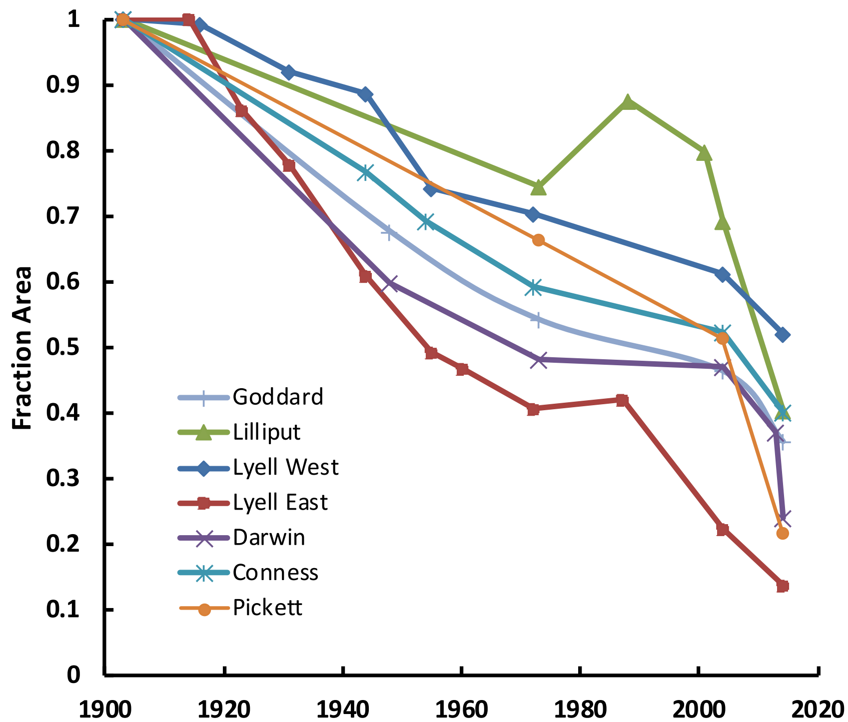
GLACIER CHANGE

Glaciers in the Sierra Nevada have retreated dramatically. From the beginning of the twentieth century to 2014, some of largest glaciers have lost an average of about 70 percent of their area, with losses ranging from about 50 to 85 percent.

Figure 1. Change in surface area of selected Sierra Nevada glaciers



Source: Basagic and Fountain, 2011 (updated 2017)

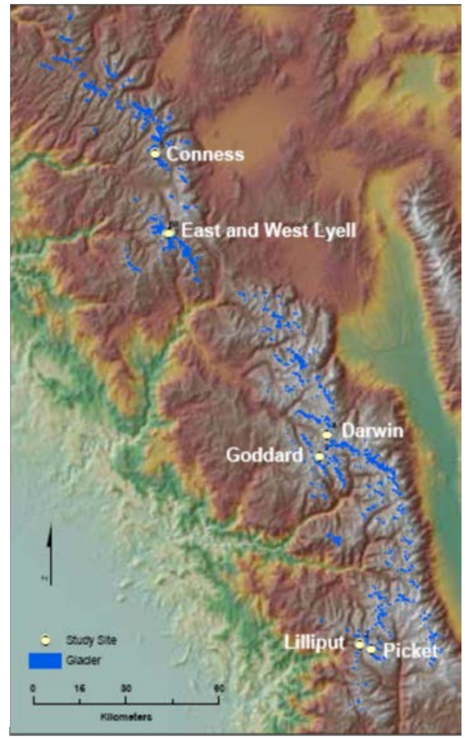
NOTE: Each glacier was divided by its area in 1903. Each glacier area starts out at 1.0 in 1903 and the area in subsequent years is a fraction of that area. For example, a fractional area of 0.5 is 50% of its 1903 area.

What does the indicator show?

Figure 1 shows that the surface area of seven Sierra Nevada glaciers (Figure 2) has decreased dramatically during the past century (Basagic and Fountain, 2008, updated to 2014). Changes in area are relative to 1903. By 2014, these seven glaciers lost between 48 to 86 percent of their 1903 area. About half the area was lost since the 1970s.

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.

