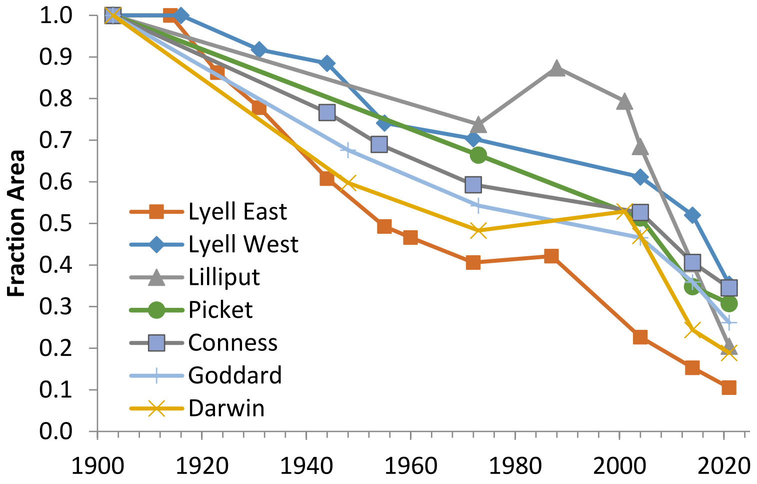
GLACIER CHANGE

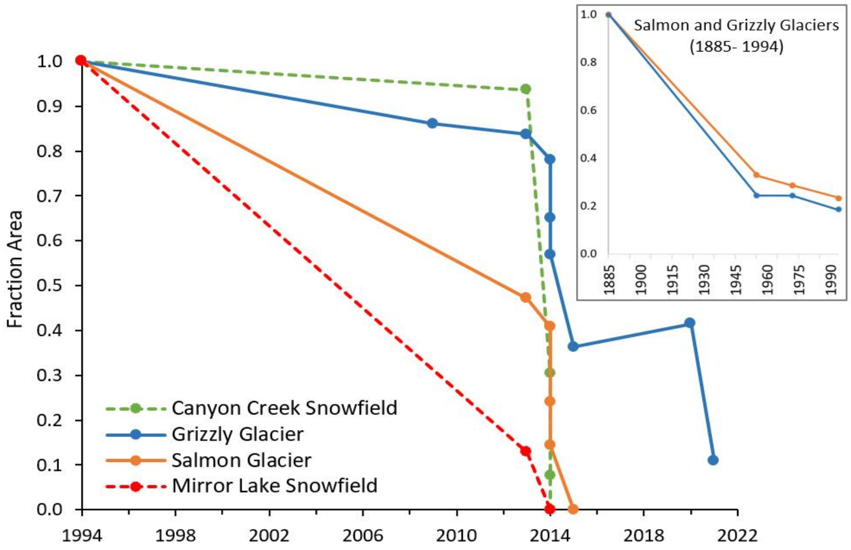
California's glaciers have melted dramatically over the past century. From the beginning of the twentieth century to 2021, some of largest glaciers in the Sierra Nevada have lost an average of about 75 percent of their area. Of the two glaciers in the Trinity Alps, one has recently disappeared and the other has lost more than 98 percent of its area.

Figure 1. Change in area, selected Sierra Nevada glaciers (as fraction 1903 area)



Source: Basagic and Fountain, 2011
(updated 2021 H. Basagic, unpublished data)

Figure 2. Change in area, Trinity Alps glaciers and snowfields (as fraction of 1994 area)



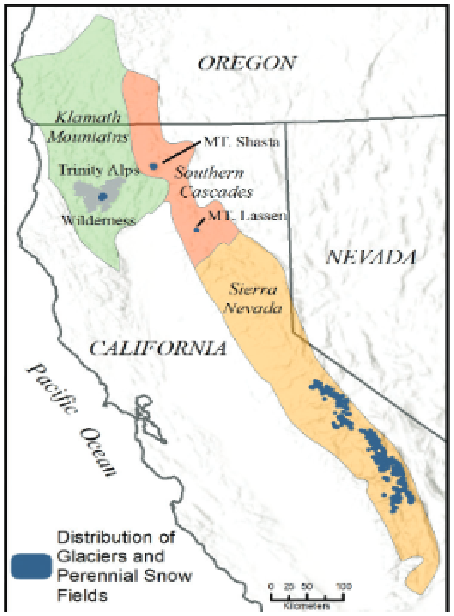
Source: Garwood et al., 2020
(updated 2021, J. Garwood, unpublished data)

Note: inset shows change in glacier areas relative to about 1885.

What does the indicator show?

Dramatic reductions in the area of selected glaciers and snowfields have occurred in California (see Figure 3 for locations). A "glacier," by definition, is a mass of perennial snow or ice that moves (Cogely et al., 2011). Figure 1 shows large declines in the area of seven Sierra Nevada glaciers relative to 1903. Figure 2 shows substantial losses in the size of glaciers and snowfields in the Trinity Alps since 1994. Historical and contemporary photographs allow for a visual comparison of the changes (see Appendix A).

