, which would become a reality in 1960 with the opening of the Missoula Fire Laboratory in Missoula, Montana.

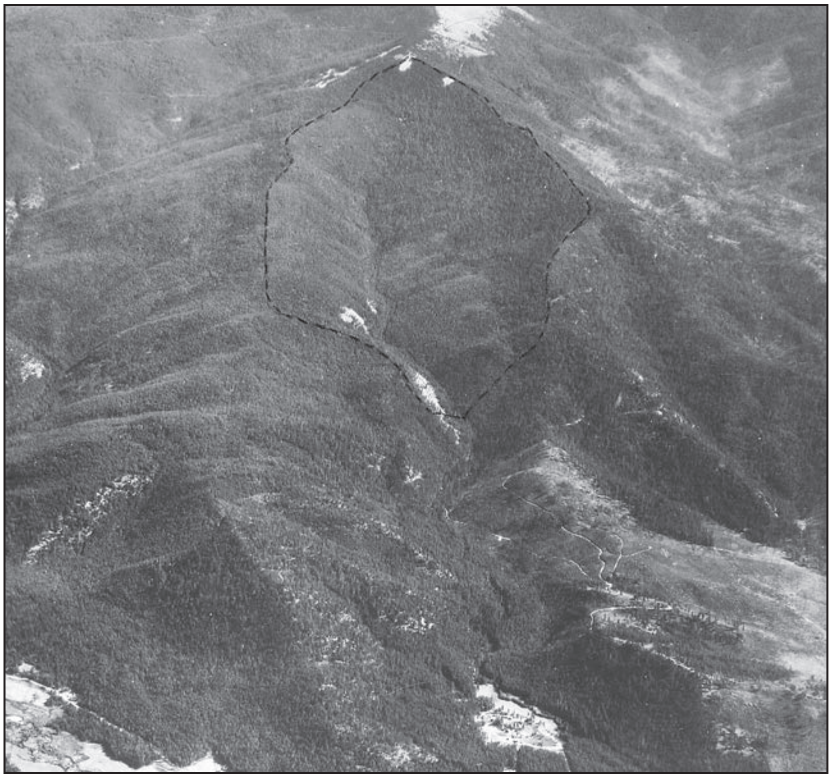

Figure 13—An overview of the Benton Creek watershed, 1935. The dotted line represents the 950-acre (384-ha) drainage that flows over Benton Dam. Note the lack of harvest units in this photo. The headquarters site is in the small clearing at the bottom of the photo; the bare ground in the lower right quadrant resulted from the High Landing wildfire in 1922. (Photo by the 116th Washington Air National Guard, Spokane, Washington.)

Figure 14—A contemporary view of Figure 13 of the Benton Creek watershed above the gauging dam, 2013. (Google Earth aerial view.)

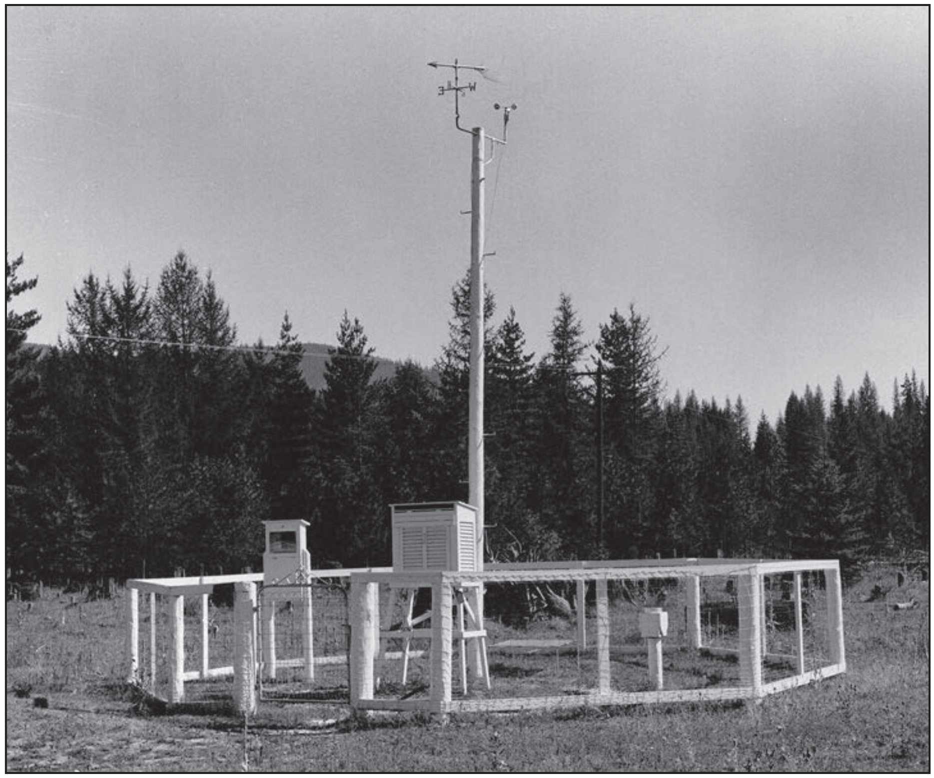

Figure 15—The fire weather station at PREF, 1962. This site was located on a cleared bench west of the county road and present entrance; it is adjacent to the Clear-Cut Inflammability Station. The small instrument shelter on the left housed the scale for weighing the fuel moisture sticks, which were placed outside to reflect the changes in humidity and fuel moisture. The Cotton instrument shelter housed a hygrothermograph and min/max thermometers. A small rain canister is at the right, with a 20-ft wind anemometer located on the central pole.

More recently, PREF became a member of the National Trends Network (NTN) of the National Atmospheric Deposition Program (NADP), with the installation of a precipitation chemistry collection gauge in January, 2003. The program is intended to provide a national framework for collecting and disseminating quality-assured atmospheric deposition data. Each site in the network is configured with an automated precipitation collector and a rain gauge (Figure 16). Site operators follow standard operating procedures to ensure data comparability and representativeness throughout the network. Weekly composite samples are collected every Tuesday morning and shipped to the Central Analytical Laboratory (CAL) at the University of Illinois in Champaign, Illinois, for analysis. The CAL performs chemical analysis of the sample and returns the results on a monthly basis. Provided sufficient volume is available, samples are analyzed for free acidity (H^+ as pH), conductance, calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), sulfate (SO_4^{2-}), nitrate (NO_3^-), chloride (Cl^-), bromide (Br^-), and ammonium (NH_4^+) concentrations. Figure 17 gives an example of the type of data available from the NADP system. Following review of the data for completeness and accuracy, where equipment failure, sample mishandling, and contamination are flagged, the data are made available on the NAPD website. A map indicating NTN sites is available on the NADP website, as is the complete data record for each site in the network. The analysis results for the PREF NTN Monitoring Location ID02 are archived at PREF and the Moscow FSL; they can also be found through links on the NADP website at: http://nadp.sws.uiuc.edu/sites/siteinfo.asp?id=ID02&net=NTN.

Figure 16—The National Atmospheric Deposition Program site in Benton Nursery. The electronic rain gauge on the left records the time, duration, and intensity of precipitation events. On the right is the precipitation collector. A heated moisture sensor activates a motor that moves the peaked roof from the wet deposition bucket to the dry deposition bucket as precipitation begins. As a rain event ends, the sensor dries, and the roof rotates back to cover the wet side bucket.

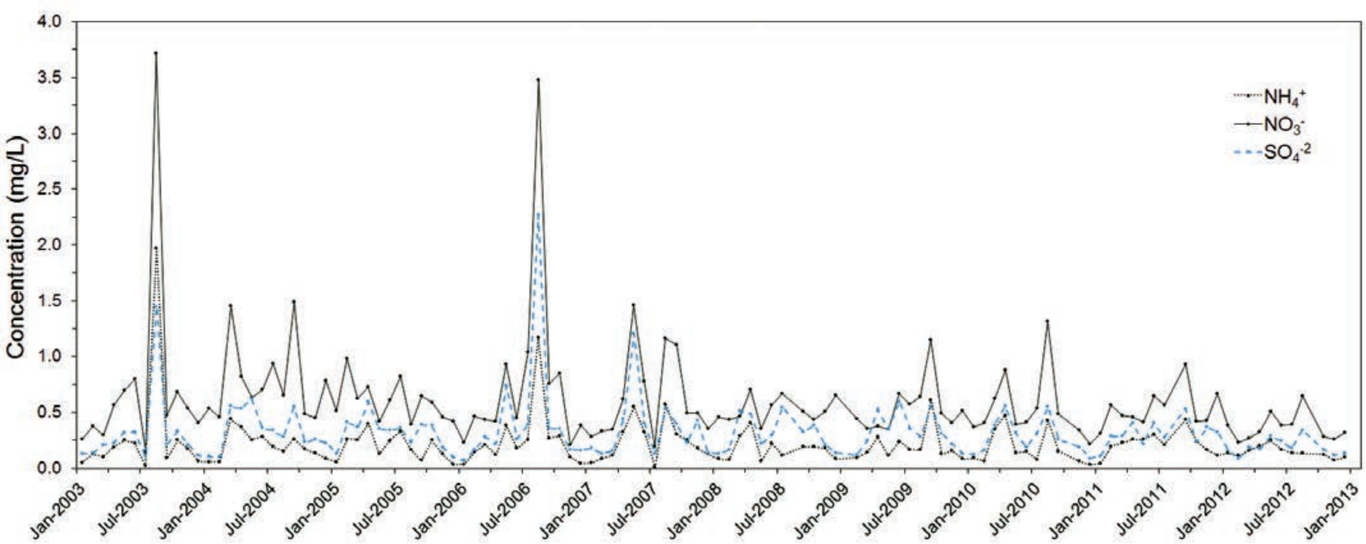

Figure 17—Example of deposition concentrations from three molecules at the PREF NADP site. The two outlier peaks in the summer of 2003 and 2006 coincide with late summer wildfire smoke emission deposition.

Condensed Climatic Summary

The climate at PREF is controlled by both large scale weather circulation patterns, such as the passage of warm and cold fronts, and by smaller-scale effects, such as the drainage of cold air downslope at night. Focusing first on the large-scale effects, the climate is generally intermediate between the mild climates on the western side of the Cascade Mountains and the harsher climate on the eastern side of the Rocky Mountains. Temperatures vary throughout the year, with mean monthly temperatures over the past century ranging from 24.4 °F (-4.2 °C) in January to 64.6 °F (18.1 °C) in July (Table 1), and an average annual temperature during the period of 44.1 °F (6.7 °C).

Seasonal temperatures demonstrate a pattern that is intermediate between the maritime conditions on the coast and the continental conditions east of the Rocky Mountains. Snow sustaining temperatures can persist within PREF from October until early April (Table 1), although temperatures are typically more moderate than those on the east side of the Rocky Mountains (Finklin 1983). Temperatures begin to increase by the end of April and by late June temperatures resemble those of the greater forested northern Rocky Mountains region until the fall storm track returns in early September. While summer temperatures rarely drop below 40 °F, below freezing temperatures have occurred in every month. From 1912 to 2013 there was an average of 173 days per year at the control station where minimum temperatures stayed above 32 °F (0 °C). The stable atmosphere PREF experiences during July, August, and September is attributed to the northward movement and weakening of the storm trade and subtropical high over the Pacific, which deters mid-latitude cyclones from impacting the region frequently and promotes warm, dry conditions in late summer. These persistent dry air masses have led to 14 days over the last 102 years with high temperatures over 100 °F (37.8 °C) in July and August.

PREF receives an average of 31.4 inches (798 mm) of precipitation annually at the control weather station near the station office, but the climate record varies widely with outliers ranging from 16.0 to 47.2 inches (406-1,199 mm) per year (Table 2). During the winter months, precipitation is carried inland along the jet stream, yielding 40% of PREF's annual precipitation during the months of November, December, and January (Table 2). The importance of winter precipitation is even more pronounced at high elevations within the Benton Creek watershed, where up to 60% of the annual precipitation can come in the form of snow that sometimes lingers into June. The months of July, August, and September account for less than 12% of the annual precipitation,

Table 1—Monthly average and daily extreme temperatures (°F) at the PREF control weather station from 1911 to 2013.

	Averages			Extremes			
Month	Daily maximum	Daily minimum	Monthly	Highest	Year	Lowest	Year
Jan.	30.5	18.3	24.4	50	2003	-33	1950
Feb.	37.0	20.3	28.7	57	1947	-35	1933
Mar.	45.6	24.7	35.2	71	2004	-18	1945
Apr.	57.0	30.2	43.6	88	1934	-1	1936
May	66.8	37.3	52.1	97	1936	18	1954
June	73.6	43.4	58.5	97	1912	24	1918
July	82.8	46.2	64.6	102	1924	29	1917
Aug.	81.9	44.6	63.3	103	1961	26	1914
Sept.	71.3	38.3	54.8	97	1988	16	1926/1934
Oct.	55.8	32.1	44	83	1935/1943	-5	1935
Nov.	38.9	26.7	32.8	64	1965	-16	1955
Dec.	31.6	21.3	26.5	55	1933	-36	1968
Year	56.1	32	44.1	103	Aug. 1961	-36	Dec. 1968

Table 2—Monthly and daily average and extreme precipitation (inches) at the PREF control weather station from 1911 to 2013.

									Snowfall				
Month	Monthly average	Maximum monthly	Year	Minimum monthly	Year	Daily average	Daily maximum	Year	Average	Maximum monthly	Year	Maximum daily	Year
Jan.	4.01	8.38	1954	0.27	1985	0.14	1.74	1967	25.7	89	1969	16	1969
Feb.	2.89	6.66	1999	0.20	2005	0.11	1.73	1970	14	53.3	1937	13.5	1948
Mar.	2.85	8.12	2012	0.36	1965	0.10	1.90	1966	6.5	35.2	1951	11	1916
Apr.	2.14	4.53	1955	0.30	1924	0.08	1.50	1982	0.9	10.3	1922	7	1915
May	2.35	7.13	1941	0.37	1937	0.08	3.34	1998	0	3	1943	2	1943
June	2.33	6.84	2012	0.14	1922	0.08	2.91	1992	0	2	1916	2	1916
July	1.03	4.03	1983	0.00	1960/1973/2003	0.04	1.34	1937	0	0		0	
Aug.	1.13	4.24	1926	0.00	1931/1969	0.04	1.66	1918	0	0		0	
Sept.	1.54	7.50	1927	0.01	1990	0.05	1.65	1927	0	1	1971	1	1971
Oct.	2.62	8.31	1947	0.13	1987	0.09	1.75	1951	0.6	9.5	1919	6	1919
Nov.	4.06	10.46	1973	0.11	1929	0.14	2.40	1959	9.9	60.2	1996	14.5	1996
Dec.	4.49	11.22	1933	0.91	1913	0.16	2.21	1951	24.1	68.8	2008	20	1951
Year	31.37	11.22	Dec. 1933	T	Jul-73	0.09	3.34	May 1998	81.9	89	Jan. 1969	20	Dec. 1951

which is in contrast to areas east of the Rocky Mountain crest, where precipitation is more heavily concentrated in the summer and is fueled by monsoonal moisture carried northward from the tropics (Whitlock and Bartlein 1993). Northern Idaho is the northernmost stronghold of the summer-dry regime characteristic of northern California and the Oregon and Washington Cascades.