Figure 2. Location of the Sierra Nevada glaciers (left), and the seven glaciers studied (right)



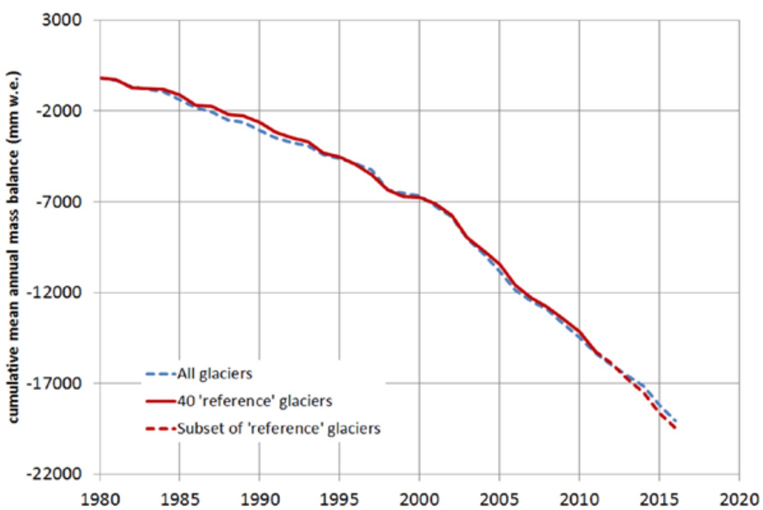
Glacier locations:

Conness:	Inyo National Forest, east of Yosemite National Park
Lyell:	Headwaters of Tuolumne River, in eastern Yosemite
Darwin and Goddard	Northern Kings Canyon National Park
Lilliput and Picket	Sequoia National Park

Source: Basagic and Fountain, 2008

The results from the Sierra Nevada are consistent with global averaged glacier mass, which has been decreasing for the past 100 years (global measurements date back to 1917 or earlier). The trend since 1980 is shown in Figure 3. The graph is based on standardized observations on glaciers around the globe collected by the World Glacier Monitoring Service (WGMS, 2017). Glacier mass change is reported as "cumulative mean annual mass balance in millimeters of water equivalent (mm w.e.)," the equivalent depth of water (spread out over the entire glacier area) that would be produced from the amount of snow or ice on the glacier. The global average smooths out the variations of individual glaciers like those shown for the Sierra.

Figure 3. Global average glacier mass changes



*"**Cumulative mean annual mass balance**" is reported in millimeters of water equivalent (mm w.e.)*

***All glaciers** — more than 130 glaciers worldwide;*

***40 reference glaciers** — glaciers in ten mountain ranges with more than 30 years of continuous data;*

***Subset of "reference" glaciers** — a subset of reference glaciers for which data have been reported*

Source: WGMS, 2017

The late summer photographs in Figure 4 show the area change in the Dana and Conness glaciers over the past century. Losses in both glacier area and volume over time are evident from the photographs. Additional photographs can be viewed at the “Glaciers of the American West” web site (PSU, 2017).

Figure 4. Historical and contemporary photographs of two Sierra Nevada glaciers

Dana Glacier

Credit: U.S. Geological Service, photo station ric046 (left); H. Basagic (right)

Conness Glacier

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

Why is this indicator important?

Glaciers are important indicators of climate change. Over the 20th century, with few exceptions, alpine glaciers were receding throughout the world in response to a warming climate. Historical glacier responses preserved in photographic records, and prehistoric responses preserved as landscape modifications are important records of past climates in high alpine areas where few other climate records exist.

Glaciers are also important to alpine hydrology. They begin to melt most rapidly in late summer after the bright, reflective seasonal snow disappears, revealing the darker ice beneath. This causes peak 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. Finally, glacier shrinkage worldwide is an important contribution to global sea level rise.

