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 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 temperature and precipitation.

Components of this indicator include:

- Cumulative trends in the mass balance of reference glaciers worldwide over the past 70 years (Figure 1).
- Cumulative trends in the mass balance of three U.S. glaciers over the past half-century (Figure 2).

2. Revision History

April 2010:	Indicator posted.
December 2011:	Updated with data through 2010.
April 2012:	Replaced Figure 1 with data from a new source: the World Glacier Monitoring Service.
June 2012:	Updated Figure 2 with data through 2010 for South Cascade Glacier.
May 2014:	Updated with data through 2012.
June 2015:	Updated indicator on EPA's website with data through 2014.

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 the World Glacier Monitoring Service (WGMS) (2013). Measurements were collected by a variety of academic and government programs and compiled by WGMS.

The U.S. Geological Survey (USGS) Benchmark Glacier Program provided the data for Figure 2, which shows the cumulative mass balance of three U.S. "benchmark" glaciers where long-term monitoring has taken place.

4. Data Availability

Figure 1. Average Cumulative Mass Balance of "Reference" Glaciers Worldwide, 1945–2014

A version of Figure 1 with data through 2011 was published in WGMS (2013). Values for 2014 were posted by WGMS at: www.wgms.ch/mbb/sum13.html. Some recent years are associated with a reduced number of associated reference glaciers (e.g., 24 instead of the full set of 37). EPA obtained the data in spreadsheet form from the staff of WGMS, which can be contacted via their website: www.wgms.ch/access.html. This indicator currently uses data from WGMS database version doi:10.5904/wgms-fog-2014-09.

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/metadatabrowser.html.

Figure 2. Cumulative Mass Balance of Three U.S. Glaciers, 1958–2014

A cumulative net mass balance data set is available on the USGS benchmark glacier website at: http://ak.water.usgs.gov/glaciology/all_bmg/3glacier_balance.htm. Because the online data are not necessarily updated every time a correction or recalculation is made, EPA obtained the most up-to-date data for Figure 2 directly from USGS. More detailed metadata and measurements from the three benchmark glaciers can be found on the USGS website at: http://ak.water.usgs.gov/glaciology.

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, 1945–2014

The global trend is based on data collected at 37 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
North America	Canadian High Arctic	Devon Ice Cap NW, Meighen Ice Cap, White
South America	Andes	Echaurren Norte
Europe	Svalbard	Austre Broeggerbreen, Midtre Lovénbreen
Europe	Scandinavia	Engabreen, Alfotbreen, Nigardsbreen, Grasubreen, Storbreen, Hellstugubreen, Hardangerjoekulen, Storglaciaeren
Europe	Alps	Saint Sorlin, Sarennes, Argentière, Silvretta, Gries, Stubacher Sonnblickkees, Vernagtferner, Kesselwandferner, Hintereisferner, Caresèr
Europe/Asia	Caucasus	Djankuat
Asia	Altai	No. 125 (Vodopadniy), Maliy Aktru, Leviy Aktru
Asia	Tien Shan	Ts. Tuyuksuyskiy, Urumqi Glacier No.1

WGMS chose these 37 reference glaciers because they all had at least 30 years of continuous mass balance records (WGMS, 2013). As the small graph at the bottom of Figure 1 shows, some of these glaciers have data extending 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.

Figure 2. Cumulative Mass Balance of Three U.S. Glaciers, 1958–2014

Figure 2 shows data collected at the three glaciers studied by USGS's Benchmark Glacier Program. All three glaciers have been monitored for many decades. USGS chose them because they represent typical glaciers found in their respective regions: South Cascade Glacier in the Pacific Northwest (a continental glacier), Wolverine Glacier in coastal Alaska (a maritime glacier), and Gulkana Glacier in inland Alaska (a continental 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.

USGS collected repeated measurements at each of the glaciers to determine the various parameters that can be used to calculate cumulative mass balance. Specific information on sampling design at each of the three glaciers is available in Bidlake et al. (2010) and Van Beusekom et al. (2010). Measurements are collected at specific points on the glacier surface, designated by a network of stakes, which facilitate keeping a running tally of accumulation and ablation for each stake. Stake measurements along with local temperature and precipitation data allow USGS scientists to derive glacier net and seasonal mass balance estimates. For more information about these methods, see: www.usgs.gov/climate_landuse/clu_rd/glacierstudies/default.asp.

Data for South Cascade Glacier are available beginning in 1959 (relative to conditions in 1958) and for Gulkana and Wolverine Glaciers beginning in 1966 (relative to conditions in 1965). Glacier monitoring methodology has evolved over time based on scientific reanalysis, and cumulative net mass balance data for these three glaciers are routinely updated as glacier measurement methodologies improve and more information becomes available. Several papers that document data updates through time are available on the USGS benchmark glacier website at: http://ak.water.usgs.gov/glaciology.

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." Annual mass balance changes are confirmed based on measurements taken the following spring.

Figure 1. Average Cumulative Mass Balance of "Reference" Glaciers Worldwide, 1945–2014

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 of the glaciers measured, rather than a sum. No attempt was made to extrapolate from the observed data in order to calculate a cumulative global change in mass balance.

Figure 2. Cumulative Mass Balance of Three U.S. Glaciers, 1958–2014

At each of the three benchmark glaciers, 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 three 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. All three time series in Figure 2 reflect the conventional mass balance method, as opposed to the reference-surface method. No attempt has been made to project the results for the three benchmark glaciers to other locations. See Bidlake et al. (2010), Van Beusekom et al. (2010), and sources cited therein for further description of analytical methods.

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. USGS is currently consolidating glacier records to better harmonize calculation methods across space and time. Future updates of EPA's indicator will reflect this harmonization.

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).

USGS periodically reviews and updates the mass balance data 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 several of the reports listed on USGS's website (http://ak.water.usgs.gov/glaciology), provides an additional level of quality control for data collection.

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 of these small differences. However, as a general indication of trends in glacier mass balance, 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 number of glaciers with data available to calculate mass balance in Figure 1 decreases as one goes back in time. Thus, averages from the 1940s to the mid-1970s rely on a smaller set of reference glaciers than the full 37 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 other records lack the detail, consistency, or length of record provided by the USGS benchmark glaciers program. USGS has collected data on these three 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, 1945–2014

Uncertainties have been quantified for some glacier mass balance measurements, but not for the combined time series shown in Figure 1. WGMS (2013) has identified greater quantification of uncertainty in mass balance measurements as a key goal for future research.

Figure 2. Cumulative Mass Balance of Three U.S. Glaciers, 1958–2014

Annual mass balance measurements for the three USGS benchmark glaciers usually have an estimated error of ±0.1 to ±0.2 meters of water equivalent (Josberger et al., 2007). Error bars for the two Alaskan glaciers are plotted in Van Beusekom et al. (2010). Further information on error estimates is given in Bidlake et al. (2010) and Van Beusekom et al. (2010). Harrison et al. (2009) describe error estimates related to interpolation methods.

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

Figures 1 and 2 both show a cumulative loss of mass or volume over time, from which analysts can derive an average annual rate of change. Confidence bounds are not provided for the trends in either figure, although both Bidlake et al. (2010) and Van Beusekom et al. (2010) cite clear evidence of a decline in mass balance at U.S. benchmark glaciers over time.

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