Figure 3. Glaciers and perennial snow regions in California



Source: Garwood et al., 2020

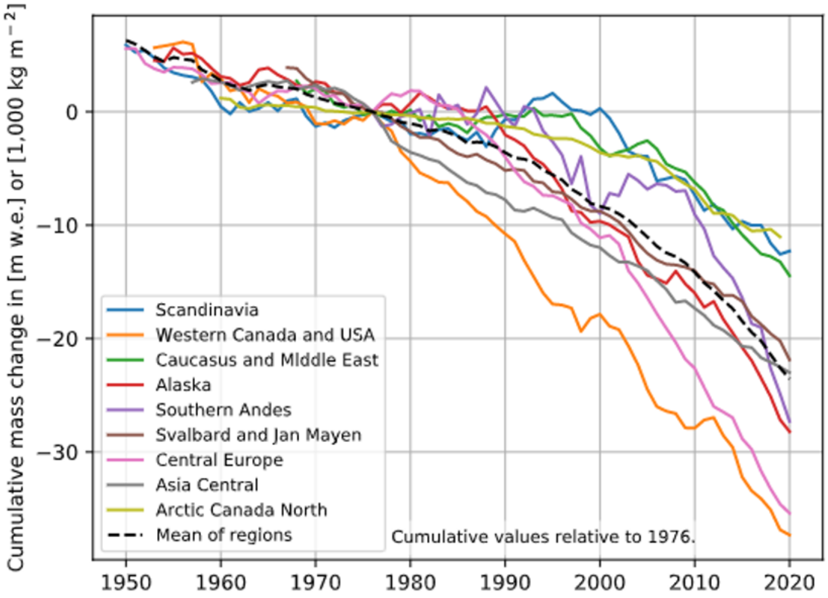
As shown in Figure 1, by 2021, the Sierra Nevada glaciers lost 65 to 89 percent (an average of about 75 percent) of their 1903 area, after having lost about half of their area since the 1970s (Basagic and Fountain, 2011, updated to 2021). These findings are consistent with those from a separate study of 769 glaciers and perennial snowfields that were identified within the Sierra Nevada in the 1970s and 1980s based on the US Geological Survey's 1:24,000-scale, topographic maps (Fountain et al., 2017). The largest 39 glaciers, free of rock debris mantling the surface, covered an area of 2.74 ± 0.12 square kilometers (km^2) in the 1970s and 1980s. By 2014, overall, they lost about 50 percent of their area.

The main graph in Figure 2 shows the percentage glacier area remaining relative to 1994 for two glaciers and two perennial snowfields in the Trinity Alps between 1994 and 2015 (Garwood et al., 2020) and subsequent measurements of Grizzly Glacier recorded through 2021 (Garwood, unpublished data). The inset shows changes in the area of Grizzly and Salmon Glaciers relative to their estimated areas around 1885; data prior to 1994 are not available for the Canyon Creek and Mirror Lake Snowfields. Both glaciers had lost 70 to 75 percent of their area between 1885 and 1955; by 1994, only about 20 percent of their 1885 area remained. Between 1994 and 2013, Salmon Glacier experienced far greater loss than Grizzly Glacier: 53 and 16 percent, respectively, of their areas in 1994. The extended drought, which occurred from 2012 to 2016, resulted in the catastrophic loss of both glaciers. In 2015, Salmon Glacier disappeared entirely and the lower half of Grizzly Glacier broke apart into large ice blocks, leaving only the upper portion of the glacier intact (see historical and contemporary photographs in Appendix A).

Measurements of Grizzly Glacier taken between the fall of 2020 and the fall of 2021 revealed more catastrophic decline with a 76 percent further reduction in area. Given this substantial reduction, it is uncertain whether what remains in the fall of 2021 is still considered a glacier, or whether it is now a perennial icefield. Appendix B shows the outlines of the glaciers for selected years between approximately 1885 to 2015 for Salmon Glacier and 1885 to 2021 for Grizzly Glacier; estimated areas from 1955 to 2021 are presented in an accompanying table.

Two prominent snowfields that were still present in 1994 completely melted during the extended drought. Mirror Lake Snowfield diminished precipitously and disappeared by 2014; Canyon Creek Snowfield melted gradually between 1994 and 2013, shrank in area by almost 70 percent from late 2013 to mid 2014, and disappeared in late 2014. Both snowfields have yet to persist more than a year through 2021 due to low winter precipitation and high summer temperatures (Garwood et al., 2020, updated to 2021).

Figure 4. Regional cumulative mass change of global reference glaciers*



Source: WGMS, 2021

*“**Cumulative mass change**” is reported in meters of water equivalent (m w.e.) or 1,000 kilogram per square meter (kg m^{-2}). Cumulative values are relative to 1976 and calculated using a single value (averaged) for each mountain range. **Regional values** are calculated as arithmetic averages. **Global values** are calculated using one single value (averaged) for each region with glaciers to avoid a bias to well-observed regions.*

Over the 20th century, with few exceptions, alpine glaciers have been receding throughout the world in response to a warming climate. Figure 4 presents trends since 1950, although global measurements date back to 1917 or earlier. The graph is based on standardized observations of a set of glaciers collected by the World Glacier Monitoring Service (WGMS, 2021) in more than 40 countries worldwide. Regional mass changes are shown relative to 1976 global mean values (dotted line). Glacier mass change is reported as “cumulative mass change in meters of water equivalent (m w.e.)”; this unit is the equivalent of a mass loss of 1,000 kilograms per square meter of ice cover or an annual glacier-wide ice thickness loss of about 1.1 meter per year. As shown in the graph, glaciers in the Western United States and Canada (two in Alaska and seven in the Cascade and Pacific Coast Ranges of Washington State and Canada) are experiencing greater glacier loss than other regions of the world.