Climate Record Trends and Patterns

Precipitation

The seasonal precipitation regime that is most typical of the northwestern Rocky Mountains has a pronounced dry season developing in July and lasting into September, while the bulk of the annual precipitation occurs during the winter months. The dry summers and the winter flow of moist maritime air lead to disproportionately high wintertime precipitation totals (Table 3 and Figure 18). This strongly seasonal distribution differs from the situation in southern Idaho and in the Yellowstone region east of the Continental Divide, where precipitation is more concentrated in the late fall and early winter (Whitlock and Bartlein 1993). The PREF control weather station receives an average of 31.4 inches with a Standard Deviation (SD) of 5.6 inches ($\overline{x}$ = 797.6, SD = 142.2 mm) annually, with no statistically significant trend in total annual precipitation over the last century (Figure 19, $p = 0.17$). Decadal and climate normal average monthly and annual precipitation totals are given in Table 3.

Precipitation accumulation often increases with elevation over short distances, but rates of increase can be difficult to predict in a given watershed. The control station (2,380 ft; 726 m) precipitation gauge, located at the bottom of the drainage, was compared to the Benton Spring gauge (4,775 ft; 1,456 m), located about three quarters of the way up the watershed (~3 horizontal miles away) (Figures 18, 19, and 20). The strong seasonal dependence in precipitation is clear at both sites, with 40% and 37% of the total annual precipitation for the control station and Benton Spring station coming from November, December, and January, respectively (Figure 19). July, August, and September account for 13% of the annual precipitation at the control station and 12% for the Benton Spring station. Both gauging stations show very similar distributions of annual precipitation with the mean of the Benton Spring distribution being approximately 4.5 inches greater than the Control Station (Figure 19).

Table 3—Ten-year (decadal) and 30-year "normal" average precipitation (inches) for the PREF control weather station.

Period	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Decade													
1912-1920[a]	3.8	3.0	2.8	2.2	2.6	2.0	1.3	1.3	2.0	2.3	4.3	3.5	31.0
1921-1930	3.4	2.8	1.8	1.6	1.7	1.7	0.5	1.3	1.8	2.4	2.8	3.9	25.8
1931-1940	4.6	3.0	2.8	1.9	1.3	1.8	0.7	0.4	1.4	2.9	3.5	5.6	29.9
1941-1950	3.1	3.1	3.2	2.4	2.6	3.3	1.1	0.9	1.6	4.1	4.0	3.8	33.3
1951-1960	5.2	3.4	2.5	2.3	2.4	2.8	0.9	1.4	1.4	2.5	4.3	4.3	33.3
1961-1970	4.9	2.5	2.8	1.9	2.1	2.2	0.8	1.3	1.7	2.5	4.5	4.8	32.0
1971-1980	3.6	3.4	2.2	1.9	2.6	1.4	1.5	1.9	1.5	1.5	4.2	5.0	30.8
1981-1990	3.7	3.1	3.3	2.2	2.4	2.2	1.3	1.4	1.4	1.7	4.8	3.3	30.7
1991-2000	4.2	2.9	2.7	2.5	2.9	2.8	1.5	0.8	1.5	2.5	4.2	4.9	33.5
2001-2010	4.1	1.8	3.3	1.9	2.7	2.5	0.8	1.2	1.4	2.8	4.0	4.6	31.0
2011-2013[a]	3.7	2.2	5.0	3.6	3.4	4.6	1.2	0.2	0.3	3.5	6.0	4.2	37.9
30 Years													
1912-1940	3.92	2.91	2.54	1.91	1.78	1.80	0.82	0.97	1.69	2.57	3.57	4.36	28.86
1921-1950	3.71	2.94	2.62	1.88	1.97	2.28	0.77	0.90	1.69	3.11	3.49	4.59	29.94
1931-1960	4.33	3.14	2.80	2.05	2.22	2.64	0.92	0.92	1.58	3.30	3.91	4.71	32.51
1941-1970	4.43	3.12	2.87	2.14	2.41	2.72	0.95	1.13	1.56	3.25	4.18	4.45	33.21
1951-1980	4.56	3.16	2.57	2.07	2.43	2.15	1.05	1.49	1.53	2.24	4.21	4.78	32.23
1961-1990	3.98	3.02	2.76	2.07	2.37	2.08	1.22	1.47	1.56	1.95	4.40	4.39	31.25
1971-2000	3.72	3.14	2.70	2.24	2.63	2.21	1.41	1.31	1.41	1.92	4.34	4.36	31.38
1981-2010	3.85	2.54	3.06	2.29	2.60	2.48	1.16	1.10	1.36	2.33	4.34	4.26	31.37

[a] Not full decades.

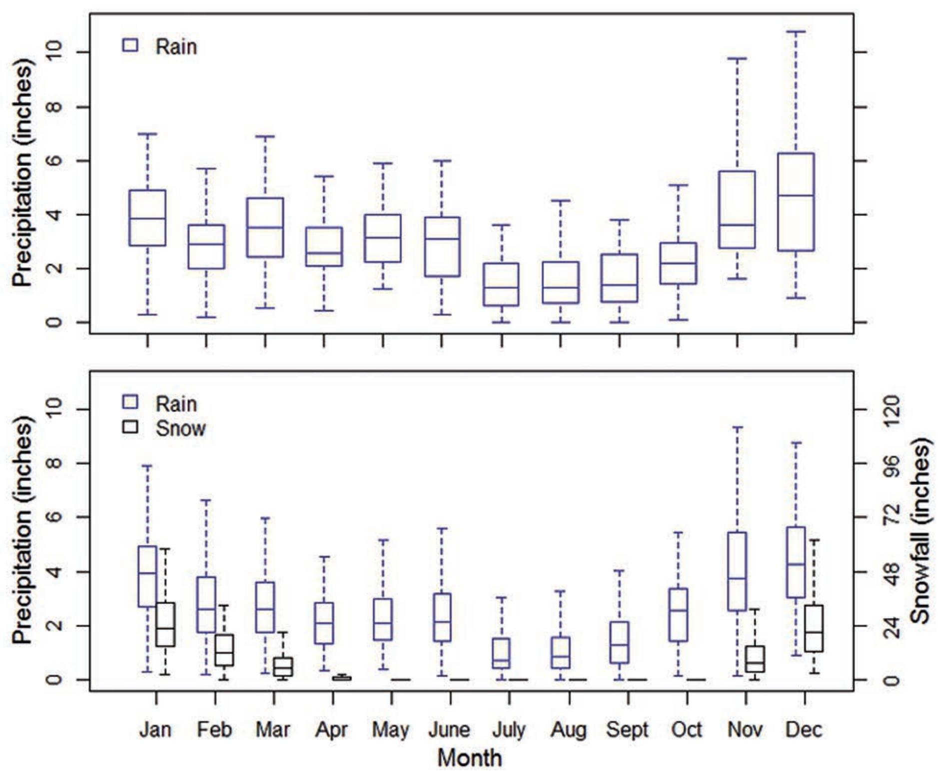

Figure 18—Monthly average precipitation and snowfall for PREF. The top chart is based on 51 years (1961-2012) of precipitation observations at the high elevation Benton Spring site. The bottom is based on 101 years (1911-2012) at the control station, with snowfall (open bars) plotted against the right axis, which has been scaled proportional to that of precipitation (black bars), assuming an average of 1.0 inch water equivalent from 12.0-inch snowfall. Error bars represent a 95% confidence interval throughout the time series.

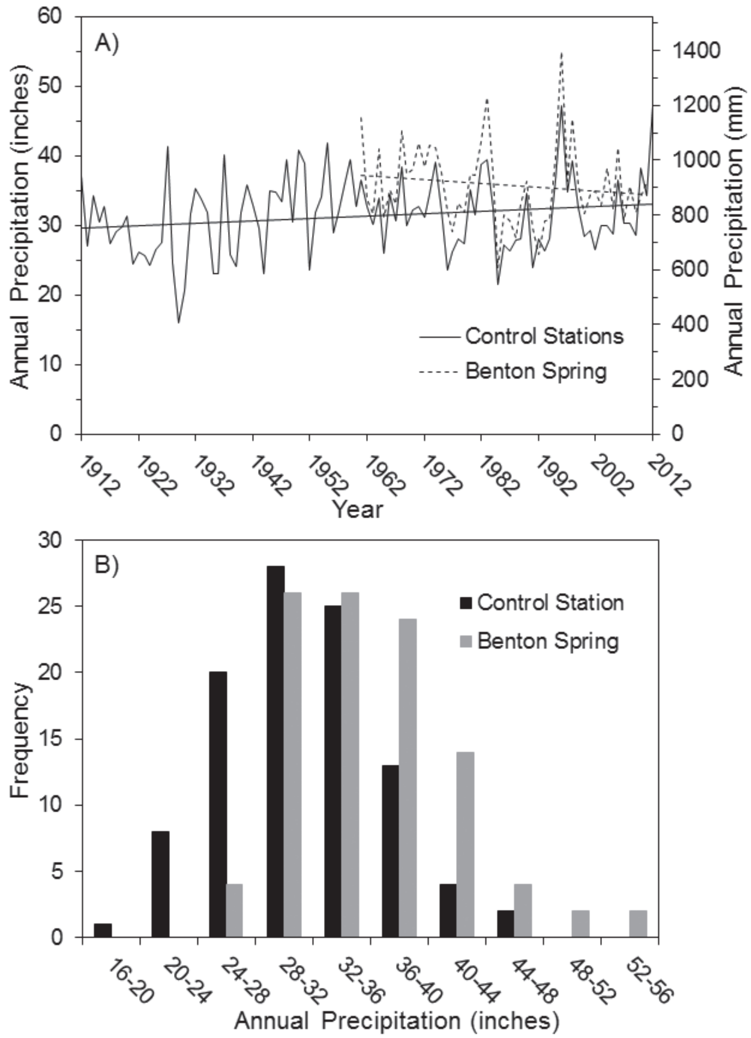

Figure 19—Annual precipitation totals at PREF for both the control station and Benton Spring station, showing (A) the temporal variation and (B) distribution of the two stations. The control station shows 101 years (1912 to 2012) of precipitation data, while the Benton Spring station shows 51 years (1961 to 2012). In order to visualize the difference in distributions, the Benton Spring station record was doubled so that it would show approximately the same number of records. While the records show contrasting trends in their slope, neither slope statistically differs from 0.

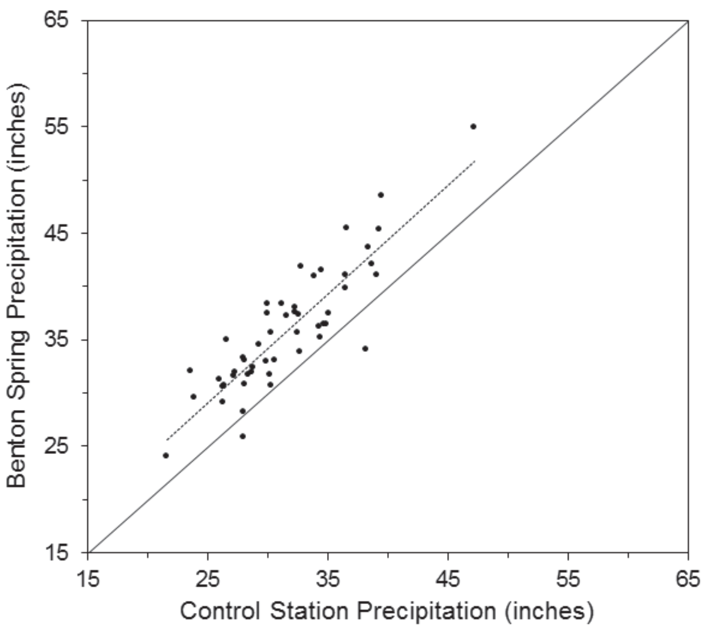

Figure 20—Comparison of annual precipitation at high-elevation Benton Spring gauge and at lower-elevation control station gauge from 1961 to 2011. The solid line represents a 1:1 reference line and the dashed line represents a linear fit through the dataset. The regression line does not significantly differ from 1 and represents an average increase of 13.5% more precipitation received at the 4,775-ft elevation Benton Spring station compared to the 2,380-ft elevation control station.

Analysis shows a consistent increase in annual precipitation along an elevation gradient, with the slope of the regression not differing from 1 ($p = 0.32$) (Figure 20). This consistent increase causes the Benton Spring site to receive on average 4.5 ($SE = 0.4$) inches ($\bar{x} = 114.3$, $SE = 10.2$ mm) more precipitation in both wet and dry years (Figure 20). In his 1983 report, Finklin proposed that the Benton Spring raingauge was underestimating snow accumulation by 13%. If true, that would increase the snowpack estimates proportionally, where the proportional increase would be added to the already described 4.5-inch increase seen between the sites. The elevation induced precipitation gradient yields a 1.8-inch increase in annual precipitation per 1,000 ft of elevation (148 mm/km). Which is substantially lower than rates reported for the Wind River mountains in Wyoming, which was 5.99 inches/1,000 ft (500 mm/km; Fontaine and others 2002), Dry Creek Watershed near Boise, Idaho, which was 5.55 inches/1,000 ft (463 mm/km; Stratton and others 2009), or the Colorado Front Range, which was 5.39 inches/1,000 ft (450 mm/km; Bigler and others 2007).

Although there appears to be no change over time in total precipitation across the watershed (Figure 19), cumulative snowfall at the low elevation control station has declined at a rate of 0.20 inches per year ($SE = 0.10$, $p = 0.054$; 5.1 mm/year) over the past century (Figure 21). If the decline in snowpack is summed over 100 years, it results in a 24% loss of the mean snowfall (81.9 inches or 2,080.3 mm) over the period. While the decline in snowfall is apparent in the statistics, the level of variation in snow accumulation ($SD = 30$ inches or 762 mm) has remained high throughout the climate record. In fact, a few heavy snowfall years cause the data to fail the Shapiro-Wilk test for normal distribution ($p = 0.009$), which violates one of the assumptions in linear regression analysis. Transforming the data by taking the natural log solves the problem, but this transformed data yields results with less intuitive parameters: -0.0028 per year, which compounds into 24% per century.

The low-elevation Benton Meadow snow course rarely accumulates a snowpack greater than 20 inches, with peak snow accumulation often in February and a March 1st snowpack depth averaging 18.6 inches (472.1 mm) (Table 4). In contrast the high-elevation Benton Spring snow course often experiences it's peak snow accumulation in March or April and has a March 1st snowpack depth averaging 51.5 inches (1,308.1 mm) (Table 4). While the Benton Meadow snowpack annually melts out before May 1st, the Benton Spring snowpack typically persists well into May and sometimes into June.

