Arctic Glaciers

Identification

1. Indicator Description

This indicator examines the balance between mass gain (snow accumulation) and loss (melting) on an annual basis in glaciers, and describes how the size of glaciers in the Arctic region has changed since 1945. 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.

This indicator includes one figure that shows the cumulative mass balance of eight reference glaciers in the Arctic since 1945 (Figure 1). This indicator and associated data are also made available on the U.S. Global Change Research Program's website at: www.globalchange.gov/browse/indicator-details/3941.

2. Revision History

July 2022: Indicator published.

Data Sources

3. Data Sources

Figure 1 shows the average cumulative mass balance of a set of eight reference glaciers. Measurements were collected by a variety of academic and government programs and compiled by the World Glacier Monitoring Service (WGMS), which maintains data for these reference glaciers and 33 others worldwide. WGMS publishes results on its website and in global glacier change bulletins available at: https://wgms.ch/ggcb.

4. Data Availability

A version of Figure 1 has been published on the GlobalChange.gov website (www.globalchange.gov/browse/indicator-details/3941). Updated data for this indicator were downloaded from: https://wgms.ch/products_ref_glaciers. This indicator currently uses data from WGMS database version doi:10.5904/wgms-fog-2021-05.

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 (http://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.

Methodology

5. Data Collection

This indicator provides information on the cumulative change in mass balance of eight representative 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 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.

This indicator is based on data collected at eight reference glaciers located above a latitude of 66°N, which are identified in Table TD-1.

Table TD-1. Reference Glaciers Included in Figure 1

Continent	Region	Glaciers
North America	Canada	Meighen Ice Cap
North America	Canada	White
Europe	Spitsbergen, Norway	Austre Broeggerbreen
Europe	Spitsbergen, Norway	Midtre Lovenbreen
North America	Canadian High Arctic	Devon Ice Cap NW
North America	Canadian High Arctic	Melville South Ice Cap
Europe	Northern Sweden	Storglaciaeren
Europe	Northern Norway	Engabreen

These eight reference glaciers are from a larger set of 41 "reference" glaciers worldwide that all have at least 30 years of continuous mass balance records (WGMS, 2017). Most of the reference glaciers have data extending back to the mid-to-late 1950s. A few have records as far back as 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.

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

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).

Annual glacier mass balance is normally calculated over a "balance" or hydrological year, starting in autumn at the end of the summer melt season, and ideally just before the onset of snow accumulation. Mass balance observations were converted to common units (meters), and the cumulative mass balance for each glacier was calculated by adding annual balances and displaying the results relative to 1970, to provide a common baseline for comparison. The cumulative mean mass balance was determined by calculating the annual mean mass balance across the eight glaciers (or as many of the eight that had data in a given year), then adding these mean net balances from year to year. The mean line was also adjusted to use 1970 as a common zero point.

The graph in Figure 1 shows the average cumulative mass balance of eight WGMS reference glaciers over time. The figure shows the individual glaciers and an average across all eight of 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 the Arctic region. No attempt was made to extrapolate from the observed data to calculate a total cumulative change in mass balance across all glaciers in the Arctic region or 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 (QA/QC). WGMS also has its own requirements for data quality. For example, WGMS incorporates only measurements that reflect the direct glaciological method (Østrem and Brugman, 1991).

Analysis

8. Comparability Over Time and Space

Glacier monitoring methods have evolved over time based on scientific reanalysis of methodologies. Peer-reviewed studies describing the evolution of glacier monitoring are listed in Mayo et al. (2004). 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.

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 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.

10. Sources of Uncertainty

Glacier mass balance measurements are inherently uncertain for a variety of reasons. Nonetheless, a mass balance record that has been maintained carefully and consistently over a long period of time (decades) provides a very robust record of change in the glacier's environment. Among the most significant sources of uncertainty is that arising from extrapolation of a limited number of point measurements to the entire glacier area. Balance measurements are also critically dependent on the seasonal measurement campaigns occurring at the right time. Measurements made at the onset of the hydrological year (autumn) should happen after the end of the melt season and before the start of snow accumulation. Similarly, measurements in spring should happen after the season's snowfall has ended but before the onset of melt. This can be difficult to accomplish, especially given the remote position of many glaciers and their inaccessibility. Another potential source of significant uncertainty is associated with determining a glacier's annual mass balance, which is done by calculating the typically small difference between two large and difficult-to-measure numbers (total mass in one year compared with the previous year)—another potential source of significant uncertainty.

Uncertainties have been quantified for some of the glacier mass balance measurements in Figure 1. WGMS has identified greater quantification of uncertainty in mass balance measurements as a key goal for future research.

11. Sources of Variability

Glacier mass balance can reflect year-to-year variations in temperature, precipitation, and other factors. 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. The processes of glacier response to changes in mass balance also act on time scales longer than most climate oscillations, so the glaciers themselves act as a low-pass filter, meaning the trends shown in Figure 1 are not simply the product of decadal-scale climate oscillations.

12. Statistical/Trend Analysis

WGMS (2021) provides average rates of change for specific time periods, both regionally (Alaska, western North America) and worldwide. WGMS (2021) Table 2.2 also provides summary statistics for the distribution of results from the 41 reference glaciers worldwide for three recent years, including the mean annual mass balance change, maximum, minimum, and standard deviation.

An ordinary least-squares linear regression reveals that the eight-glacier average mass balance declined at an average rate of 0.23 mwe/year from 1945 to 2020. This trend is highly significant ($p < 0.0001$).

References

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