Why is this indicator important?

Glaciers are important indicators of climate change. Because glaciers are sensitive to fluctuations in temperature, they provide visual evidence of warming. Glacier loss can lead to cascading effects on hydrology, alter aquatic habitats, contribute to sea level rise, and impact recreation and tourism (USGS, 2021a).

Glaciers are important to alpine hydrology by acting as frozen reservoirs of snow. They begin to melt most rapidly in late summer after the bright, reflective seasonal snow disappears, revealing the darker ice beneath. This often causes peak glacial runoff to occur in late summer when less water is available and demand is high. Glacier shrinkage reduces this effect, resulting in earlier peak runoff and drier summer conditions. These changes are likely to have ecological consequences for flora and fauna in the area that depend on available water resources. For example, many aquatic species in alpine and subalpine environments require cold water temperatures to survive. Some aquatic insects – fundamental components of the food web – are especially sensitive to stream temperature and require glacial meltwater for survival. Finally, glacier shrinkage worldwide is an important contribution to global sea level rise (IPCC, 2019).

The Trinity Alps is a glaciated subrange of the Klamath Mountains in northwest California (see Figure 3 map). This region has experienced much greater fractional losses of glacier area than the Sierra Nevada and other glaciated regions of the western US. Around 1885, at least six glaciers existed in the Trinity Alps (Garwood et al., 2020). Grizzly and Salmon glaciers are the only two that persisted into the 21st century. In addition, all snowfields throughout the Trinity Alps and greater Klamath Mountains of southern Oregon and northern California had fully disappeared by 2014.

The Trinity Alps and entire Klamath Range ecoregion are globally recognized for their rich biodiversity (DellaSala et al., 1999; Olson et al., 2012). Glacial ice and persistent snow influence local species composition and their distributions by extending perennial wetlands into high elevations that normally lack surface waters. The freshwater habitats of the region support exceptionally high levels of endemic species. Most mollusk populations have declined dramatically throughout the region, and over 10 fish taxa have a special status designation due to habitat degradation and changes in hydrology and water quality. A beetle species (*Nebria praedicta*) endemic to the Grizzly Glacier basin depends on perennial snow and ice to maintain the cool microclimate needed to survive (Kavanaugh and Schoville, 2009). The coastal tailed frog (*Ascaphus truei*), a California Species of Special Concern (see Figure 5), is adapted to cold-water streams.

Its highest known population across its range was discovered in 2009 directly below the Canyon Creek snowfield, which disappeared in 2014 (Garwood et al., 2020).

Figure 5. Coastal Tailed Frog

Photo credit: Thompson *et al.*, 2016

The Coastal tailed frog (Ascaphus truei) ranges from British Columbia to northern California, from near sea level in Humboldt County up to elevations of 2150 meters in the Trinity Alps (CDFW, 2016).

Three watersheds in this region contribute glacial and/or snowmelt cold-water streamflow directly to fish-bearing streams containing small populations of spring Chinook salmon (*Oncorhynchus tshawytscha*) and summer steelhead (*Oncorhynchus mykiss*). The Klamath-Trinity River spring Chinook salmon were listed as threatened by the State of California in June 2021 (CDFW, 2021) and are currently being considered for listing as endangered under the Federal Endangered Species Act (Federal Register 2018, 2019). These species migrate from the Pacific Ocean to these streams and stage in deep cold-water pools throughout the summer months before spawning in the fall. The dramatic local declines of glacial ice and annual snowpack in the Klamath Range foretell how climate change threatens the unique distributions and resiliency of fish adapted to local glacier and snow dependent environments (Garwood et al, 2020).

What factors influence this indicator?

A glacier is a product of regional climate, responding to the combination of winter snow and spring/summer temperatures. Typically, glaciers exist in areas with significant accumulations of snow, temperatures during the year that do not result in the complete loss of the winter snow accumulation, and average annual temperatures near freezing, (USGS, 2021b). Winter snowfall nourishes the glaciers; winter temperature determines whether precipitation falls as rain or snow, thus affecting snow accumulation and glacier mass gain. The greater the winter snowfall, the healthier the glacier. Spring and summer air temperature affects the rate of snow and ice melt.

In the early 20th century, glaciers retreated (decreased in size) rapidly throughout the western US in response to the end of the Little Ice Age and warming air temperatures (Basagic and Fountain, 2011). In recent years, increasing winter and spring temperatures across North America have led to less snowpack in spring and early summer (Mote *et al.*, 2018). Based on their assessment of studies of glaciers in various parts of the world, the Intergovernmental Panel on Climate Change concluded that human-induced warming likely contributed substantially to widespread glacier retreat during the 20th century (IPCC, 2021).