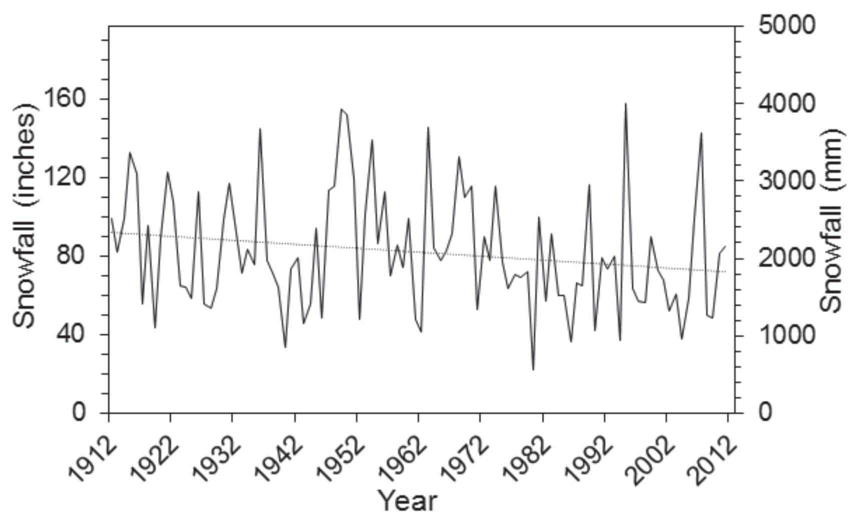

Figure 21—Cumulative annual snowfall at the low-elevation control station for 1912 to 2012, with a linear regression line plotted through the data. Over the last century cumulative snowfall at the lower elevations of the watershed has declined by approximately 20 inches.

Table 4—Summary of monthly snow course depth and snow water depth (SWE) in inches for the Benton Spring and Benton Meadow snow courses from 1937-2013. Snow depth and SWE equivalent were collected within three days of the first of the month and then averaged.

	January 1		February 1		March 1		April 1		May 1		June 1	
	Depth	SWE	Depth	SWE	Depth	SWE	Depth	SWE	Depth	SWE	Depth	SWE
Benton Spring (4,775 feet)												
1937-1946	26.9	7.3	41.2	12.3	50.9	16.7	48.7	18.4	25.7	11.7	0.0	0.0
1947-1956	32.9	9.4	52.8	16.1	63.2	21.8	64.7	24.4	42.6	18.6	1.4	0.8
1957-1966	33.1	8.4	46.0	12.5	50.3	16.2	53.1	19.0	35.7	14.9	0.0	0.0
1967-1976	31.7	8.9	50.4	15.2	58.1	20.0	60.1	22.2	46.5	19.6	3.0	1.3
1977-1986	29.4	7.7	35.7	10.8	44.0	14.8	43.6	15.5	24.7	10.7	0.0	0.0
1987-1996	22.7	6.2	37.6	11.7	41.6	13.8	38.3	14.2	12.4	6.3	0.0	0.0
1997-2006	34.2	10.0	46.5	14.5	52.8	18.2	50.0	19.6	26.8	12.2	1.5	0.8
2006-2013	32.6	9.0	40.5	12.6	50.7	16.6	56.5	20.5	40.0	16.5	0.0	0.0
Overall	30.4	8.3	44.0	13.3	51.5	17.3	51.7	19.2	31.7	13.7	0.8	0.4
Benton Meadow (2,380 feet)												
1937-1946	7.7	2.1	17.2	4.4	20.0	6.6	4.1	1.8	0.0	0.0	0.0	0.0
1947-1956	17.2	3.5	24.4	6.1	23.2	7.0	11.5	3.9	0.0	0.0	0.0	0.0
1957-1966	16.8	3.4	21.6	5.6	20.3	6.2	13.1	4.6	0.0	0.0	0.0	0.0
1967-1976	12.6	2.6	21.0	5.1	20.1	6.0	14.7	5.1	0.0	0.0	0.0	0.0
1977-1986	13.8	2.7	17.8	4.2	17.2	5.4	6.4	2.3	0.0	0.0	0.0	0.0
1987-1996	9.1	1.9	13.4	3.6	13.0	4.1	4.8	1.9	0.0	0.0	0.0	0.0
1997-2006	12.0	3.0	17.2	4.6	15.3	4.8	4.7	1.6	0.0	0.0	0.0	0.0
2006-2013	15.7	3.6	20.7	5.1	20.3	6.0	11.0	4.0	0.0	0.0	0.0	0.0
Overall	13.0	2.8	19.1	4.8	18.6	5.8	8.7	3.1	0.0	0.0	0.0	0.0

However, when looking at the climate record for both snow courses it becomes apparent that snow accumulation at the two sites is changing (Figure 22). At Benton Meadow, the data show an 0.11-inch (2.8-mm) per year ($p = 0.03$) decline in March 1st snow depth, suggesting the snowpack is on average 30% shallower than it was in the 1930s. This trend holds constant for the snow water equivalent (SWE) data ($p = 0.03$), with the snowpack containing approximately one-third less water than it did on March 1st in the 1930s. While regression of the March 1st snowpack for the Benton Spring site shows a negative slope, there was no significant decline in either snow depth or SWE in any of the sampling periods (Figure 22, Table 4).

Streamflow

Collection of streamflow data began in 1939, almost three decades after the climate data collection began, currently providing 73 years of data. Benton Creek resembles that of a typical hydrograph for most first order mountain streams of the western United States. It has a pronounced peak flow occuring during mid-May (Julian Date = ~140) averaging 7.19 cubic ft per second (cfs; 0.20 cubic meters per second (cms)) (Figures 23, 24) and a historic maximum flow on May 16th, 1997 of 30.06 cfs (0.85 cms). The hydrologic system also shows the prolonged summer baseflow period, beginning in mid-July and tappering off in December. This baseflow corresponds with the temporal lag commonly seen between snowmelt and streamflow. Benton Creek streamflow is presented in correlation with daily weather observations from the control station within Appendix A. The stream reaches its baseflow level in early October (Julian Date = ~275) averaging 0.44 cubic ft per second (Figure 23), with a record low of 0.197 cfs (0.006 cms) on October 21st, 1981.

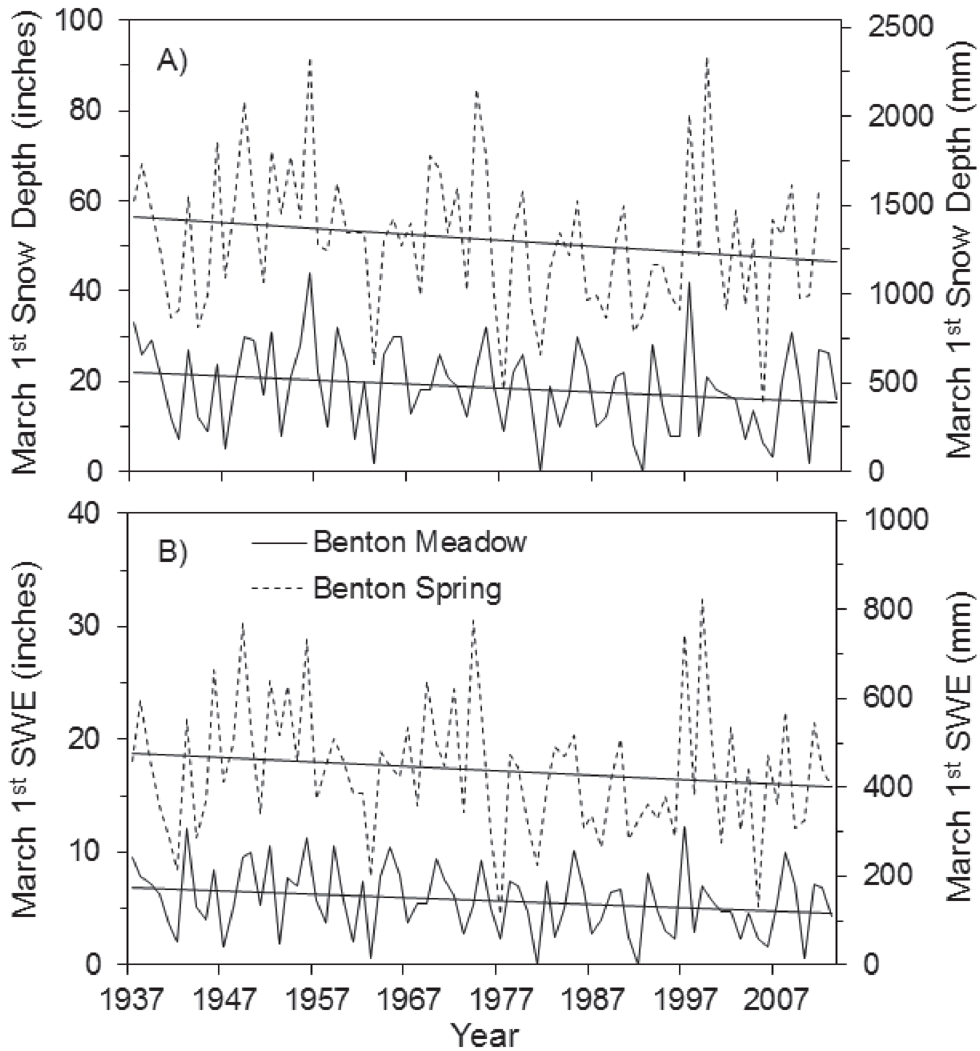

Figure 22—Comparison of the low elevation Benton Meadow (solid line) and high elevation Benton Spring (dashed line) snow courses from 1937 to 2013. The comparisons show the March 1st (A) snowpack depth and (B) snow water equivalent (SWE), where the line through each dataset represents a linear regression.

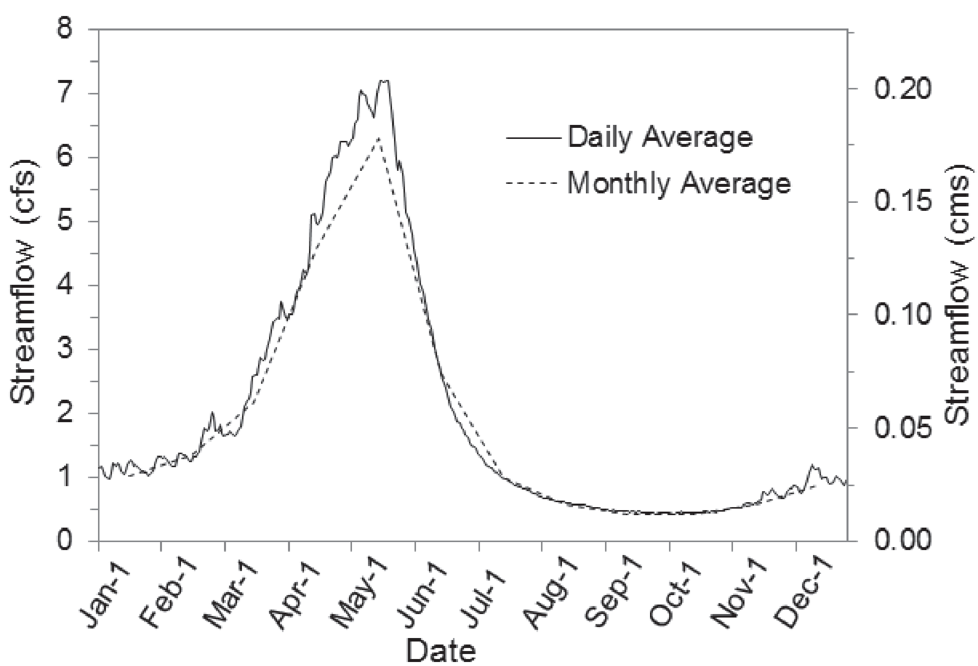

Figure 23—Seasonal distribution of streamflow in both cubic feet per second (cfs) and cubic meters per second (cms) averaged monthly since 1939 and daily since 1955 until early 2012 at the Benton Dam gauging station.

Figure 24—Benton dam during spring runoff, May 2011; the flat bottom weir on the left is the overflow weir, 0.75 ft above the V-notched reference weir on the right. The pool level is 1.161 ft (35.39 cm) above the V-notch, equivalent to a discharge rate of 13.1 cfs (0.37 cms).

The months of April and May account for 48% of the annual streamflow (Figure 23), while September and October contribute less than 4% of the annual total. Evenly distributing the average annual runoff across the catchment places 17 inches (431.8 mm) of water everywere, which is approximately 51% of the average catchment precipitation of 33.6 inches (853.4 mm). The unaccounted for 16.6 inches (421.6 mm) of precipitation is apparently removed from the system through evapotransporation or lateral subsurface flow processes. The annual runoff depth has increased in variation since Finklin (1983) reported a maximum and minimum of 25.3 and 6.0 inches (642.6 and 152.4 mm), respectively, to a new maximum of 33.5 in 1999 and a minimum of 4.6 inches (850.9 and 116.8 mm) in 1977.

Similar to the snowfall data presented earlier, streamflow data were log-normally distributed, so we log-transformed the data prior to analysis. This transformation reduced the influence of a few years with very high or low flows and allowed the distribution to pass the Shapiro-Wilk normality test (Figure 25). Streamflow has increased over the period of record ($p = 0.0043$) by 7.38 acre ft per year. When extrapolated over 73 years,

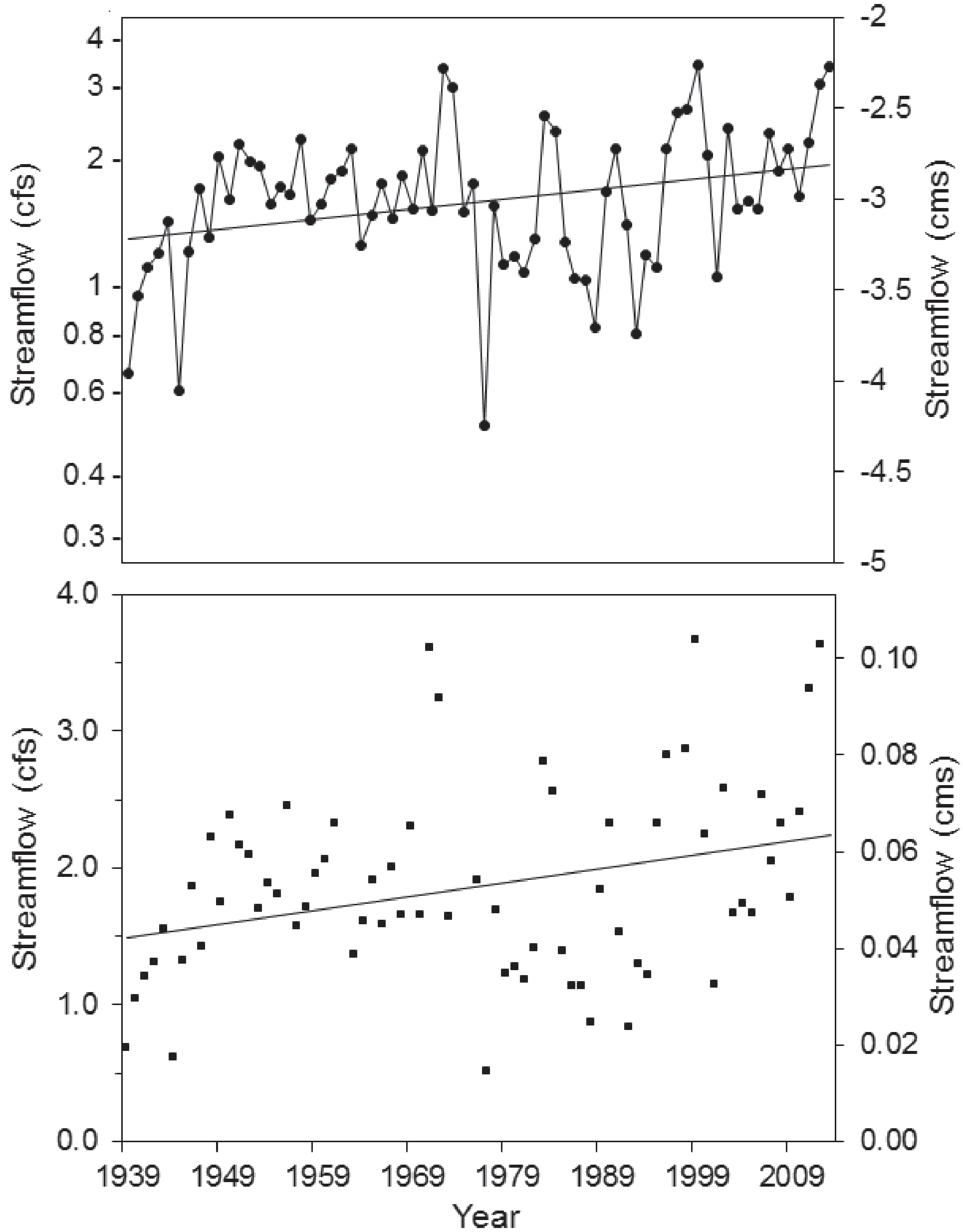

Figure 25—Average annual stream flow from 1939 through 2012, log transformed on top and presented as the raw data on bottom. Both graphs are plotted with a linear regression through the data, showing an approximate 33% increase in streamflow over the 73 years of observation.

this compounds to a 33% increase in the average annual runoff total. While there is an increase in annual streamflow, it can also be seen that the level of variation increases during the last three decades (Figure 26). The greatest variation in monthly streamflow occures in April and May, which can be linked to the high level of temperature variation and the influence that it has on snowmelt timing. This high variation also becomes apparent when looking at the timing of peak streamflow, which has moved 3.75 days per decade earlier or approximately 19 days earlier over the last 50 years ($p = 0.0024$; Figure 27).