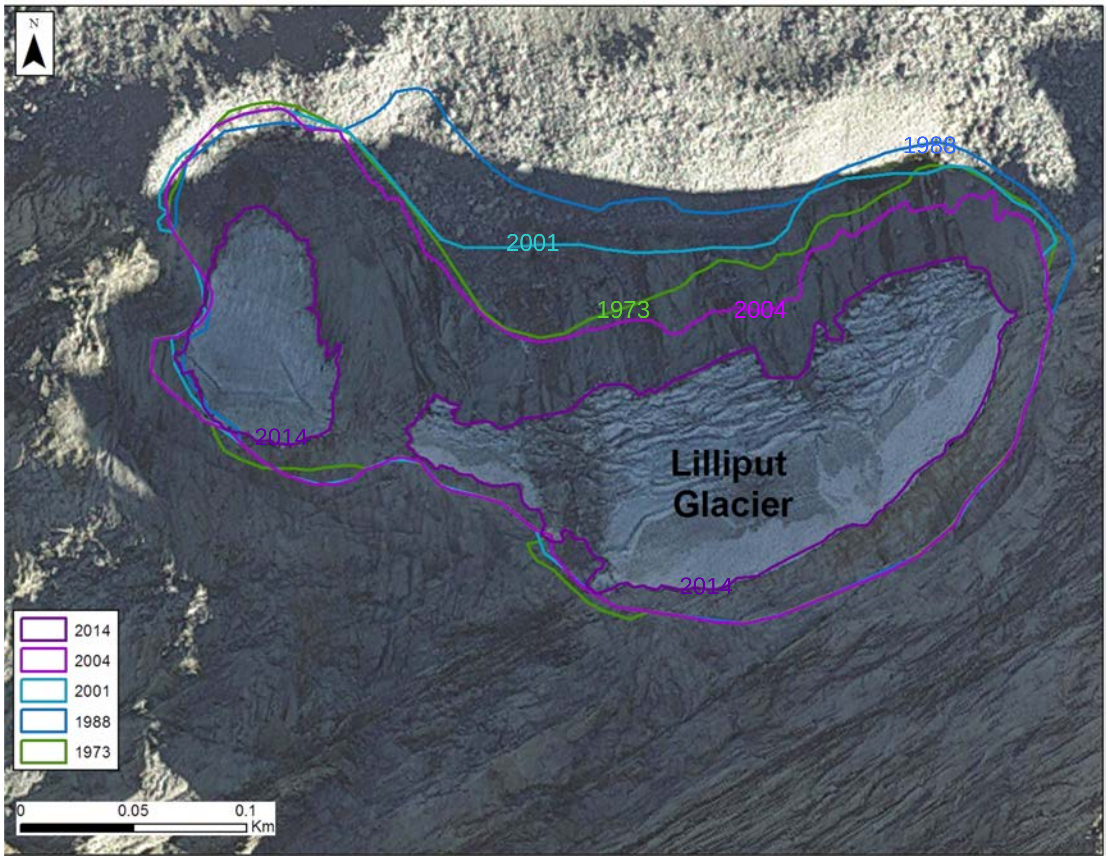
What factors influence this indicator?

A "glacier," by definition, is a mass of perennial snow or ice that moves (Cogely et al., 2011). As such, glaciers are a product of regional climate, responding to the combination of winter snow and spring/summer temperatures. Winter snowfall nourishes the glaciers, and spring/summer temperatures melt ice and snow. Summer air temperature affects the rate of snow and ice melt. Winter temperature determines whether precipitation falls as rain or snow and therefore affects snow accumulation and glacier mass gain. The greater the winter snowfall, the healthier the glacier. 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, 2014).

Analysis for the Sierra Nevada (Basagic and Fountain, 2008) shows a 0.6 degree centigrade (°C) increase in mean annual air temperature over the past century. Seasonal spring, summer and winter mean temperatures likewise increased, with spring mean temperatures showing the greatest change (+1.8°C). The glacier retreat (i.e., decrease in size) in the Sierra Nevada occurred during extended periods of above average spring and summer temperatures. Winter snowfall appears to be a less important factor. Following a cool and wet period in the early part of the 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.

Figure 5 illustrates how the area of Lilliput Glacier changed over time and split into two glaciers. The changing glacier boundary is derived from five aerial photographs from 1973 to 2014, by Portland State University.

Figure 5. Changes in boundary, Lilliput glacier



Source: Portland State University

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.

A glacier gains or loses mass through climatic processes, then responds by either advancing or retreating. The area changes observed in the photographs of the study glaciers were instigated by climatic changes, but 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 unique.

Technical Considerations

<u>Data Characteristics</u>

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 are 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 (2-3 m accuracy), and imported into the GIS database. Glacier area was calculated within the GIS database.

The Fountain et al. (2017) study cited above as having consistent findings provided estimates of area change considered to be preliminary. The area estimates of glaciers and perennial snowfields in that study are based on a comparison of recent aerial photographs to older US Geological Survey topographic maps. The recent photography is quite good, with little seasonal snow obscuring the glacier boundaries. The older maps were also based on aerial photographs taken when the landscape was snowy, thus masking some glacier boundaries. This could have caused a small overestimate of the glacier area; consequently, the difference in area between then and now is likely to be larger than in reality in the Fountain et al. (2017) study. However, the similarity in the findings from two entirely different sources using different methods provides confidence in the results.

Strengths and Limitations of the Data

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. 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.

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This work was supported by the Western Mountain Initiative of the US Geological Survey and by the US Forest Service. Bryce Glenn helped in the preparation of this report.

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