Alpine glaciers gain or lose mass primarily through climatic processes controlling energy and mass exchange with the atmosphere, then respond by either growing (advancing) or shrinking (retreating). The area changes observed in the Sierra Nevada study glaciers were triggered by a changing climate and modified by the dynamics of ice flow. Hence, glacier change is a somewhat modified indicator of climate change, with local variations in topography and climate either enhancing or reducing the magnitude of change so that each glacier's response is somewhat unique. Because glaciers persist across decades and centuries, they can serve as indicators of long-term climatic change.

Sierra Nevada

The glacier retreat in the Sierra Nevada occurred during extended periods of above average spring and summer temperatures; winter snowfall appears to be a less important factor (Basagic and Fountain, 2011). Following a cool and wet period in the early part of the 20th century, during which glacier area was constant, the Sierra Nevada glaciers began to retreat rapidly with warmer and drier conditions in the 1920s. The glaciers ceased retreating, while some glaciers increased in size (or "advanced") during the wet and cool period between the 1960s and early 1980s with below average temperatures. By the late 1980s, with increasing spring and summer temperatures, glacier retreat resumed, accelerating by 2001. Hence, the timing of the changes in glacier size appears to coincide with changes in air temperatures. In fact, glacier area changes at East Lyell and West Lyell glaciers were found to be significantly correlated with spring and summer air temperatures. In the past century, average annual temperatures in the Sierra Climate Region have warmed by almost 2 degrees Fahrenheit (°F), with summer and fall having warmed the most (2.6 and 2.5°F, respectively) (WRCC, 2021).

As can be seen from Figure 1, the seven glaciers studied have all decreased in area. However, the magnitude and rates of change are variable, suggesting that factors other than regional climate influenced these changes. One of these factors is glacier geometry. A thin glacier on a flat slope will lose more area compared to a thick glacier in a bowl-shaped depression, even if the rate of melting is the same. In addition, local topographic features, such as headwall cliffs, influence glacier response through shading solar radiation, and enhancing snow accumulation on the glacier through avalanching from the cliffs.

Trinity Alps

Grizzly and Salmon Glaciers and Canyon Creek and Mirror Lake Snowfields in the Trinity Alps occur at 2,460 meters, an elevation far lower than other glaciated areas in California. The high latitude region has a particularly wet climate during the winter months due to its proximity to the Pacific Ocean (Garwood et al., 2020). Although a marginal climate for glaciers, these glaciers have persisted into the 21st century due to topographic features where tall headwalls increase shading and enhance localized snow accumulation through avalanching and wind transport.

Although large data gaps exist, clearly the largest amount of ice loss in the Trinity Alps occurred during the first half of the 20th century with a combined area loss of 72 percent for Grizzly and Salmon glaciers (inset, Figure 2) (Garwood et al., 2020; also see Appendix B). Since then, the glaciers receded at a much slower but steady rate and persisted even while winter precipitation in the Trinity Alps was below the long-term average (using 1895 to 2015 as baseline) in 9 of the 20 years from 1996 to 2015, and summer temperatures exceeded the long-term average in 18 years of the same period. Scientists attribute the recent glacial retreat in the Trinity Alps (see Appendix, Figures A-2 and A-3) largely to unprecedented and consistently high summer temperatures coincident with record-low winter precipitation in the region during the 2012 to 2016 drought (Garwood et al., 2020) and thereafter in 2020 and 2021 (Garwood, unpublished data).

California's recent drought differed from earlier periods of persistent low precipitation by coinciding with a period of consistently record-high summer temperatures (see *Drought* indicator). During the severe drought, snowpack was at an all-time low – no other year since 1950 reported an April 1st snowpack of less than 34 percent in the Klamath Mountains (Garwood et al., 2020). As shown in Figure 2, it was this time period where Salmon Glacier melted completely and Grizzly Glacier partially broke apart and declined greatly in size.

Technical considerations

Data characteristics

Sierra Nevada

To quantify the change in glacier extent, seven glaciers in the Sierra Nevada were selected based on the availability of past data and location: Conness, East Lyell, West Lyell, Darwin, Goddard, Lilliput, and Picket glaciers. Glacier extents were reconstructed using historical photographs and field measurements. Aerial photographs were scanned and imported into a geographic information system (GIS). Only late summer photographs, largely snow free, were used in the interpretation of the ice boundary. The historic glacier extents were interpreted from aerial photographs by tracing the ice boundary. Early 1900 extents were based on ground-based images and evidence from moraines. To obtain recent glacier areas, the extent of each glacier was recorded using a global positioning system (GPS) in 2004. The GPS data were processed (2 to 3 meter accuracy), and imported into the GIS database. Glacier area was calculated within the GIS database. The 2014 outlines were derived from aerial photographs acquired by the US Department of Agriculture National Agricultural Imagery Program, 1-meter ground resolution. The 2021 imagery were acquired from DigitalGlobe WorldView © 2021 Maxar, 0.5-meter ground resolution. For both years, the imagery was loaded into ArcGIS and the glacier outlines digitized at a scale of about 1:500.