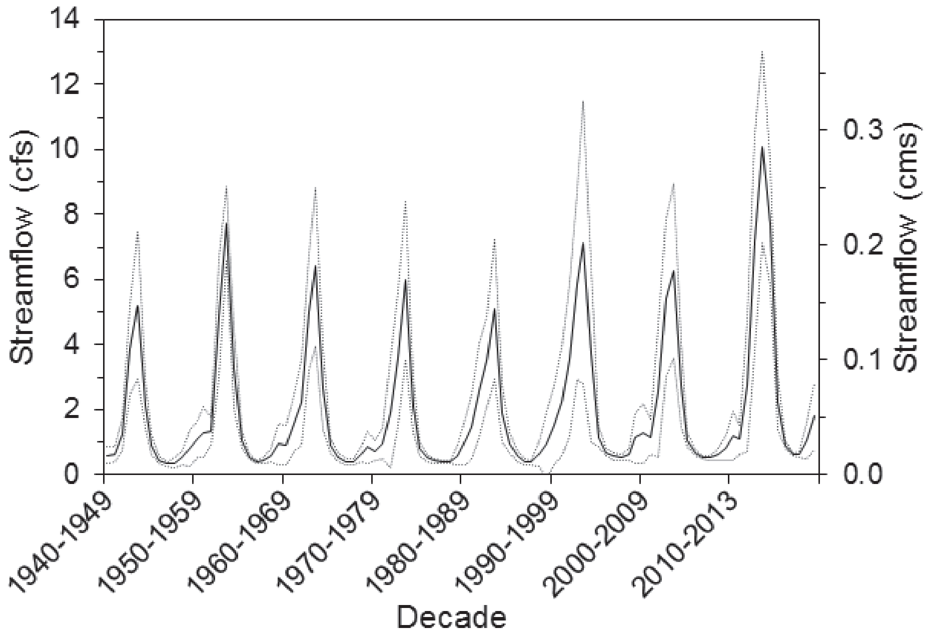

Figure 26—Averaged decadal streamflow hydrographs (solid line) with a 95% confidence interval (dotted line), where the x-axes marks denote the start of the decade. Although it appears that annual streamflow is increasing, this shows that the overall level of annual variation has also increased in the more recent decades.

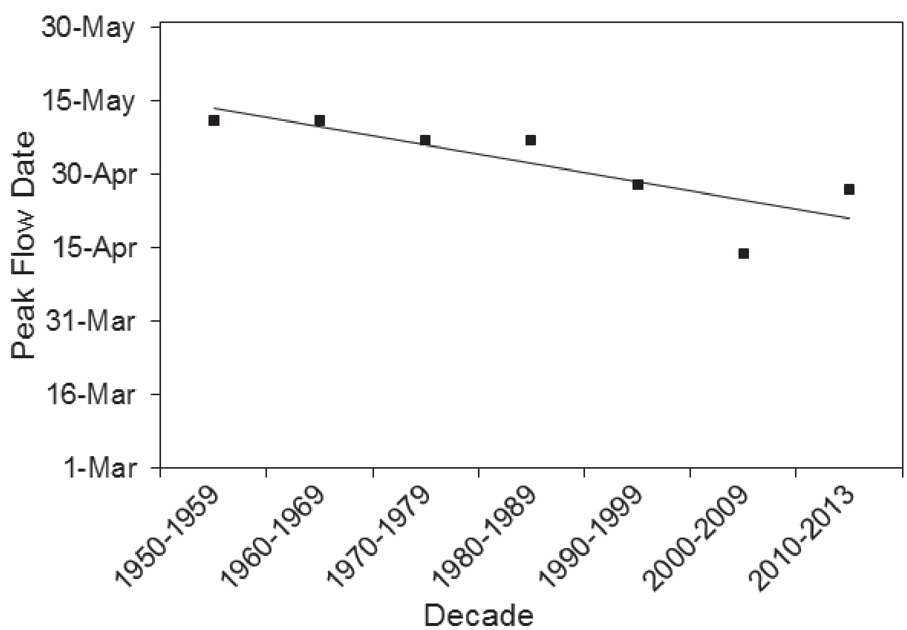

Figure 27—Timing of peak decadal streamflow over the last 60 years, with a linear regression plotted through the data. The regression shows that peak streamflow has shifted 3.75 days early each decade.

Temperature

Throughout the climate record of PREF, the average annual temperature has been 44.1 °F (6.7 °C), with July being the hottest month with an average daily maximum temperature of 82.8 °F (28.2 °C) and January being the coldest with a average daily maximum temperature of 30.5 °F (-0.8 °C). While freezing temperatures have occurred in every month, they are not common between May and October (Figure 28). A summary of decadal and climate normal average monthly temperatures for the control weather station at PREF can be found in Table 5.

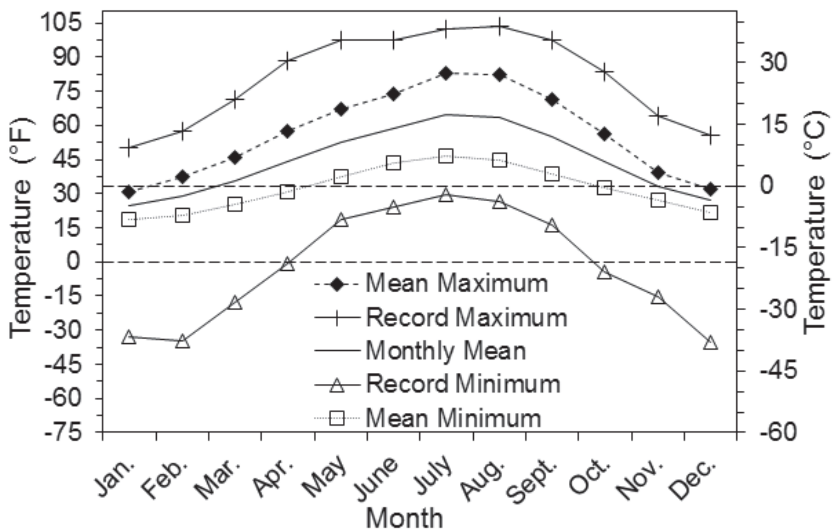

Figure 28—Temperature variation as recorded at the weather station, 1912-2012.

Table 5—Ten-year (decadal) and 30-year "normal" average monthly temperature (°F) for PREF control weather station.

Period	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Decade													
1912-1920[a]	22.8	27.1	33.9	42.9	49.3	56.7	62.8	61.8	52.9	42.5	32.8	25.0	42.5
1921-1930	21.9	27.7	35.4	43.6	51.8	58.5	65.1	63.1	54.0	44.1	33.3	25.5	43.7
1931-1940	24.6	25.0	35.4	44.6	52.8	59.1	65.0	62.8	55.9	45.6	33.6	29.4	44.5
1941-1950	20.3	28.3	33.9	43.8	52.3	57.6	64.1	62.8	55.4	44.8	33.3	26.9	43.6
1951-1960	25.0	28.5	33.4	42.7	52.3	57.9	64.1	61.8	55.2	44.7	31.8	28.4	43.8
1961-1970	24.6	30.0	34.0	42.3	51.6	58.9	64.0	62.9	55.6	44.2	34.3	27.1	44.1
1971-1980	22.1	30.0	35.3	43.6	52.3	59.6	65.4	64.1	56.3	45.3	32.0	27.6	44.5
1981-1990	26.0	27.9	36.7	44.7	52.4	60.0	64.1	63.9	54.4	43.5	32.3	23.4	44.1
1991-2000	26.5	29.5	36.5	44.2	53.2	58.3	64.0	63.4	54.7	42.9	31.8	25.8	44.2
2001-2010	26.8	30.1	35.9	43.7	52.2	59.0	66.2	63.6	54.5	42.6	32.1	25.4	44.3
2011-2013[a]	25.9	28.6	35.7	42.7	50.8	57.0	65.1	64.0	56.9	44.0	34.1	28.4	44.4
30 Years													
1912-1940	23.5	26.8	34.9	43.6	51.4	58.1	64.2	62.6	54.0	44.1	33.1	26.5	43.6
1921-1950	22.8	27.3	35.2	44.2	52.4	58.4	64.9	62.9	54.9	44.8	33.4	27.3	44.0
1931-1960	23.6	27.5	34.3	43.9	52.5	58.2	64.5	62.5	55.3	45.0	33.1	28.0	44.0
1941-1970	23.5	29.1	33.8	43.0	52.1	58.2	64.2	62.7	55.2	44.5	33.0	27.2	43.9
1951-1980	24.1	29.7	34.3	42.8	52.2	58.9	64.6	63.3	55.4	44.6	32.6	27.5	44.1
1961-1990	24.5	29.4	35.4	43.5	52.2	59.3	64.4	63.9	55.3	44.2	33.0	26.0	44.2
1971-2000	24.9	29.4	36.2	44.1	52.6	59.1	64.4	63.9	55.2	43.8	32.2	25.8	44.3
1981-2010	26.3	29.3	36.3	44.1	52.6	59.0	64.7	63.8	54.7	42.9	32.2	25.2	44.3

[a] Not full decades.

To look at any possible long-term trends that may be occurring in the climate record temperature data, we combined daily temperature data into annual averages. We analyzed daily mean temperatures and both the daily maximum temperature, which normally occurs sometime in mid-afternoon, and the daily minimum temperature, which normally occurs shortly following sunrise, but before the sun begins to warm the ground (Figure 29). Regression analysis showed that neither the daily mean nor daily maximum temperatures had changed over the past century, maintaining average value of 43.9 °F and 55.9 °F (6.6 °C and 13.3 °C), respectively (Figure 29). In contrast, daily minimum temperatures have increased ($p < 0.001$). If the increase is assumed linear (Figure 29), then minimum temperatures have increased by 0.0283 °F (0.0157 °C) per year, or 2.8 °F (1.6 °C) per century. Changes in minimum temperatures during the right portion of the year can hold serious implications for snowpack energetics and ablation timing and growing season length. When looking at Figure 29 it appears that the minimum daily temperatures begin to decline during the 1980s. This decline in minimum temperatures is supported by using a second order polynomial regression of the data, which resulted in an $r^2 = 0.36$ compared to the linear regressions $r^2 = 0.23$, with both relationships being significant ($p < 0.001$).

When minimum temperature is analyzed by month, the increase in temperature was not evenly distributed throughout the year (Figure 30). While every month showed a positive increase in minimum temperature with an average increase rate of +0.028 (SE = 0.005) °F per year ($p = 0.0001$), January and February have warmed more rapidly than the mean (+0.062 and +0.060 °F per year, SE = 0.013 for both,

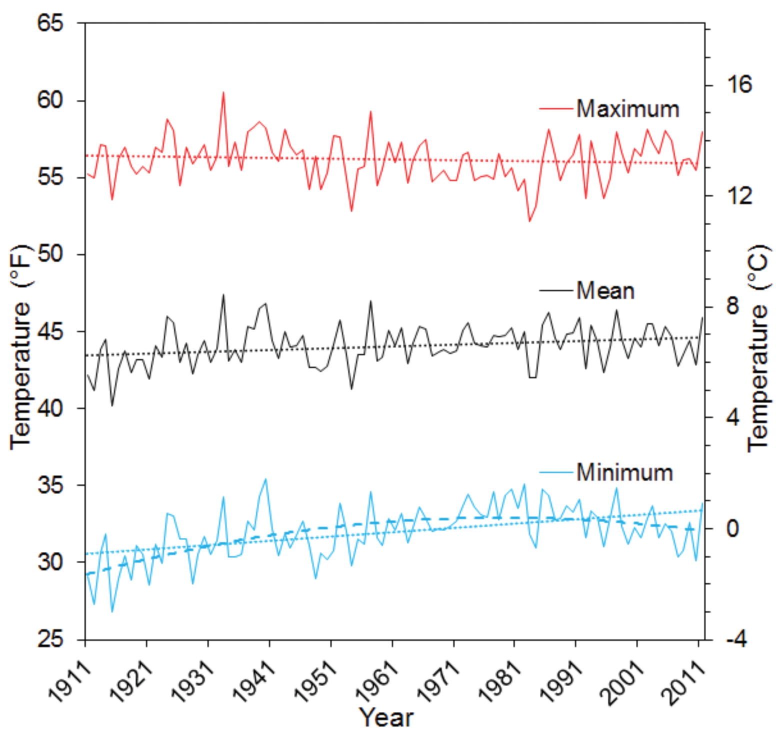

Figure 29—Annual average daily maximum, mean, and minimum temperatures for 1912 to 2012 at the control weather station in PREF, with lines of linear (dotted) and polynomial (dashed) regression overlaid. Analyses show no change in the maximum and mean daily temperatures, while annual daily average minimum temperatures have increasing by 2.8 °F over the last century.

p = 0.003 and 0.008, respectively). This would yield net increases of over 6 °F per century during these months (Figure 30). In contrast, October and November showed no significant change over the period (Standard Error [SE] = 0.013 °F, p = 0.04 for both). Comparing Figures 28 and 30, it becomes clear that the two coldest months are the ones that have warmed the most. This trend can be seen in Table 5 where winter temperatures appear to have become milder over the past four decades.

Finally, we looked at the effect that the increase in minimum temperatures may have on other environmental factors, such as the number of frost-free days per year and length of snow cover per year. These parameters have strong implications for their influences on system production through photosynthesis and economics through frost damage. Because it is derived from minimum temperatures, it is not surprising that the trend in the probability of frost resembles the trend in minimum temperature, with an increasing rate of approximately 0.2 days per year (Figure 31). Propagating this increase in frost-free days over a century shows an increase of 19.6 days per century. When looking at which months account for most of this change in frost frequency, it is apparent that April and May or the spring shoulder months to the winter weather account for most of this change (Figure 32). These two months account for approximately 9 of the 20-day difference in frosts over the last century. Along with this, length of snow cover was calculated as the number of days per year with at least 1 inch of snow at the control weather station (Figure 33). Here we see an inverse relationship with the minimum temperature increase, with there being a decline of 0.086 days of snow cover per year or 8.6 days less snow cover per century.

