Glaciers

Identification

1. Indicator Description

This indicator examines the balance between snow accumulation and melting in glaciers and describes how the size of glaciers around the world has changed since the 1950s. On a local and regional scale, changes in glaciers have implications for ecosystems and people who depend on glacier-fed streamflow. On a global scale, loss of ice from glaciers contributes to sea level rise. Glaciers are important as an indicator of climate change because physical changes in glaciers—whether they are growing or shrinking, advancing or receding—provide visible evidence of changes in climate variables such as temperature and precipitation.

Components of this indicator include:

- Cumulative trends in the mass balance of reference glaciers worldwide over the past 60 years (Figure 1).
- Cumulative trends in the mass balance of four U.S. glaciers with data extending back to the 1950s (Figure 2).

2. Revision History

April 2010:	Indicator published.
December 2012:	Updated indicator with data through 2010. Replaced Figure 1 with data from a new source, the World Glacier Monitoring Service (WGMS).
May 2014:	Updated indicator with data through 2012.
June 2015:	Updated indicator with data through 2014.
August 2016:	Updated Figure 1 with data through 2015.
April 2021:	Updated indicator with data through 2019. Incorporated minor methodological improvements received from data providers during the past few years, as described under "Indicator Development." Added Lemon Creek Glacier to Figure 2.
June 2024:	Updated indicator with data through 2023.

Data Sources

3. Data Sources

Figure 1 shows the average cumulative mass balance of a global set of reference glaciers, which was originally published by WGMS (Zemp et al., 2015). Measurements were collected by a variety of academic and government programs and compiled by WGMS.

Figure 2 shows the cumulative mass balance of four U.S. "benchmark" glaciers where long-term monitoring has taken place: Gulkana, Wolverine, Lemon Creek, and South Cascade Glaciers. Data for these four glaciers were collected through the U.S. Geological Survey's (USGS's) Benchmark Glacier Program. All four of these glaciers are part of WGMS's global set of reference glaciers.

4. Data Availability

Figure 1. Average Cumulative Mass Balance of "Reference" Glaciers Worldwide, 1956–2023

A version of Figure 1 with data through 2013 was published by WGMS (Zemp et al., 2015). Values through 2023 have been posted by WGMS at: www.wgms.ch/data_databaseversions. Some recent years are associated with a reduced number of associated reference glaciers (e.g., in 2023, 53 glaciers had available data instead of the full set of 61). EPA obtained the data in spreadsheet form from the staff of WGMS, which can be contacted at: www.wgms.ch/contact_wgms. This indicator currently uses data from the WGMS database (version available at: https://doi.org/10.5904/wgms-fog-2024-01).

Raw measurements of glacier surface parameters around the world have been recorded in a variety of formats. Some data are available in online databases such as the World Glacier Inventory (https://nsidc.org/data/glacier_inventory/index.html). Some raw data are also available in studies by USGS. WGMS maintains perhaps the most comprehensive record of international observations. Some of these observations are available in hard copy only; others are available through an online data browser at: www.wgms.ch/fogbrowser.

Figure 2. Cumulative Mass Balance of Four U.S. Glaciers, 1952–2023

Mass balance data sets are available for Gulkana, Wolverine, Lemon Creek, and South Cascade Glaciers on the USGS Benchmark Glacier website at: https://alaska.usgs.gov/products/data.php?dataid=79. As of the time of this data update, the most recent data available were for 2023 for all four glaciers.

Methodology

5. Data Collection

This indicator provides information on the cumulative change in mass balance of numerous glaciers over time. Glacier mass balance data are calculated based on a variety of measurements at the surface of a glacier, including measurements of snow depths and snow density. The net balance is the average mass balance of the glacier from data collected over a glaciological year, the time between the end of the summer ablation season from one year to the next. These measurements help glaciologists determine changes in snow and ice accumulation and ablation that result from snow precipitation, snow compaction, freezing of water, melting of snow and ice, calving (i.e., ice breaking off from the tongue or leading edge of the glacier), wind erosion of snow, and sublimation from ice (Mayo et al., 2004). Both surface size and density of glaciers are measured to produce net mass balance data. These data are reported in meters of water equivalent (mwe), which corresponds to the average change in thickness over the entire surface area of the glacier. Because snow and ice can vary in density (depending on the degree of compaction, for example), converting to the equivalent amount of liquid water provides a more consistent metric.