Trinity Alps

Long-term changes in glaciers and perennial snowfields were quantified using clearly defined moraines (loose sediment and rock debris deposited by glacier ice); vertical aerial orthophotos (photographs geometrically corrected such that the scale is uniform); high-resolution satellite images; and GPS mapping (Garwood et al., 2020; Garwood, unpublished data). The 1885 outlines were generated by mapping the ridgelines of prominent Holocene moraines coupled with mapping the near vertical bedrock headwalls at the upper extent of the glaciers. Eleven aerial and satellite images were acquired from 1955 to 2021. All aerial photographs had spatial resolutions of 1 meter; satellite imagery resolutions ranged from 0.33 to 0.5 meter. In addition, glacier perimeters were mapped using a GPS with an accuracy ± 2.6 meters. Ground-based photograph monitoring stations were established at each of the two glaciers to document qualitative changes in glacier geometry and morphology during field visits between the years of 2009 and 2018.

To examine the response of glaciers and perennial snowfields in the Trinity Alps to variations in climate, changes in glacier area were compared to winter precipitation and summer air temperature from the PRISM re-analysis data (Daly et al. 2008, PRISM Climate Group 2018), employing a similar analysis as Sitts et al. (2010), using data for the 4 km × 4 km PRISM grid cell centered on Thompson Peak for the period of January 1895 to September 2015.

<u>Strengths and limitations of the data</u>

The observation of tangible changes over time demonstrates the effects of climate change in an intuitive manner. This indicator relies on data on glacier change based on photographic records, which are limited by the availability and quality of historical photographs. The use of both aerial photographs and satellite images provides high quality visual data for measuring changes in glacier area. Detailed information about uncertainties associated with mapping the area of glaciers can be found in the methods section of Garwood et al. (2020). A limitation in relying on satellite and photographic images is that change in glacial volume cannot be assessed.

Increasing the number of studied glaciers and the number of intervals between observations would provide a more robust data set for analyzing statistical relationships between glacier change and climatological and topographic parameters. Additionally, volume measurements would provide valuable information and quantify changes that area measurements alone may fail to reveal.

OEHHA acknowledges the expert contribution of the following to this report:

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APPENDIX A. Historical and Contemporary Glacier Photographs

Historical glacier responses preserved in photographs are important records of past climates in high alpine areas where few other climate records exist. Repeat photographs – paired historical and contemporary images – for selected glaciers are presented below. Additional photographs of the Sierra Nevada, Trinity Alps and other western glaciers can be viewed at the "Glaciers of the American West" web site (PSU, 2017).

Figure A-1. Historical and contemporary late summer photographs of two Sierra Nevada glaciers