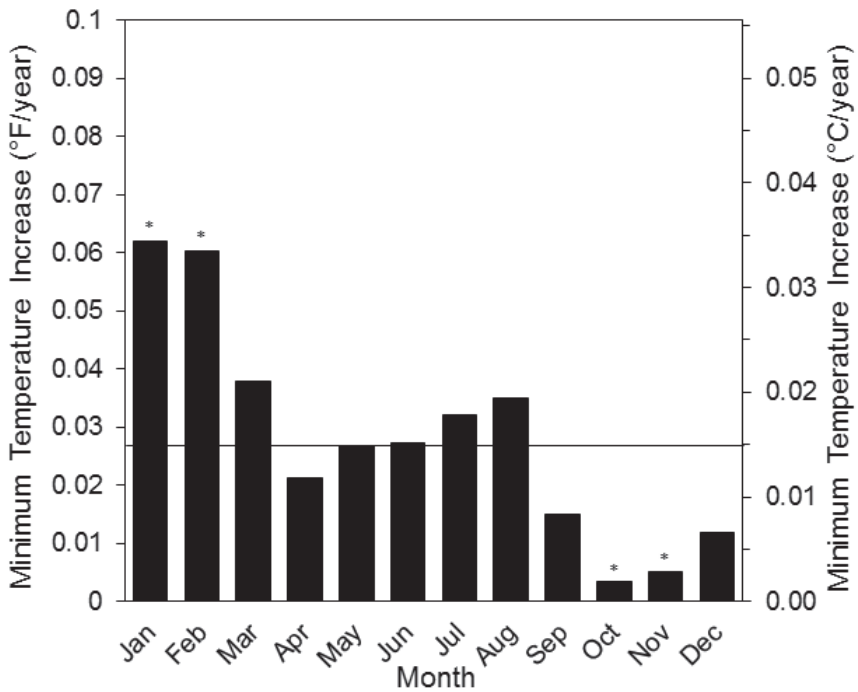

Figure 30—Monthly rate of increase in minimum temperatures from 1911-2012, with the average annual increase represented by the horizontal line. Asterisks represent rates of change significantly different from the average rate of increase. While minimum temperatures increase in every month, the greatest changes occur in midwinter and early spring.

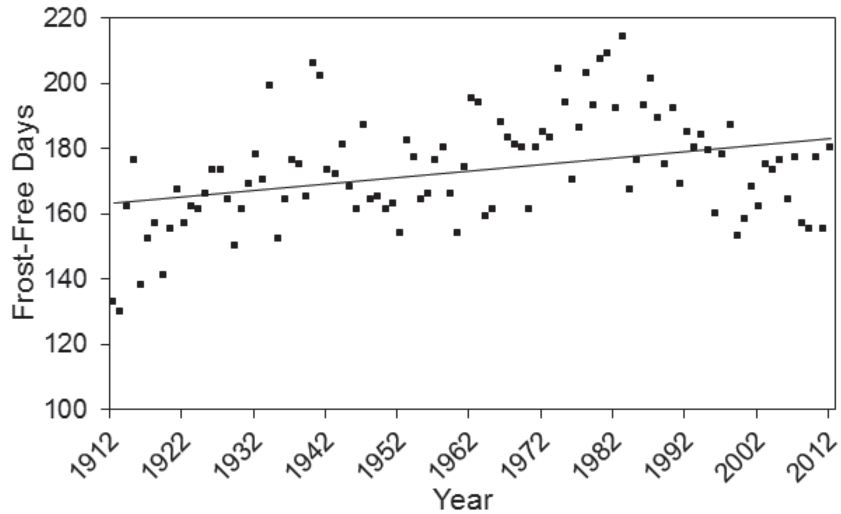

Figure 31—Number of frost-free days per year from 1912-2012; a day was counted if the minimum temperature did not go below 32 °F (0 °C). The line denotes a linear regression and shows that over the last century the growing season length has increased by approximately 20 days.

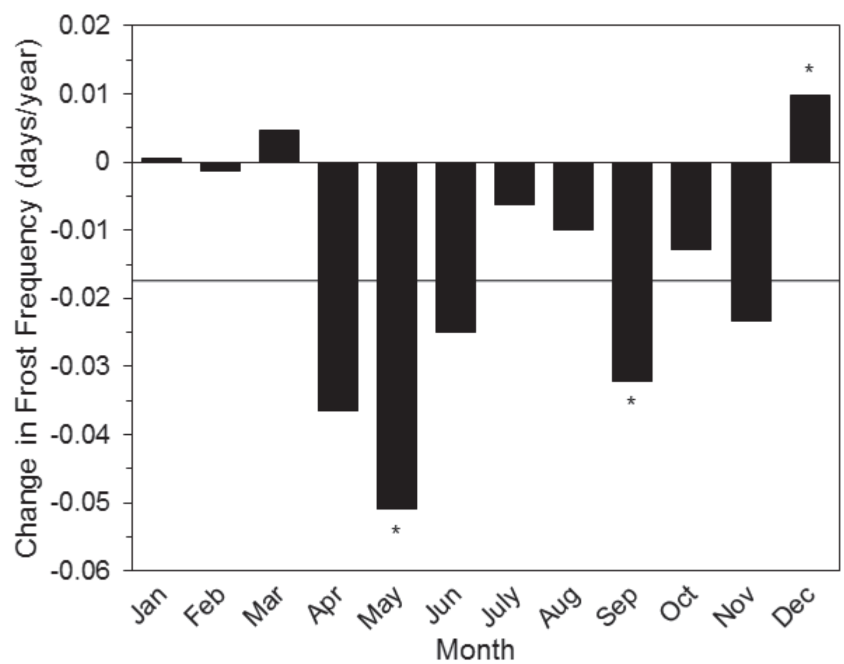

Figure 32—Change in monthly frost frequency from 1912-2012. The horizontal line represents the mean change in frost frequency if it was normally distributed across all months, with asterisks signifying months that significantly deviate from the mean. The decline in frost frequency during April and May influences the timing of peak streamflow and snowpack persistence.

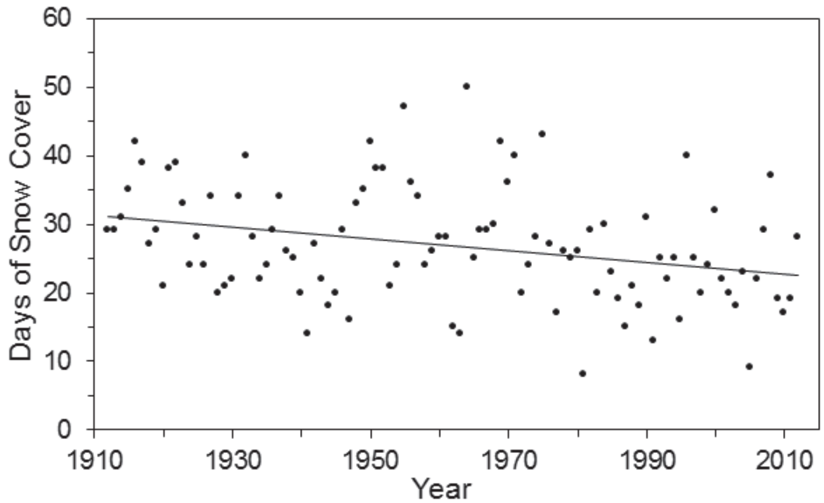

Figure 33—Number of days per year with at least 1 inch of snow at the control weather station in PREF, with a linear regression plotted through the data. Over the last century there has been a decline of approximately 9 days of snow cover.

Discussion

Over the period from 1912 to 2012, the climate record from PREF shows several signs of climatic warming expressed primarily through increases in the minimum daily temperature. This change manifested over the century as (1) decreased snow cover days, (2) decreased snow acumulation totals in spite of constant precipitation, (3) earlier melting of snowpacks in the spring, (4) earlier peak streamflows due to earlier melting of the snowpack, and (5) lower frequency of frosts. Increases in minimum temperature were greatest in January and February, but they appeared significant in all months except October and November. We also detected a significant long-term increase in Benton Creek streamflow from the almost continuous 73-year record. The increase in minimum temperatures during the century is what one would expect based on climate models (Russo and Sterl 2011) and supports earlier summaries of climate data from around the world (Frich and others 2002). Most climate models make predictions of future temperatures based on the physical linkage between atmospheric CO_2 and temperature, with minimum temperatures being more strongly influenced by atmospheric CO_2 concentrations than are maximum temperatures. More puzzling was the apparent decrease seen in minimum daily temperatures starting around 1980. To further explore the downturn in minimum temperatures after 1980, other weather stations within the region were analyzed for the same phenomenon. This comparison will distinguish if the cooling is in response to the bulk atmosphere, which is to say a "climate" effect, rather than a characteristic of the particular spot where the weather station was located, which is to say a "microclimate" effect. Three regional stations located between 70 and 110 miles south of PREF with nearly continuous data back to 1930 were analyzed. For each station, 7 years were removed from the records because they presented outliers that were not uniformly consistent and doubtful for the region; most of these records were in the 1930s, immediately after the weather stations were established and none occured after 1980. Regression analysis found similar increases in minimum daily temperatures at each of the stations, but at slightly reduced rates compared to the linear fit at PREF (Kellogg, ID +0.023 °F per year, $p = 0.027$; St. Maries, ID +0.036 °F per year, $p < 0.01$; Wallace, ID +0.031 °F per year, $p < 0.01$). However, none of these other stations showed a decline after 1980. The reduced warming rates for 1981 to 2012 have been well documented throughout the region and explained by natural climate variations.

The uniqueness of the pattern leads to questions about the location of the control weather station. In particular, there are large trees growing near the station and these may have grown tall enough to influence the weather data. For both temperature and precipitation measurements, the Environmental Protection Agency (Bennett and others 1987) recommends that sensors be no closer than four times the obstruction's height. The National Wildfire Coordinating Group (2012) states "Ideally, when dealing with tall, dense vegetation the station should be located a distance that is equal to 7 times the height of the obstructing vegetation."

A National Agricultural Imagery Program (NAIP) view of this area, produced in 2009, (Figure 34, top photo) clearly illustrates the extent and location of trees in relation to the Control weather station and Benton Meadow snowcourse. There are several trees over 95 ft (30 m) tall about 50 ft (15 m) northeast of the weather station. There is also a closed-canopy forest edge 65 ft (20 m) south of the station; these trees are approximately 65 ft (20 m) tall and may begin to influence the solar heating and nighttime cooling at the station. All of these obstructions are clearly within a distance that could influence the accuracy of observations (Bennett and others 1987, NWCG 2012). While Finklin (1983) was aware of these issues and discussed them in context of the Benton Spring precipitation gauge, he barely mentioned this issue with respect to the headquarters site. Certainly, the trees at the headquarters site were much shorter thirty years ago and may not have posed an issue at the time. Notably, above average minimum temperatures in 2012 and 2013 call for a more detailed analysis to assess the influence the land surface is having. In the spring of 2012, the vegetation around the weather station and snow-course was cleared, removing these interfering trees (Figure 33, bottom photo). Further work will be needed to see how the weather data responds over the next several years. Cutting the trees should allow for a targeted analysis and potential correction to the data collected since 1980 (Figure 35). If the trees were indeed the cause of the minimum daily temperature downturn in the 1980s, then the temperature increase should resume along the trajectory it had established before 1980 and should resemble the data from other stations in the region. For our purposes here, we have simply taken the minimum temperature data as they were and focused on the long-term increase.

With the biggest increases in minimum temperature occurring in January and February, there are serious linkages to the phase of precipitation with some snowfall shifting to rain at low elevations, reducing the snowpack. The relatively warm winters at PREF tend to maintain the snowpack at temperatures near 32 °F (0 °C), placing the snowpack "at risk" of melting during any warm period (Nolin and Daly 2006). The rise in minimum temperature increases the probability that precipitation will come as rain rather than snow as demonstrated by the decline in annual snowfall while precipitation remained unchanged (Figures 20 and 21). It seems unlikely that the lower-elevation snowpack will completely disappear any time soon, but it is at considerable risk of earlier melting and rain on snow events, with the length of time of snow cover having reduced by over 8 days in the last century (Figure 33). This warming has also reduced the depth and water content of the spring snowpack at low elevation by over 30% (Figure 22).

Figure 34—(Top) 1.0-m resolution NAIP aerial photo from 2009 of the area surrounding the control station (A) and Benton Meadow snowcourse (B). (Bottom) 0.5-m resolution NAIP image from 2013 showing the vegetation in the vicinity of the control station (A) and Benton Meadow snowcourse (B) after vegetation removal in May of 2012.

Figure 35—Before and after photos of the weather station and the Benton Meadow snowcourse. A selective harvest in May of 2012 removed trees that may have influenced weather and snowcourse measurements.

Similar decreases in snowpack water content have been reported across much of the western United States (Mote 2003, Mote and others 2005). At PREF, the smaller spring snowpacks are accompanied by a shift toward earlier peaks in streamflow (Figure 27), may ultimately lengthen the summer dry period. Such shifts toward earlier peaks in streamflow are being observed in several parts of North America, but especially in the headwaters surrounding the Columbia Basin (Luce and Holden 2009) and in the northern Sierra Nevada Mountains (Stewart and others 2005). Of all these interlocking variables, only minimum temperatures show a change of direction, starting in 1980. Snowfall, snowpack depth, and snow water equivalent all continue to fall throughout the record, even with the Benton Meadow snowcourse data (Figure 22) coming from immediately adjacent to the control weather station. The lack of change in these variables since 1980 at or near the control weather station location supports the idea that the minimum temperature measurement has been influenced by vegetation or some other variable at the headquarters station.

The ecosystems of PREF may see the strongest physiological response to the decrease in frost frequency (Figures 32 and 33). Over the last century April and May alone experienced 3.7 and 5.1 fewer days of frost per year, respectively. This change occurs at a critical time when days are long, buds are expanding, and soil moisture is high. The potential influence this may have on photosynthesis could be significant for overall system production (Öquist and Hunter 2003). Separate from photosynthesis, tissue susceptibility to frost is also high during periods when new tissues are expanding rapidly (Rehfeldt 1989); therefore, the risk of permanent damage to new tissues in May would be reduced if frost frequency declines.

The most surprising result of this analysis is the pronounced increase in annual streamflow in Benton Creek. This finding contradicts some earlier studies, including one conducted in the Pacific Northwest that focused on much larger basins from 1948 to 2006 (Luce and Holden 2009). These authors found a decrease in mean flow in 58% of the rivers for the lowest quartile of years studied, with the smallest basin being 142 km^2 and the majority of the decreasing rivers found in the Cascade and northern Rocky Mountain ranges. The Benton Creek drainage above Benton Dam is only 3.84 km^2 or about 1/37 the size of the smallest catchments considered by Luce and Holden (2009). With such strong differences between the hydrograph of this "little water" and the surrounding larger basins, perhaps Harry Gisborne was right about the need to establish such a study on a smaller drainage. Other studies have found results similar to Benton Creek in small mountian headwater streams thoughout the region (Birsan and others 2005, Jones 2011).