Measurement techniques have been described and analyzed in many peer-reviewed studies, including Josberger et al. (2007). Most long-term glacier observation programs began as part of the International Geophysical Year in 1957–1958.

Figure 1. Average Cumulative Mass Balance of "Reference" Glaciers Worldwide, 1956–2023

The global trend is based on data collected at 61 reference glaciers around the world, which are identified in Table TD-1.

Table TD-1. Reference Glaciers Included in Figure 1

Continent	Region	Glaciers
North America	Alaska	Gulkana, Wolverine
North America	Pacific Coast Ranges	Place, South Cascade, Helm, Lemon Creek, Peyto, Columbia (2057), Rainbow, Easton
North America	Canadian High Arctic	Devon Ice Cap NW, Meighen Ice Cap, White, Melville South Ice Cap
South America	Andes	Echaurren Norte, Zongo
Europe	Iceland	Brújarjökull, Eyjabakkajökull, Hofsjökull E, Hofsjökull N, Hofsjökull SW, Tungnárjökull
Europe	Svalbard	Austre Broeggerbreen, Midtre Lovénbreen
Europe	Scandinavia	Engabreen, Aalfotbreen, Nigardsbreen, Graasubreen, Storbreen, Hellstugubreen, Remebesdalskaaka, Storglaciären, Langfjordjoekelen, Marmaglaciären, Rabots Glaciär, Riukojietna
Europe	Alps	Saint Sorlin, Sarennes, Argentière, Silvretta, Gries, Allalin, Giétro, Basòdino, Vernagtferner, Pasterze, Kesselwandferner, Jamtalferner, Hintereisferner, Goldbergkees, Caresèr, Ciardoney, Maladeta
Europe/Asia	Caucasus	Djankuat, Garabashi, Leviy Aktru
Asia	Tien Shan	Abramov, Golubin, Kara-Batkak, Ts. Tuyuksuyskiy, Urumqi Glacier No. 1

WGMS chose these 61 reference glaciers because they all had at least 30 years of continuous mass balance records (Zemp et al., 2015). As the small graph at the bottom of Figure 1 shows, several of these glaciers have data extending back to the mid- to late 1950s. A few have records dating back to the 1940s. WGMS did not include data from glaciers that are dominated by non-climatic factors, such as surge dynamics or calving. Because of data availability and the distribution of glaciers worldwide, WGMS's compilation is dominated by the Northern Hemisphere. For the latest inventory of reference glaciers, visit: www.wgms.ch/products_ref_glaciers.

All of the mass balance data that WGMS compiled for this indicator are based on the direct glaciological method (Østrem & Brugman, 1991), which involves manual measurements with stakes and pits at specific points on each glacier's surface.

Figure 2. Cumulative Mass Balance of Four U.S. Glaciers, 1952–2023

Figure 2 shows data collected at four of the U.S. reference glaciers used in Figure 1. All four glaciers have been monitored for many decades. South Cascade Glacier, Wolverine Glacier, Gulkana Glacier, and Lemon Creek Glacier were each studied as part of USGS's Benchmark Glacier Program. USGS chose these as benchmark glaciers because they represent typical glaciers found in their respective regions: the Pacific Northwest for South Cascade Glacier, coastal Alaska for Wolverine Glacier, inland Alaska for Gulkana Glacier, and southeastern Alaska for Lemon Creek Glacier. Hodge et al. (1998) and Josberger et al. (2007) provide more information about the locations of these glaciers and why USGS selected them for the benchmark monitoring program.

The mass balance data in this indicator are derived from repeated measurements made at specific times and locations on each reference glacier. Lemon Creek Glacier monitoring has been led by the Juneau Icefield Research Program (JIRP), while the other three reference glaciers have been monitored directly by USGS. In general, USGS and JIRP researchers used a combination of snow pits, reference stakes, and other methods to gather data on snow thickness, accumulation, and density at specific index sites on each glacier. USGS researchers typically visited their sites twice per year (spring and autumn), while JIRP collected field measurements once per year in July. USGS provides technical assistance to JIRP by taking measurements during different times of the year and augmenting data collected by JIRP for continuous analysis. Specific information on sampling design at each of the USGS benchmark glaciers is available in Bidlake et al. (2010) and Van Beusekom et al. (2010). Specific information on the sampling design at Lemon Creek Glacier is available in Pelto et al. (2013).