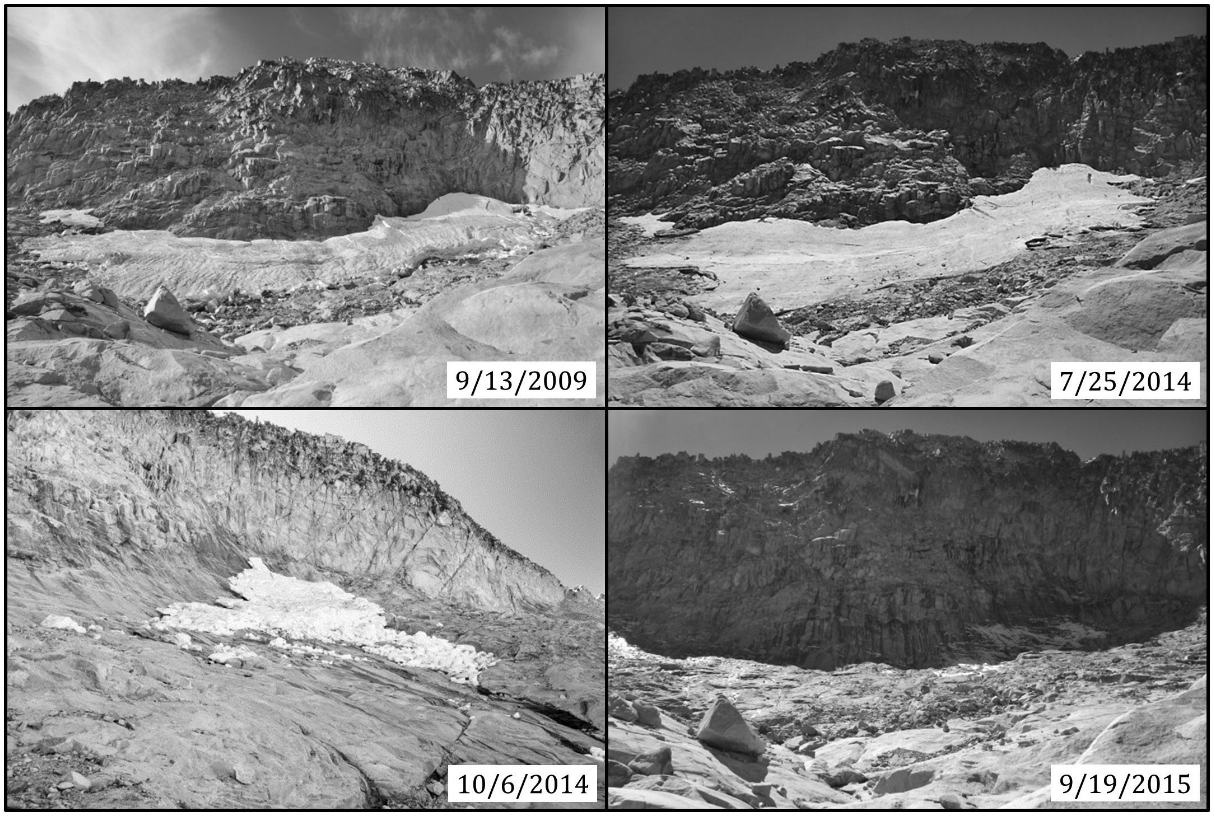
Dana Glacier

Credit: U.S. Geological Service, photo station ric046: I.C. Russell, 1883 (left); R. Hallnan (right)

Conness Glacier

Credit: National Park Service, photo station Conness 5555 (left); H. Basagic (right)

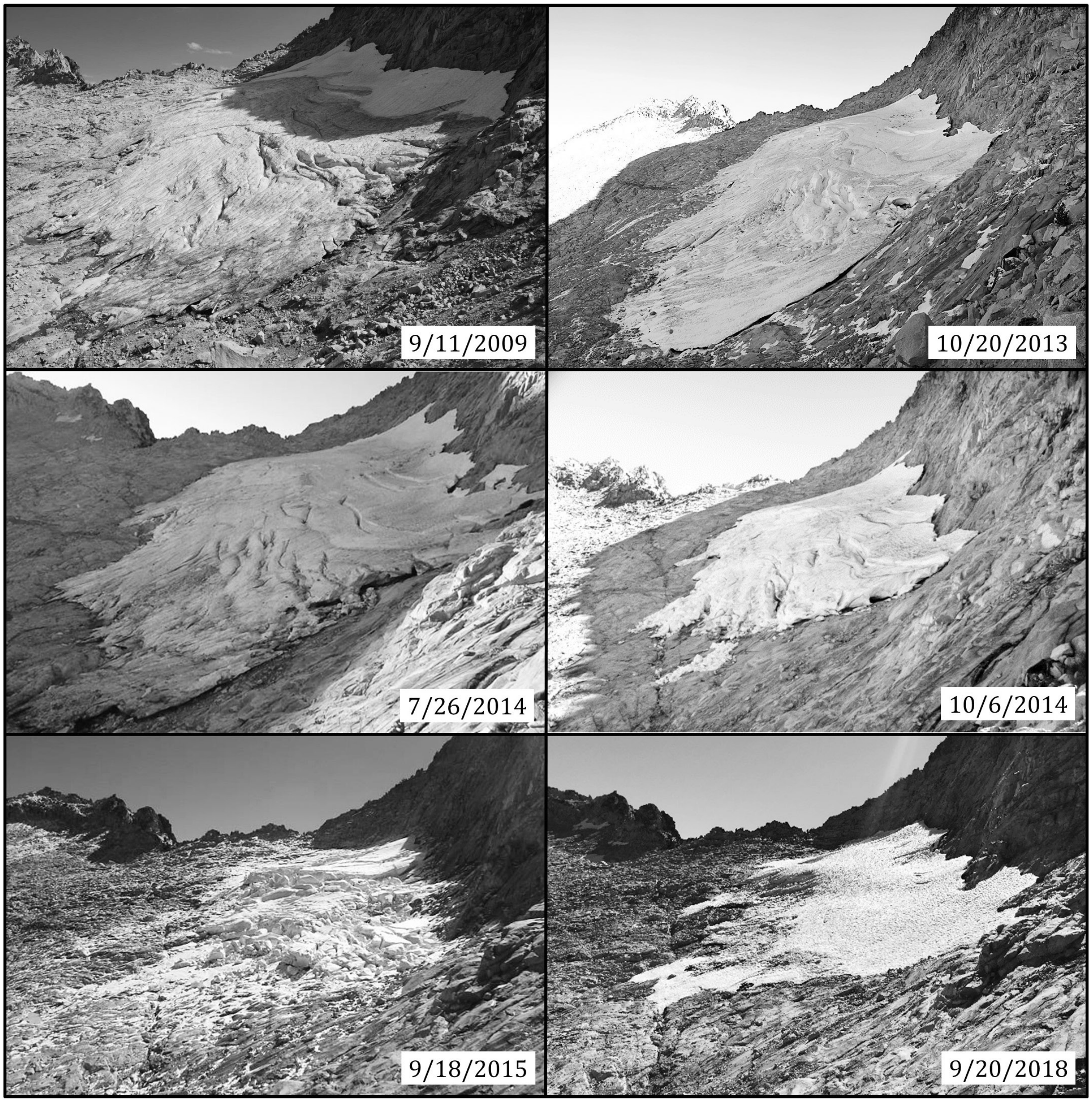
Figure A-2. Salmon Glacier, repeat photographs