Understanding how such an increase in streamflow could occur is particularly interesting at PREF because annual precipitation amounts have not changed. The main water losses not accounted for are evaporation (including sublimation of snow and interception of precipitation by the canopy), transpiration, and deep drainage to aquifers. Canopy area is one control over transpiration and interception losses. However, it seems unlikely that canopy area has changed enough since 1912 to account for the 33% increase in streamflow. The management actions within the catchment, at any given timeframe, amount to no more than 10% of the catchment being in a highly disturbed state. It is also unlikely that deep drainage would have been modified during this period as it is mostly determined by soils and geology.

The most likely cause of the streamflow increase is a reduction in transpiration rate per unit area by the canopy. Two possible drivers of this process are (1) a change in species composition, and (2) tree height. Species composition has changed substantially since 1912. The canopy was dominated by western white pine during the early years of the record (Wellner and others 1951), but was later replaced by Douglas-fir and western larch (Finklin 1983). By 2000, the canopy was reportedly dominated by western red-cedar, Douglas-fir, and western hemlock (Duursma and others 2003). The stomatal conductance and transpiration rates per unit leaf area are much lower for the late-successional species at the end of this sequence than for the early successional western white pine (Pangle 2008). This successional change in species composition will have increased water use efficiency and may have reduced the transpiration losses. Secondly, as trees grow taller, it becomes more difficult for them to lift water to the canopy. Therefore, even within the same species, trees will have reduced conductance and transpiration of water per unit leaf area with increased tree height (Koch and others 2004, Pangle 2008).

This combination of successional change and height growth could reduce transpiration substantially. Utilizing the streamflow record and the Theisien Polygon method of distributing precipitation observations from the then sixteen rain gauges, Stage (1957) estimated that for 1911 to 1955 there was an average precipitation loss of 69% to evapotranspiration, with only 31% seen as streamflow. In 1983, Finklin estimated, by difference, that evapotranspiration utilized 60% of the precipitation reaching the forest. In 2004, Pangle (2008) directly measured transpiration from trees as utilizing 42% of precipitation, which is more in line with the 53% of total precipitation that the 2004 streamflow accounts for. It would be interesting to extend this comparison to account for shrub transpiration over several years.

Conclusion

PREF is uniquely positioned within the northern Rocky Mountains and contains a diverse wealth of data records, from the climate records and streamflow data to continuous forest inventory observations. This long-term climate record has the potential to provide insight into future projections of change within these systems. The potential for advancing our understanding of single processes and also coupled interactions, like those seen in the change in streamflow, needs to be investigated further.

It is humbling to consider that when Finklin last summarized these data in 1983, climate change was just a speck on the horizon. At the time, climate was known to fluctuate but it was not expected to undergo directional change; instead, interest was focused on the 11-year sunspot cycle. In the almost 30 years since then, the accumulating evidence of climatic warming has changed the conversation. What is required now is collaboration between managers and scientists to develop new means of dealing with the changes already being seen on the landscape. The long-term record at PREF can be an important tool in this collaboration, but only if maintained, critically evaluated, validated, and applied. PREF data confirm long-term temperature increases and enhance our awareness of the potential secondary effects and feedbacks that may result from climate warming in this region, including changes in snow hydrology and streamflow volume and timing. PREF's location at the western edge of the Rocky Mountains, inclusion of low and high-elevation snowpack data, limited disturbance history, and its headwater stream gauging station provide it with a unique opportunity to serve as our canary in the face of climate change within the northern Rocky Mountains.

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Appendix: Streamflow correlated to other weather variables.

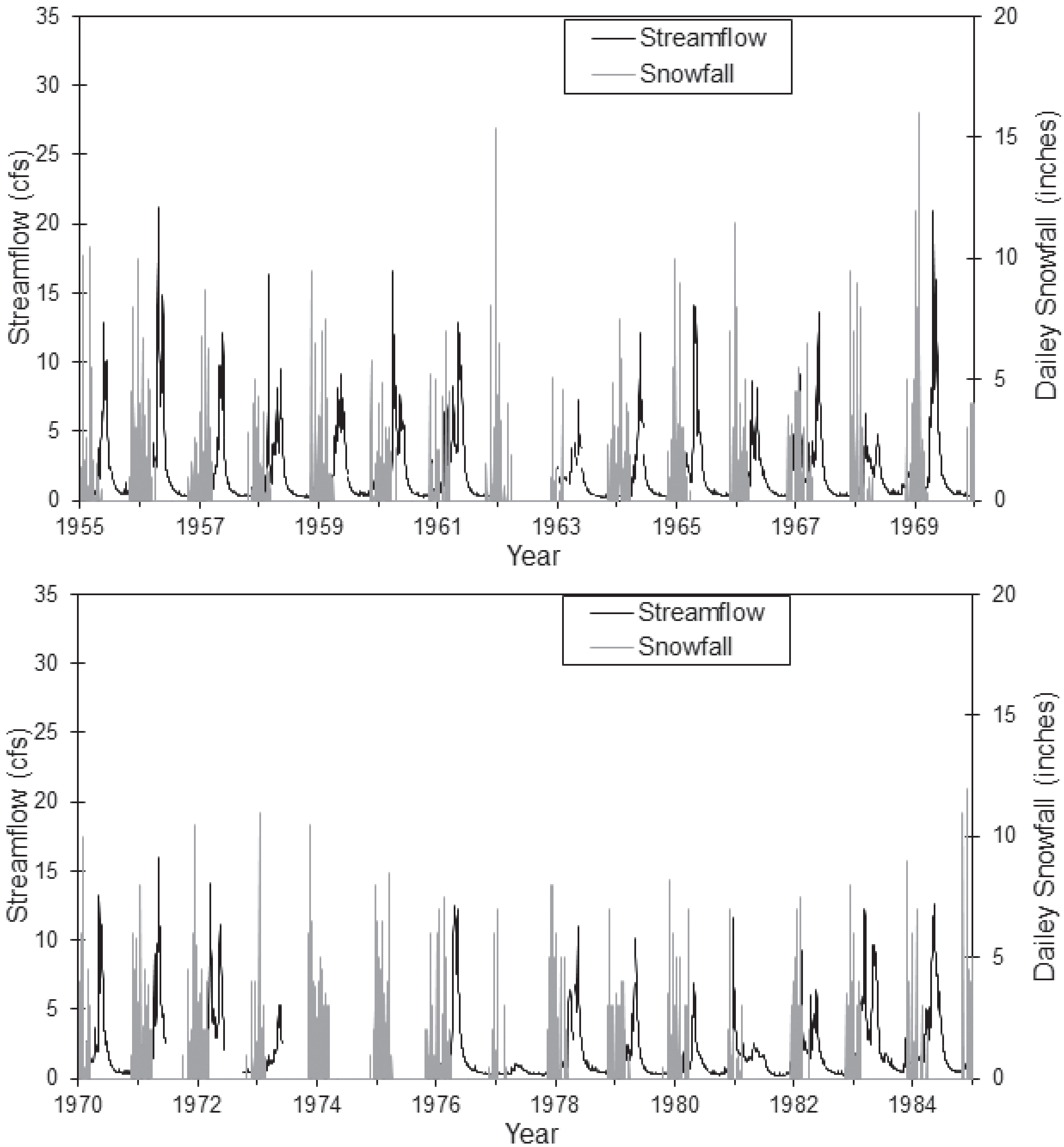


Figure A.1—Benton Creek streamflow correlation with daily snowfall, presented in fifteen year intervals from daily observations collected at the Benton Dam gauging station and control weather station. The data was originally synthesized and prepared for a report by Link and Wei (2010).

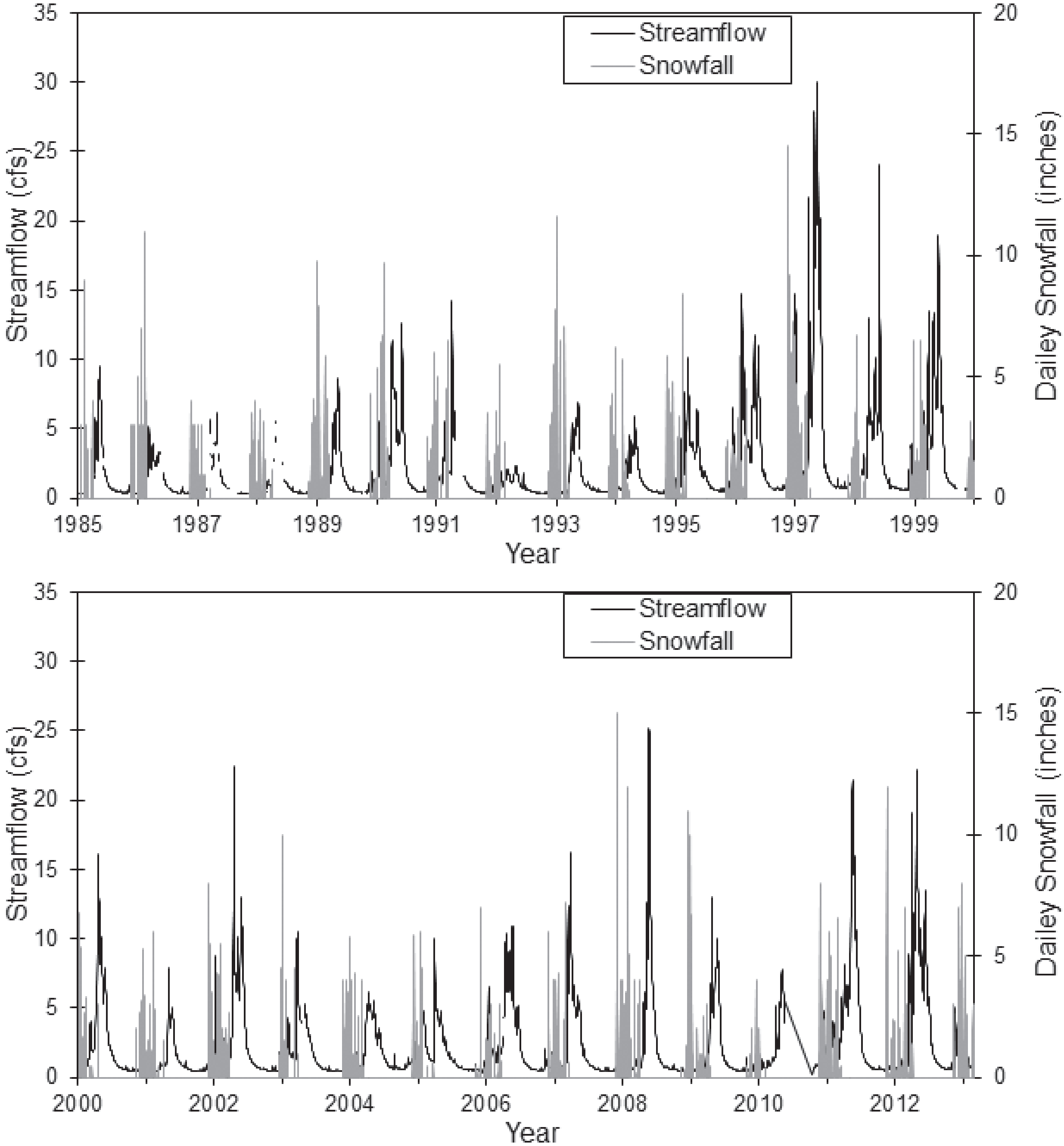


Figure A.1—Continued

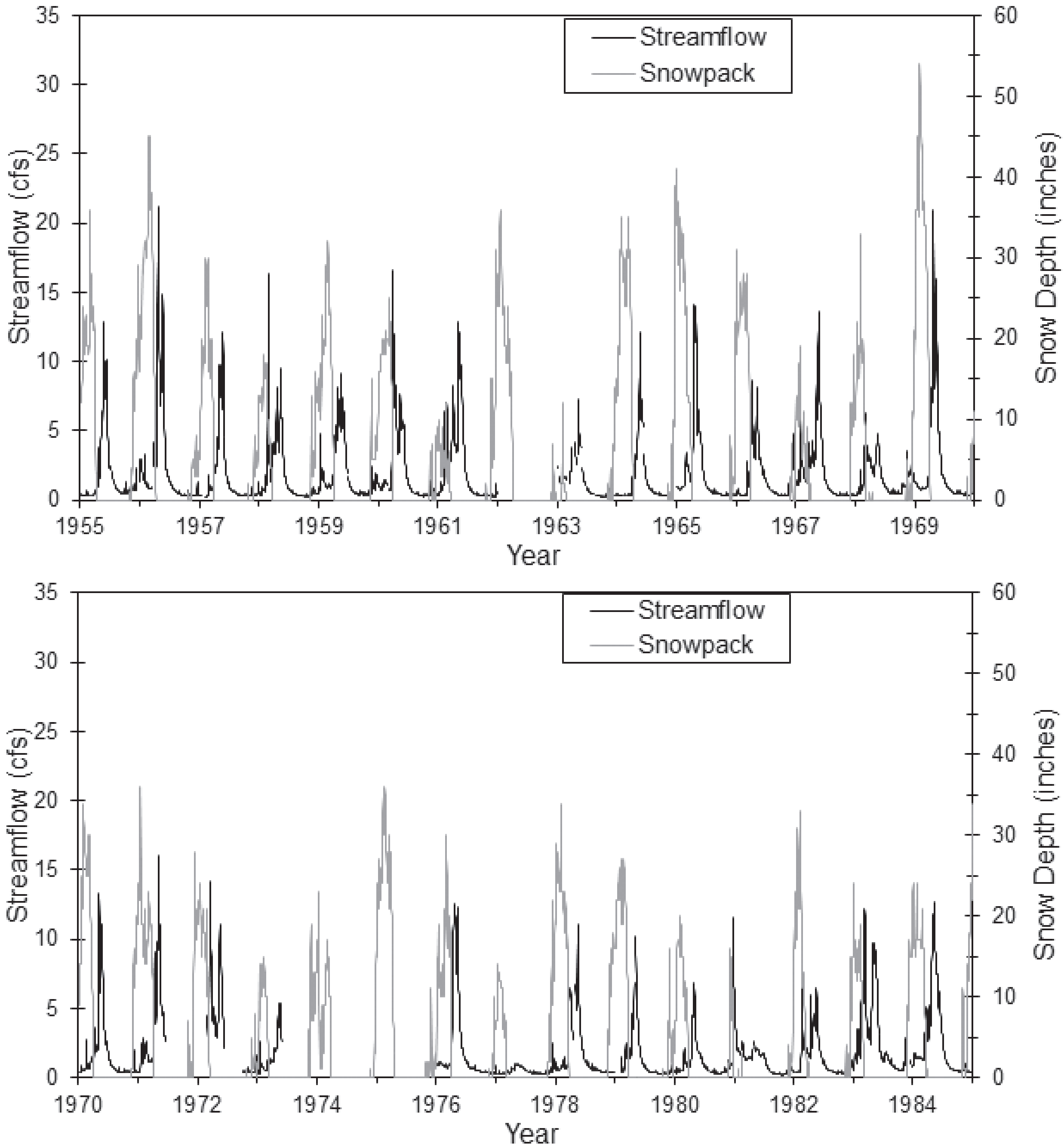
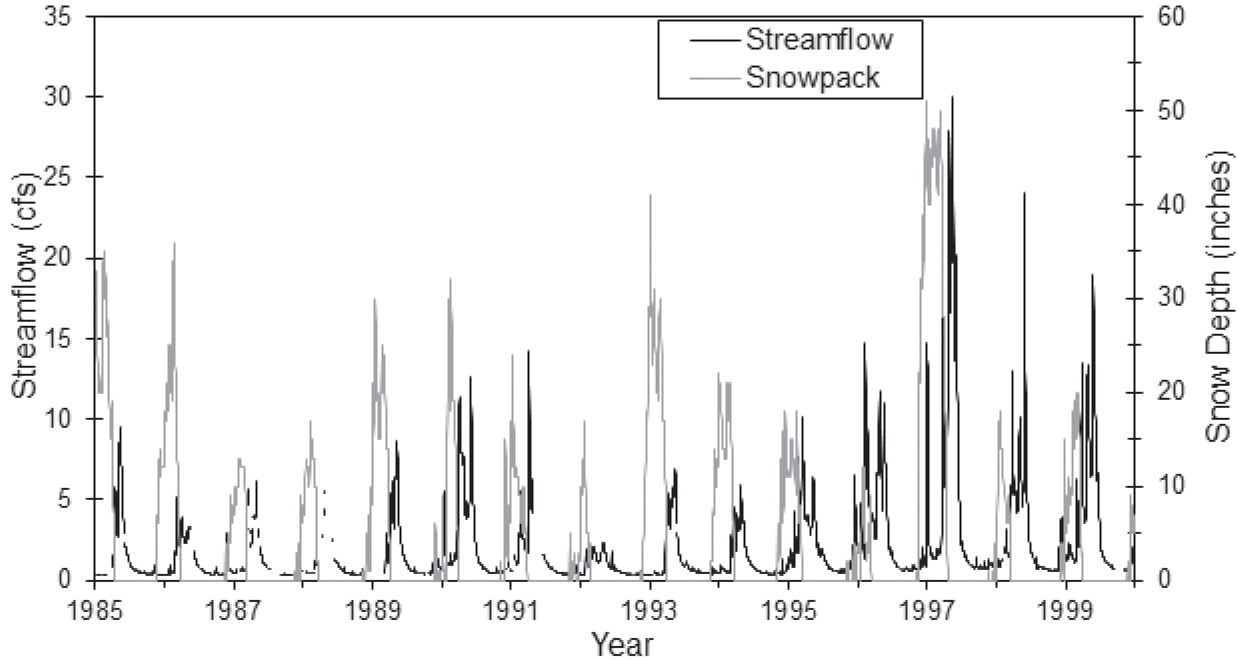