Data for Lemon Creek Glacier are available beginning in 1953. Data for South Cascade Glacier are available beginning in 1959, and data for Gulkana and Wolverine Glaciers are available beginning in 1966. Glacier monitoring methodology has evolved over time based on scientific reanalysis, and cumulative net mass balance data for these four glaciers are routinely updated as glacier measurement methodologies improve and more information becomes available.

6. Indicator Derivation

For this indicator, glacier surface measurements have been used to determine the net change in mass balance from one year to the next, referenced to the previous year's summer surface measurements. The indicator documents changes in mass and volume rather than total mass or volume of each glacier because the latter is more difficult to determine accurately. Thus, the indicator is not able to show how the magnitude of mass balance change relates to the overall mass of the glacier (e.g., what percentage of the glacier's mass has been lost).

Glaciologists convert surface measurements to mass balance by interpolating measurements over the glacier surface geometry. Two different interpolation methods can be used: conventional balance and reference-surface balance. In the conventional balance method, measurements are made at the glacier each year to determine glacier surface geometry, and other measurements are interpolated over the annually modified geometry. The reference-surface balance method does not require that glacier geometry be redetermined each year. Rather, glacier surface geometry is determined once, generally the first year that monitoring begins, and the same geometry is used each of the following years. A more complete description of conventional balance and reference-surface balance methods is given in Harrison et al. (2009).

Mass balance is typically calculated over a balance year, which begins at the onset of snow and ice accumulation. For example, the balance year at Gulkana Glacier starts and ends in September of each year. Thus, the balance year beginning in September 2013 and ending in September 2014 is called "balance year 2014." For the three glaciers where USGS conducts measurements directly, annual mass balance changes are confirmed based on measurements taken the following spring. At Lemon Creek Glacier, additional local data—temperature, precipitation, and other parameters—are combined with annual field measurements to determine annual mass balance change.

Figure 1. Average Cumulative Mass Balance of "Reference" Glaciers Worldwide, 1956–2023

The graph shows the average cumulative mass balance of WGMS's reference glaciers over time. The number of reference glaciers included in this calculation varies by year, but it is still possible to generate a reliable time series because the figure shows an average across all the reference glaciers measured, rather than a sum.

To generate annual averages, WGMS first calculated the average annual mass balance change for the reference glaciers within each major glaciated mountain region (WGMS has delineated 19 regions, 10 of which have at least one reference glacier each; see Zemp et al., 2015, Figures 2.1 and 2.3). Next, WGMS calculated the mean of these regional averages, which it reports as the global mean. This approach has less bias than a simple arithmetic mean of all the reference glaciers, which would be biased toward regions that happen to have more reference glaciers, such as Scandinavia and the Alps.

Although a few reference glaciers have mass balance data from as early as the mid-1940s, this indicator starts with 1957 mass balance data, which refer to a base year of 1956, because that was the first year data were available from at least 10 reference glaciers.

No attempt was made to extrapolate from the observed data to calculate total cumulative change in mass balance across all glaciers worldwide.

Figure 2. Cumulative Mass Balance of Four U.S. Glaciers, 1952–2023

This graph shows the average cumulative mass balance of four U.S. glaciers over time. At each glacier, changes in mass balance have been summed over time to determine the cumulative change in mass balance since a reference year. For the sake of comparison, all four glaciers use a reference year of 1965, which is set to zero. Thus, a negative value in a later year means the glacier has lost mass since 1965. No attempt has been made to project the results for these four glaciers to other locations. See Bidlake et al. (2010), Van Beusekom et al. (2010), Pelto et al. (2013), and sources cited therein for further description of analytical methods.

For each glacier, the year prior to the first mass balance measurement has been inserted in the graph as a point of reference. For example, Gulkana Glacier's first mass balance measurement shows that the glacier lost 0.69 mwe during 1966. For graphing purposes, 1965 is set at zero, which allows 1966 to be plotted as -0.69.