Credit: Photos taken by J. Garwood (September 2009 and 2015), R. Bourque (July 2014) and J. Barnes (October 2014)

Repeat photographs of Salmon Glacier were taken between September 2009 and September 2015. The October 2014 image was taken northeast of the feature facing southwest whereas the others were taken north of the feature facing due south. The glacier broke apart in 2014 and completely melted away by the fall of 2015. The patchy snow observed in shadows of the 2015 image accumulated during a small storm that occurred two days prior to the image date (Garwood et al.*, 2020).*

Figure A-3. Grizzly Glacier, repeat photographs



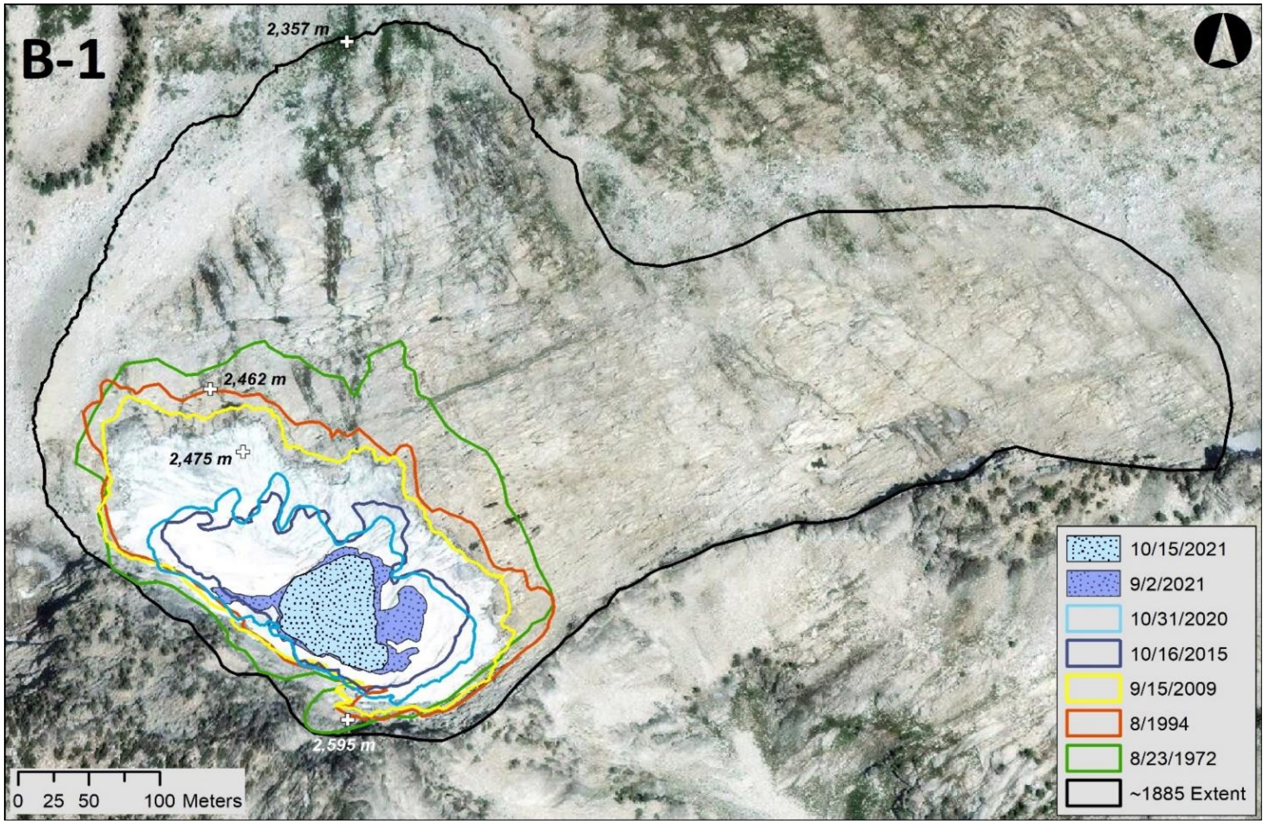
Credit: All photographs taken by J. Garwood
with exception of October 2013 by K. Lindke and October 2014 by J. Barnes

Repeat photographs of Grizzly Glacier were taken between September 2009 and September 2018. The lower half of the glacier broke apart in the fall of 2015. A thin layer of fresh snow visible in the September 2015 image accumulated during a brief storm that occurred two days prior to the image date. This snow cover visually exaggerates the actual glacier size beyond the visible pile of scattered ice debris visible in the photo; a result of extreme calving in the lower half of the feature during the summer of 2015 (Garwood et al., 2020).