Figure A.2—Benton Creek streamflow correlation with snowpack depth, presented in fifteen year intervals from daily observations collected at the Benton Dam gauging station and control weather station. The data was originally synthesized and prepared for a report by Link and Wei (2010).



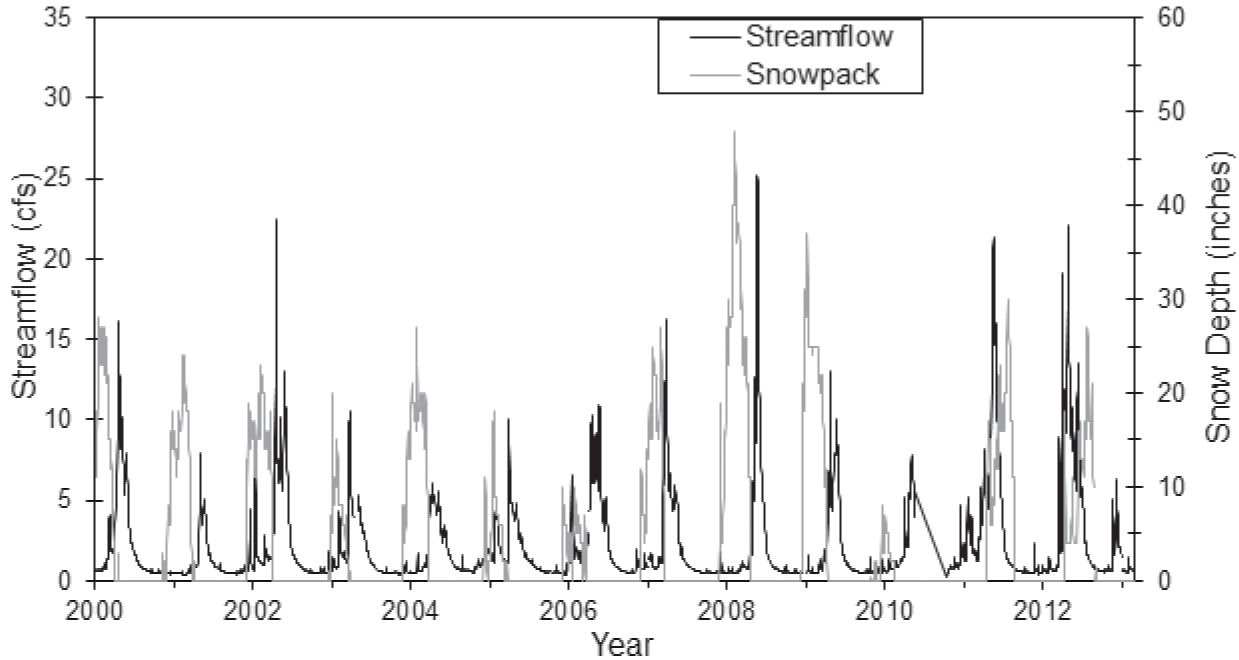


Figure A.2—Continued

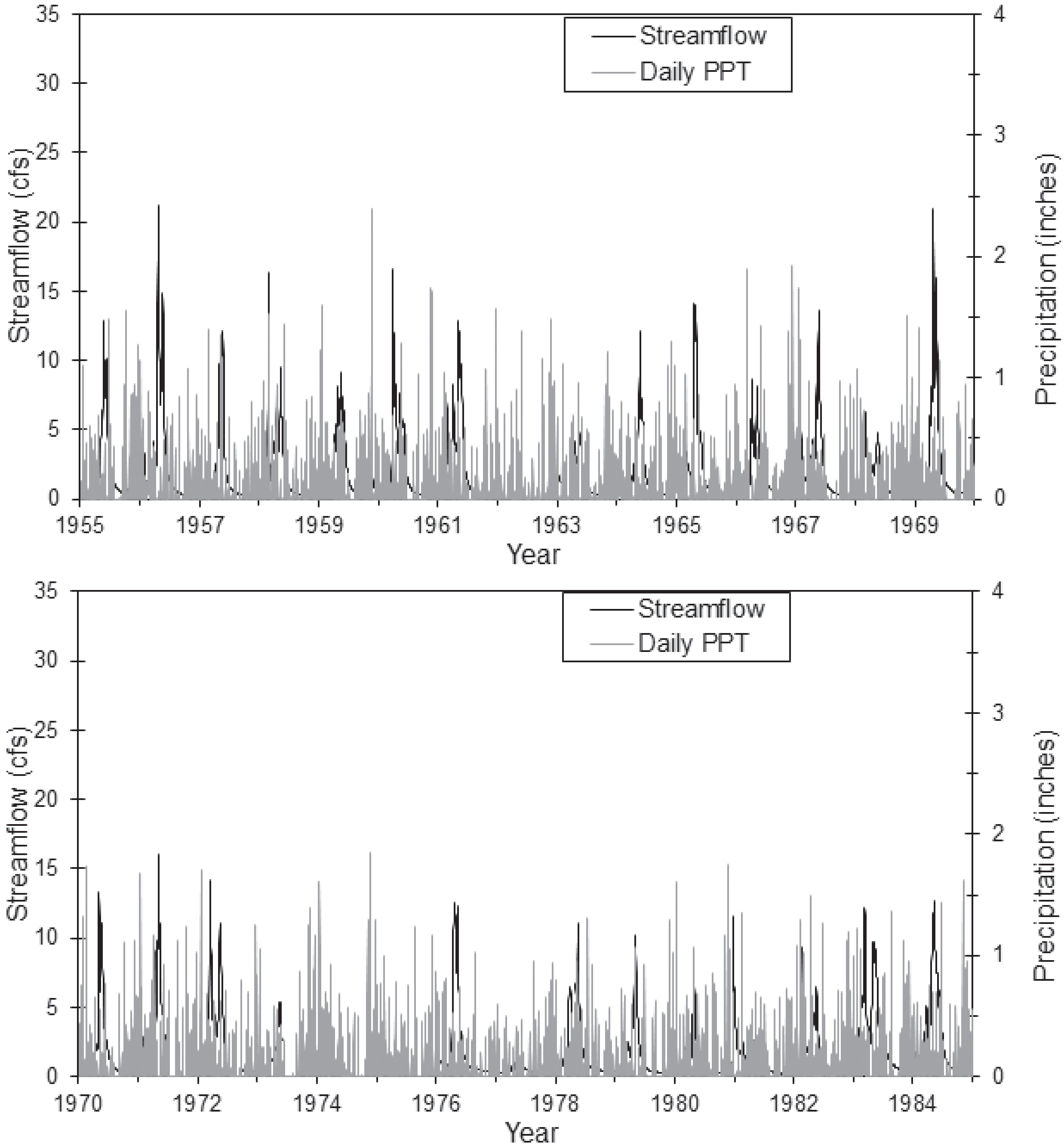
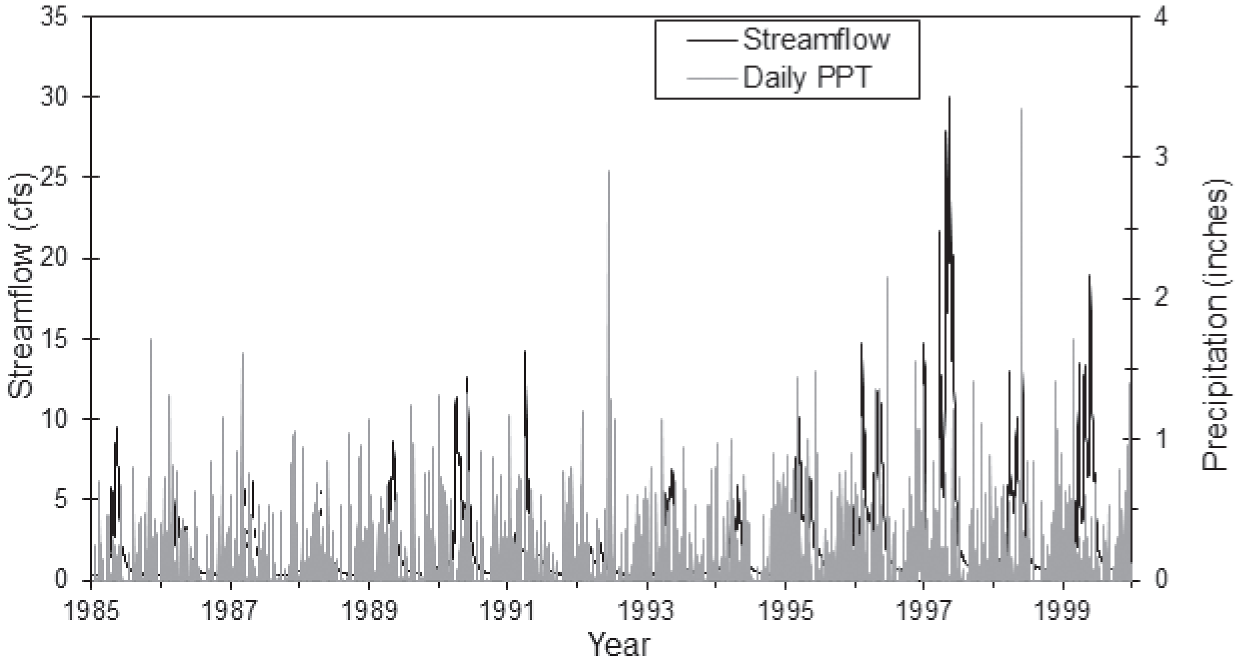


Figure A.3—Benton Creek streamflow correlation with precipitation, presented in fifteen year intervals from daily observations collected at the Benton Dam gauging station and control weather station. The data was originally synthesized and prepared for report by Link and Wei (2010).