In the past, USGS formally designated annual mass balance estimates as preliminary or final. USGS no longer does this, choosing instead to continually refine and update mass balance estimates according to the best available science and data. Accordingly, USGS provides new data to support regular updates of this indicator with measurements that are comparable across glaciers. See O'Neel et al. (2019) for a summary of USGS's most recent reanalysis and harmonization of methods across glaciers.

Indicator Development

In 2017, WGMS made two methodological improvements that EPA has incorporated into this indicator:

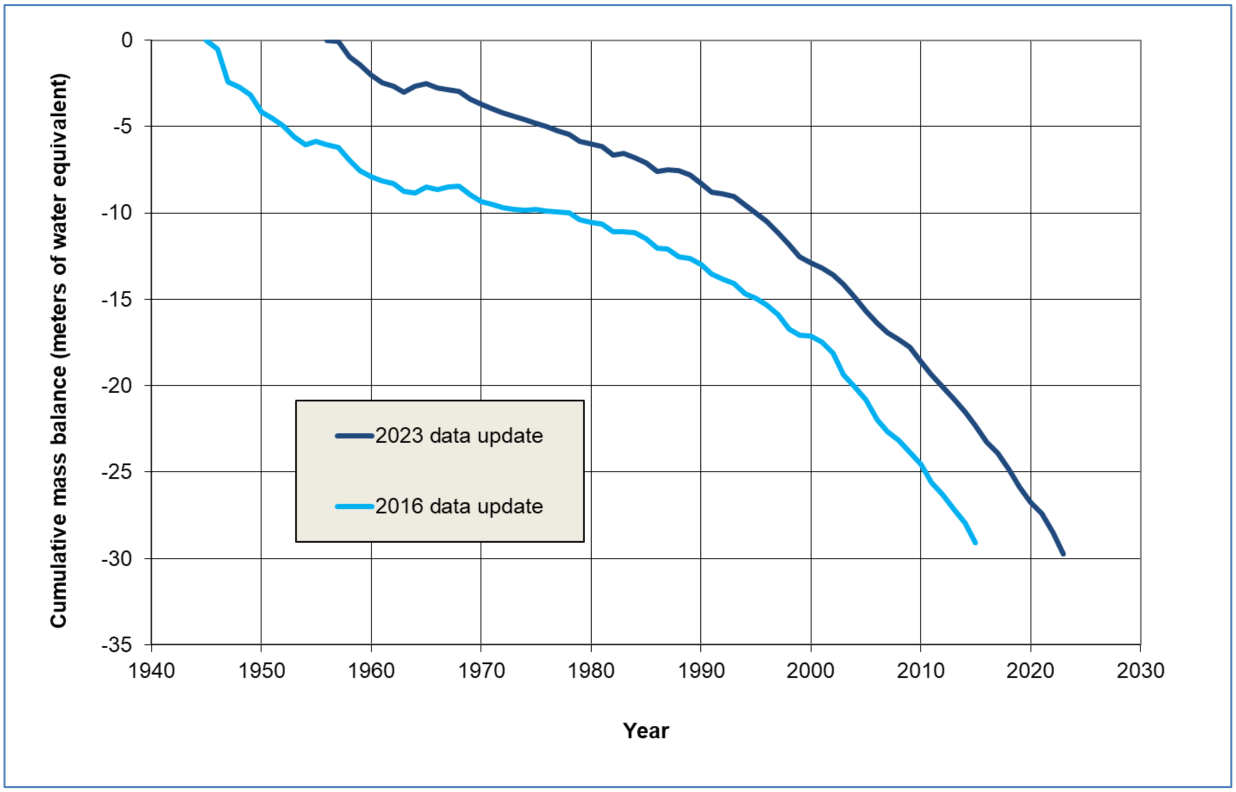
1. WGMS updated the averaging method to include two steps: first calculating regional means, then calculating the mean of the regional means. Prior versions of this indicator were based on an unweighted arithmetic mean across all reference glaciers with data for a given year. WGMS introduced the regional averaging approach so the reported global mean would be less biased toward conditions in regions that happen to have more well-studied glaciers, such as Scandinavia and the Alps.