APPENDIX B. Glacier area loss for in the Trinity Alps, California

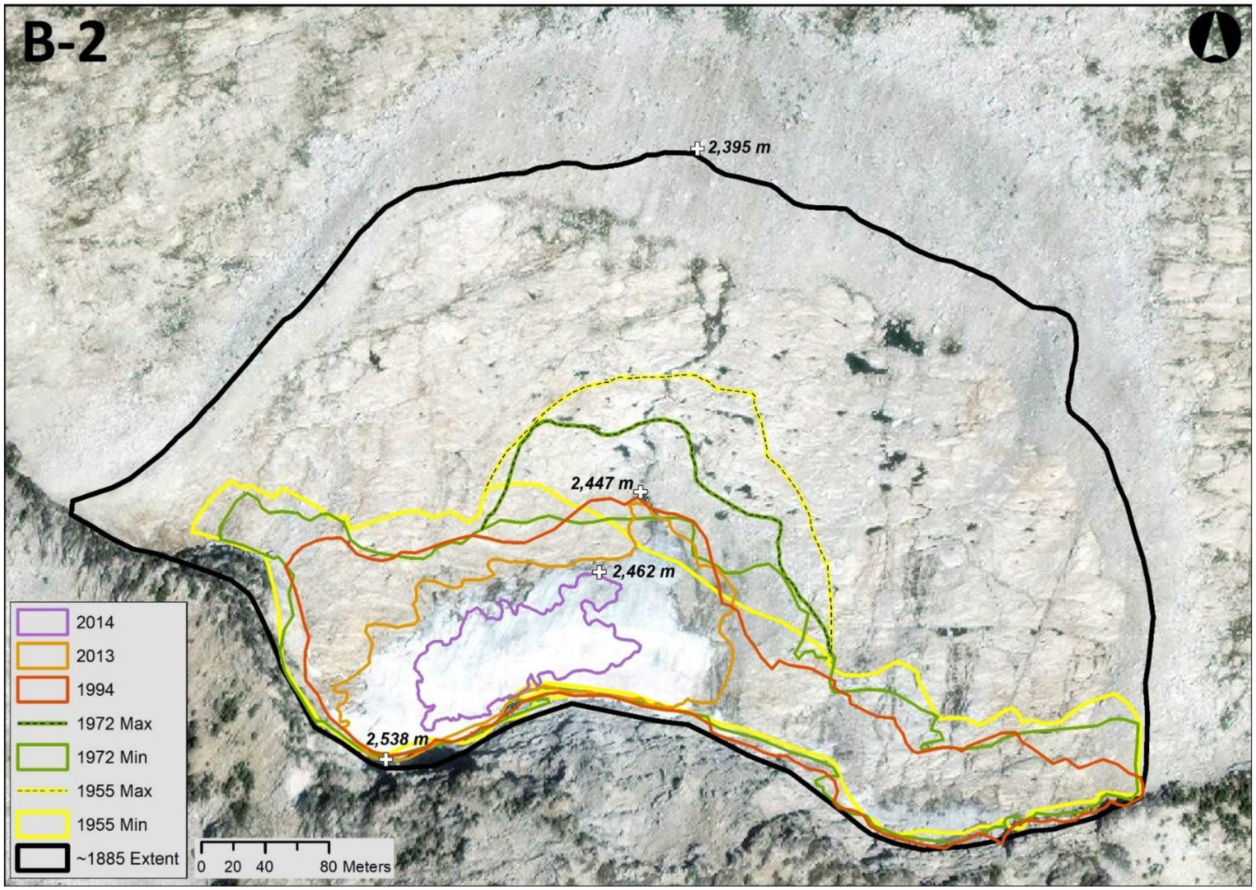
Digitized outlines of Grizzly Glacier (B-1) and Salmon Glacier (B-2) from approximately 1885 to 2021. Salmon Glacier disappeared completely by the fall of 2015 while Grizzly Glacier maintained a similar area between 2015 and 2020 before losing 76 percent of its 2020 area during the summer and early fall of 2021. The 1885 outlines were generated by mapping the ridgelines of prominent Holocene moraines coupled with mapping the near vertical bedrock headwalls at the upper extent of the glaciers. The 1885 outlines represent the most recent Little Ice Age glacial advance. Due to extensive residual snow cover on Salmon Glacier in 1955 and 1972, outlines include a minimum estimated area (solid colors) and additional maximum estimated area dotted lines. Satellite base image date is from 26 July 2014. Approximate surface elevations are noted at four locations at each glacier.

Figure B-1. Grizzly Glacier, digitized outlines



Source: Garwood et al., 2020 (updated 2021; J. Garwood, unpublished data)

Figure B-2. Salmon Glacier, digitized outlines



Source: Garwood et al., 2020

Table 1. Estimated areas* in hectares of glaciers in the Trinity Alps, from ca. 1885 to 2021

Year	**Grizzly Glacier**	**Salmon Glacier**
ca. 1885	24.44	19.40
1955	6.01*	6.45
1972 (Aug)	6.00*	5.58
1994 (Aug)	4.60	4.54
2009 (Sept)	3.96	not measured
2013 (Oct)	3.85	2.14
2014 (July)	3.59	1.85
2014 (Sept)	2.99	1.09
2014 (Oct)	2.62	0.65
2015 (Oct)	1.67	extinct
2020 (Oct)	1.91	extinct
2021 (Oct)	0.45	extinct

Source: Garwood et al., 2020 (updated 2021; J. Garwood, unpublished data)

* Average areas shown are estimated due to residual snow cover partially obscuring lower glacier margin;
1 hectare = 10,000 square meters or 2.5 acres