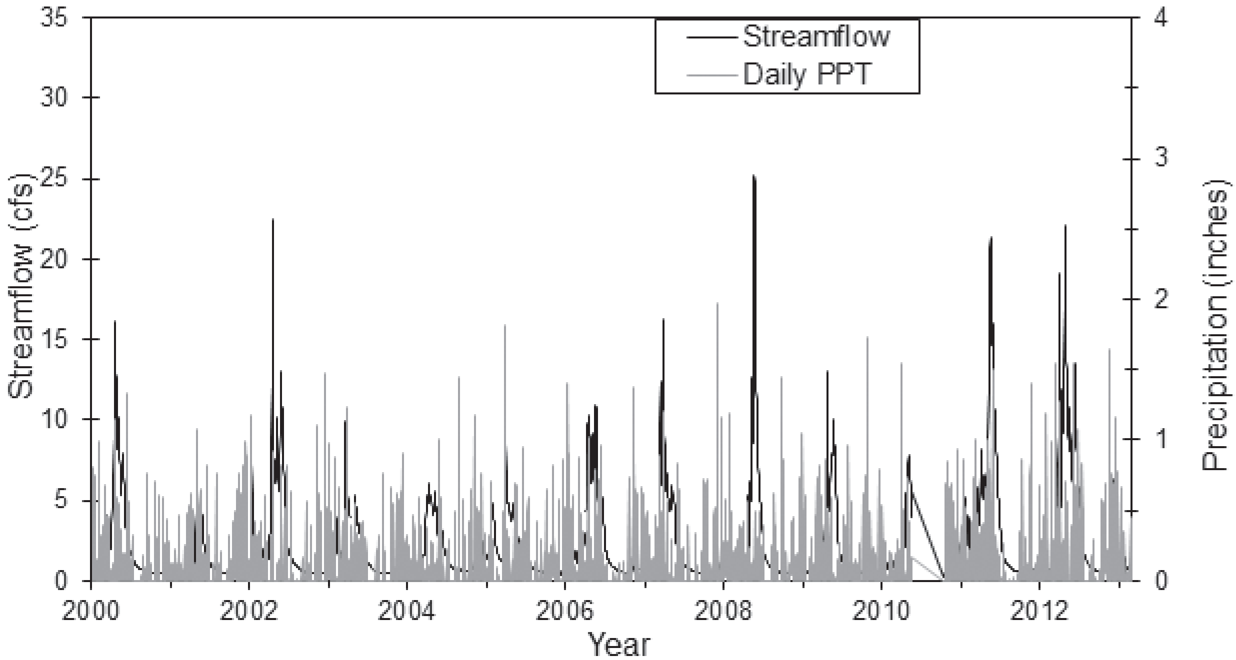


Figure A.3—Continued

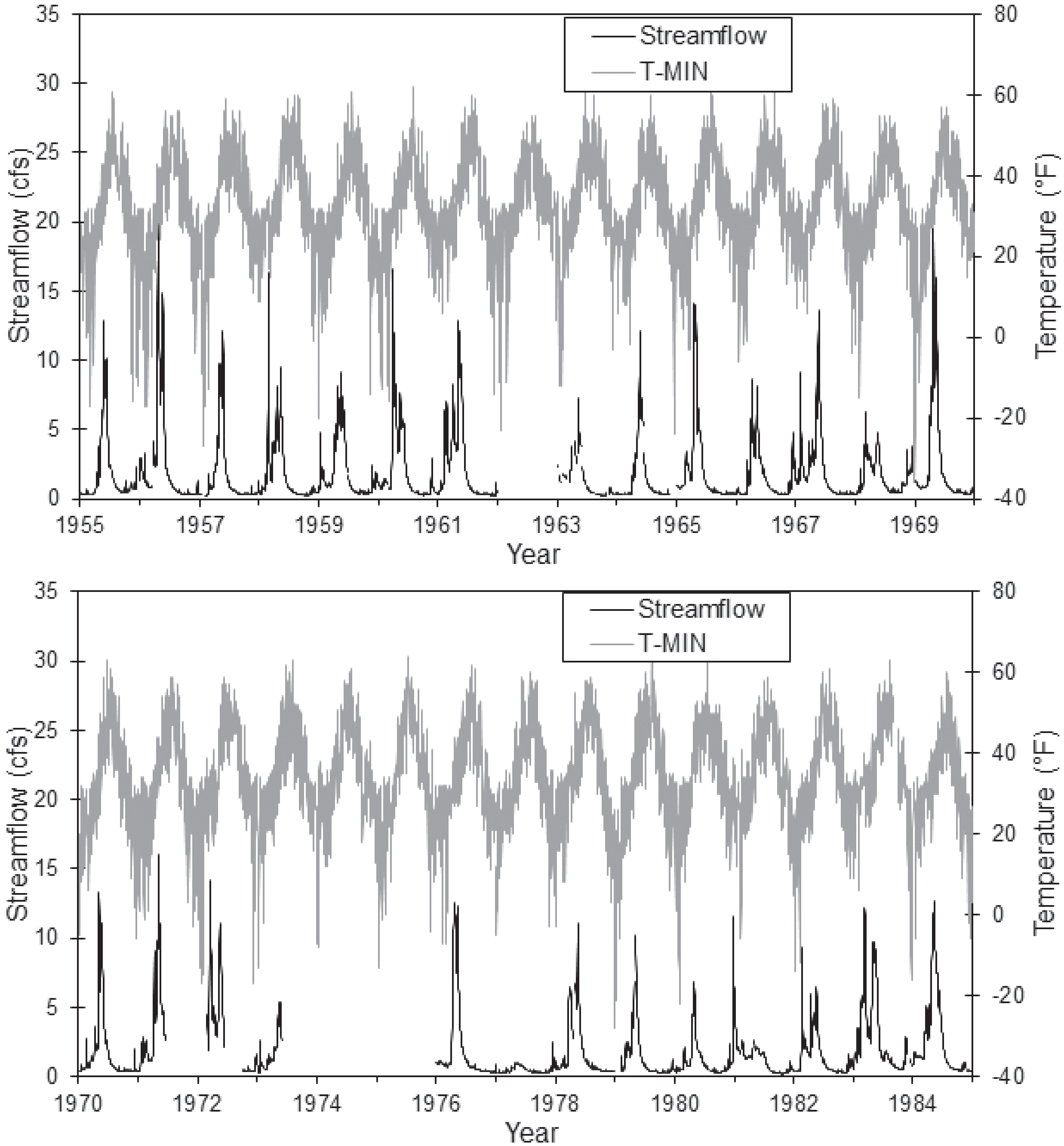


Figure A.4—Benton Creek streamflow correlation with minimum temperature, presented in fifteen year intervals from daily observations collected at the Benton Damn gauging station and control weather station. The data was originally synthesized and prepared for report by Link and Wei (2010).

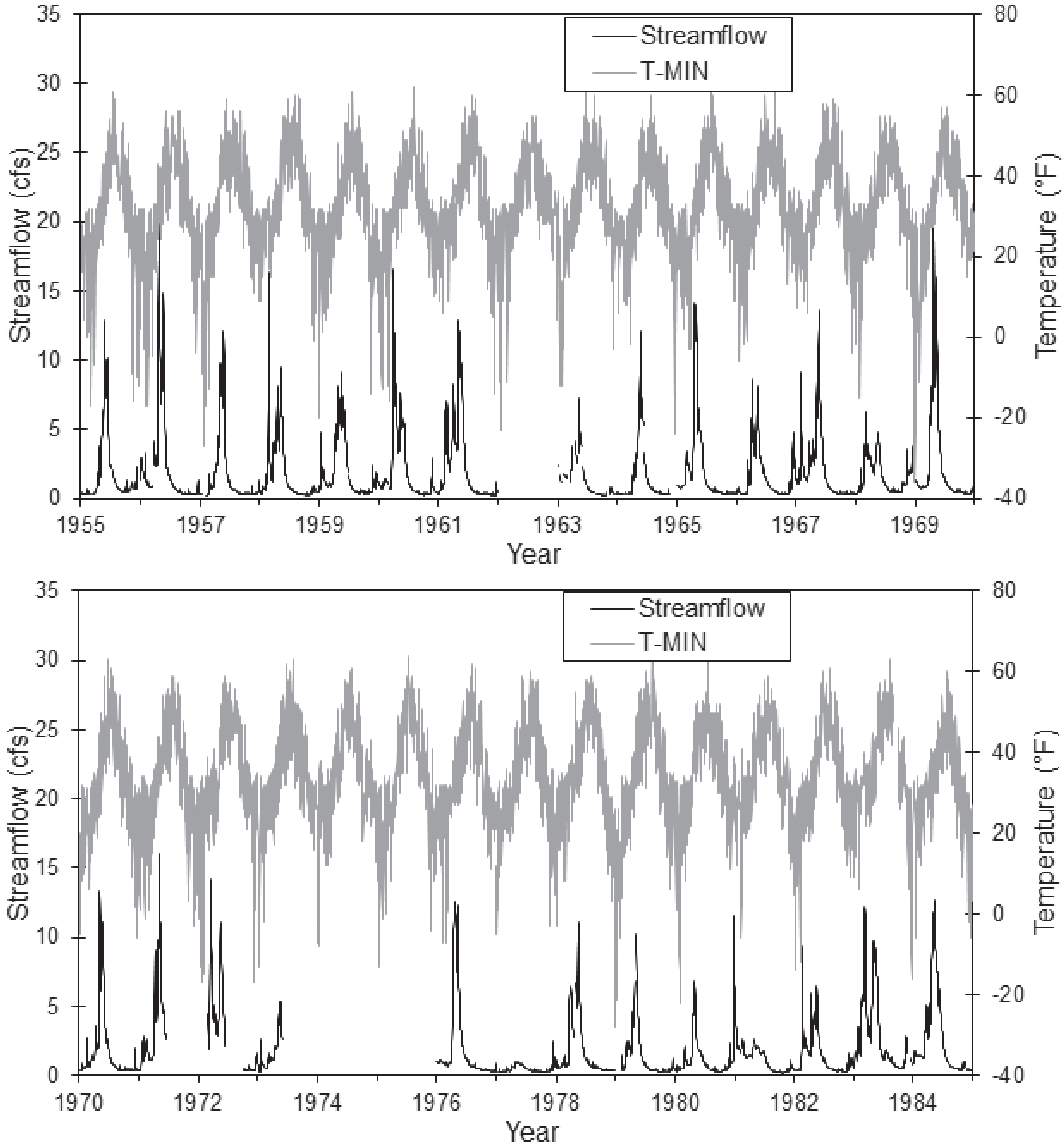


Figure A.4—Continued

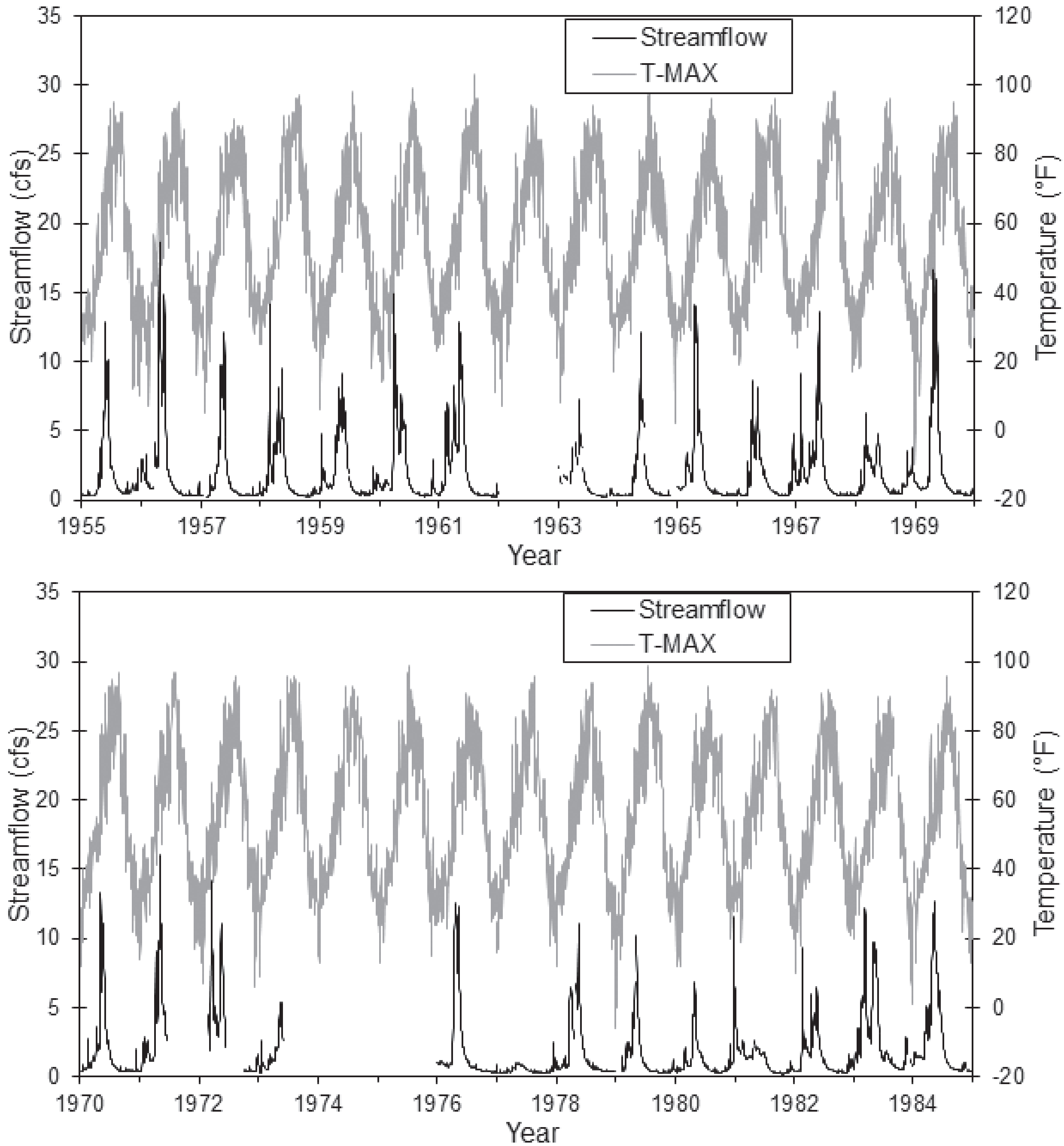


Figure A.5—Benton Creek streamflow correlation with maximum temperature, presented in fifteen year intervals from daily observations collected at the Benton Damn gauging station and control weather station. The data was originally synthesized and prepared for report by Link and Wei (2010).

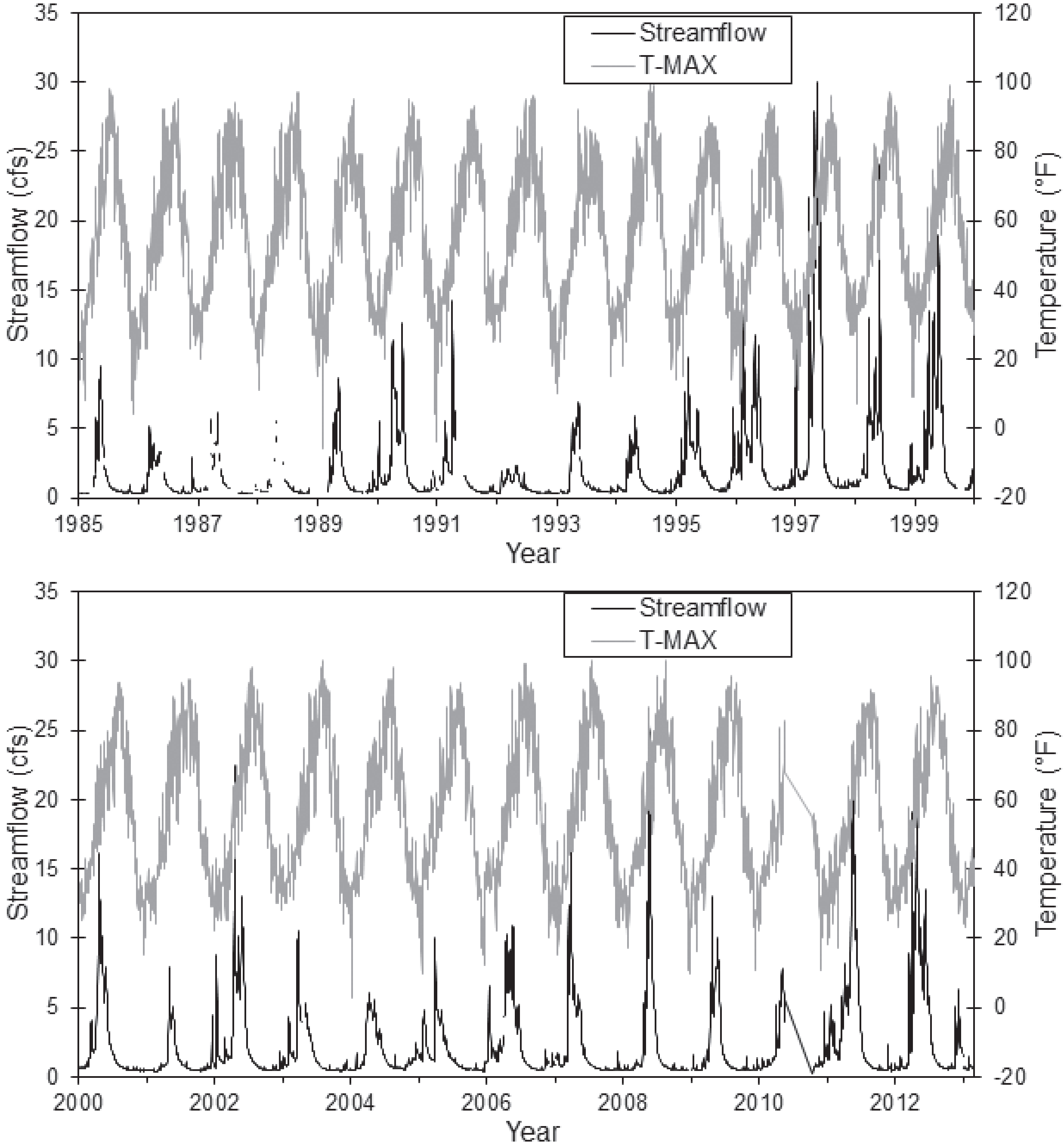


Figure A.5—Continued

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