2. Figure 1 previously presented mass balance data starting in 1946 (base year 1945), when the first reference glacier began to be measured consistently. For future data updates, WGMS recommended that Figure 1 start with 1957 mass balance data and exclude prior years, which had data from fewer than 10 reference glaciers, to avoid presenting averages that could be heavily influenced by a single glacier. This change was particularly advisable in conjunction with the switch to a regional averaging approach, which ideally requires data to be available from reference glaciers in several regions.

Figure TD-1 shows how these two changes affected Figure 1 of EPA's indicator. The revised averaging method used in updates after 2017—including the most recent update shown below—adjusted the year-to-year change in some cases, but did not noticeably alter the overall shape of the data over time. The new baseline year caused the entire data set to shift upward on the graph, but did not change the overall shape of the curve from 1956 to present. Figure 1 no longer shows changes in glacier mass balance that occurred prior to 1956/1957, as earlier data are based on fewer glaciers.

As part of the 2021 data update to Figure 2, EPA added data from Lemon Creek Glacier. Previous versions of this figure had only presented data from Gulkana, South Cascade, and Wolverine, the original three USGS benchmark glaciers. USGS has now formally adopted Lemon Creek Glacier as a benchmark glacier. EPA elected to add Lemon Creek Glacier because it is representative of southeastern Alaska—a heavily glaciated part of North America that is not represented by USGS's original three benchmark glaciers. This indicator previously left a large spatial gap between Washington and south-central Alaska, which Lemon Creek Glacier helps to fill. Lemon Creek is also one of WGMS's 61 long-term global reference glaciers.

Figure TD-1. The Effect of Adjusting the Starting Point and Averaging Method for Mass Balance of Reference Glaciers Worldwide



7. Quality Assurance and Quality Control

The underlying measurements for Figure 1 come from a variety of data collection programs, each with its own procedures for quality assurance and quality control. WGMS also has its own requirements for data quality. For example, WGMS incorporates only measurements that reflect the direct glaciological method (Østrem & Brugman, 1991).

USGS periodically reviews and updates the mass balance data for the benchmark glaciers shown in Figure 2. For example, in Fountain et al. (1997), the authors explain that mass balance should be periodically compared with changes in ice volume, as the calculations of mass balance are based on interpolation of point measurements that are subject to error. In addition, March (2003) describes steps that USGS takes to check the weighting of certain mass balance values. This weighting allows USGS to convert point values into glacier-averaged mass balance values. Ongoing reanalysis of glacier monitoring methods, described in O'Neel et al. (2019) and studies cited therein, provides an additional level of quality control for data collection.

Pelto et al. (2013) note that their results for annual mass balance at Lemon Creek Glacier compare well with those calculated using independent geodetic methods from 1957 to 1989 and from 1957 to 1995. In addition, they note that their results from 1994 to 2007 compare well with the results of airborne surface profiling over the same period.

Analysis

8. Comparability Over Time and Space

Glacier monitoring methodology has evolved over time based on scientific reanalysis of methodology. Peer-reviewed studies describing the evolution of glacier monitoring are listed in Mayo et al. (2004). Figure 2 accounts for these changes, as USGS periodically reanalyzes past data points using improved methods.

The reference glaciers tracked in Figure 1 reflect a variety of methods over time and space, and it is impractical to adjust for all these small differences. As a general indication of trends in glacier mass balance, however, Figure 1 shows a clear pattern whose strength is not diminished by the inevitable variety of underlying sources.

For Figure 2, differences exist in the methods used at each of the four reference glaciers included in the figure. For example, the annual mass balances at the three USGS-measured benchmark glaciers are derived using index site data collected in the spring and autumn. In contrast, annual mass balances at Lemon Creek Glacier are derived using index site data collected in July, which are then corrected for the additional ablation that occurs through the end of the summer ablation season. Like Figure 1, however, Figure 2 shows a clear pattern that is not diminished by the differences in the methods used at each glacier. Further information on the specific methods used for each glacier may be found in the sources cited in Sections 6 and 7.

9. Data Limitations

Factors that may impact the confidence, application, or conclusions drawn from this indicator are as follows:

1. Slightly different methods of measurement and interpolation have been used at different glaciers, making direct year-to-year comparisons of change in cumulative net mass balance or volume difficult. Overall trends among glaciers can be compared, however.

2. The number of glaciers with data available to calculate mass balance in Figure 1 decreases as one goes back in time. Thus, averages from the 1950s to the mid-1970s rely on a smaller set of reference glaciers than the full 61 compiled in later years.

3. The relationship between climate change and glacier mass balance is complex, and the observed changes at a specific glacier might reflect a combination of global and local climate variations.

4. Records are available from numerous other individual glaciers in the United States, but many of these records lack the detail, consistency, or length of record provided by the reference glaciers used in Figure 2. USGS and JIRP scientists have collected data on these four glaciers for decades using consistent methods, and USGS experts suggest that at least a 30-year record is necessary to provide meaningful statistics. Due to the complicated nature of glacier behavior, it is difficult to assess the significance of observed trends over shorter periods (Josberger et al., 2007).

10. Sources of Uncertainty

Glacier measurements have inherent uncertainties. For example, maintaining a continuous and consistent data record is difficult because the stakes that denote measurement locations are often distorted by glacier movement and snow and wind loading. Additionally, travel to measurement sites is dangerous and inclement weather can prevent data collection during the appropriate time frame. In a cumulative time series, such as the analyses presented in this indicator, the size of the margin of error grows with time because each year's value depends on all of the preceding years.

Figure 1. Average Cumulative Mass Balance of "Reference" Glaciers Worldwide, 1956–2023

Uncertainties have been quantified for some glacier mass balance measurements, but not for the combined time series shown in Figure 1. WGMS has identified greater quantification of uncertainty in mass balance measurements as a key goal for future research.

Figure 2. Cumulative Mass Balance of Four U.S. Glaciers, 1952–2023

Annual mass balance measurements for the benchmark glaciers measured by USGS usually have an estimated error of ±0.1 to ±0.2 mwe (Josberger et al., 2007). Error bars for the Wolverine and Gulkana Glaciers are plotted in Van Beusekom et al. (2010), and further information on error estimates for all three USGS-measured glaciers is given in Bidlake et al. (2010) and Van Beusekom et al. (2010). Harrison et al. (2009) describe error estimates related to interpolation methods.

Pelto et al. (2013) and Miller and Pelto (1999) discuss potential sources of uncertainty in the JIRP Lemon Creek Glacier annual mass balance data set. These sources do not provide uncertainty estimates for the measurements that were used to construct this indicator, but they note that the field results are comparable to mass balance estimates generated using geodetic methods that have an error of less than 1.5 mwe.

11. Sources of Variability

Glacier mass balance can reflect year-to-year variations in temperature, precipitation, and other factors. Figure 2 shows some of this year-to-year variability, while Figure 1 shows less variability because the change in mass balance has been averaged over many glaciers around the world. In both cases, the availability of several decades of data allows the indicator to show long-term trends that exceed the "noise" produced by interannual variability. In addition, the period of record is longer than the period of key multi-year climate oscillations such as the Pacific Decadal Oscillation and El Niño–Southern Oscillation, meaning the trends shown in Figures 1 and 2 are not simply the product of decadal-scale climate oscillations.

12. Statistical/Trend Analysis

This indicator does not report on the average rate of change in either figure, nor does it calculate the statistical significance of these trends or provide confidence bounds. Josberger et al. (2007) note that the rate of change appears to have accelerated for Gulkana, South Cascade, and Wolverine Glaciers, which means that a higher-order regression would likely be more appropriate than the standard linear regression that has been applied in certain other indicators. Similarly, Pelto et al. (2013) note that the rate of change in mean annual mass balance for Lemon Creek Glacier approximately doubled from -

0.30 mwe/year in the 1953–1985 period to -0.60 mwe/year in the 1986–2011 period. WGMS provides average rates of change for specific time periods, both regionally (Alaska, western North America) and worldwide (Zemp et al., 2021). Zemp et al.'s (2021) Table 2.2 also provides summary statistics for the distribution of results from the 61 reference glaciers worldwide for the three most recent years, including the mean annual mass balance change, maximum, minimum, and standard deviation.

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