Ice Sheets

Identification

1. Indicator Description

This indicator examines the balance between snow accumulation and loss (through melting and dynamic ice loss such as calving of icebergs) in the Earth's two largest regions of land-based ice—Greenland and Antarctica—based on satellite and supporting ground measurements that have been collected since 1992. Loss of ice from these ice sheets contributes to global sea level rise. Ice sheets are important as an indicator of climate change because physical changes in land-based ice—whether it is growing or shrinking, advancing or receding—are sensitive to and provide visible evidence of changes in climate variables such as temperature and precipitation. Over the last few decades, there is high confidence that global warming has led to mass loss from the ice sheets of Greenland and Antarctica (IPCC, 2019).

2. Revision History

April 2021:	Indicator published.
June 2024:	Indicator updated with IMBIE data through 2020 and NASA JPL data through 2023.

Data Sources

3. Data Sources

This indicator shows the cumulative change in the mass balance of ice on Greenland and Antarctica from two data sources.

The core data source for this indicator is the Ice Sheet Mass Balance Inter-comparison Exercise (IMBIE), a collaboration between scientists supported by the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA). IMBIE compiles peer-reviewed estimates of ice sheet mass balance from numerous sources, based on a variety of methods. IMBIE then synthesizes these data sets into combined estimates. This use of multiple sources allows IMBIE to show trends back to 1992, which is a longer timeframe than most individual data sources can cover.

For comparison, this indicator also presents data collected by NASA's Gravity Recovery and Climate Experiment (GRACE) satellite mission since 2002. GRACE is one of the many sources used in the IMBIE analysis described above, but it is also featured separately in this indicator because (a) it has been widely published and cited and (b) it provides sub-annual resolution to reveal seasonal patterns. NASA's Jet Propulsion Laboratory (JPL) processed the raw GRACE data and translated them into measurements of mass, aggregated over the entirety of Greenland and Antarctica. These data come from the GRACE and GRACE Follow On (GRACE-FO) JPL RL06.1M Mascon Solution, Version 3.

4. Data Availability

EPA obtained IMBIE data from the IMBIE website at: http://imbie.org/data-downloads. For additional source data information, see Table 1 and Table A1 in Otosaka et al. (2023). Abridged information from Otosaka et al. Table A1, including citations, is listed in Table TD-1 in Section 5 below. Additionally, information from Otosaka et al. Table 1 is listed in Table TD-2 in Section 5 below.

The NASA GRACE data were obtained from NASA's "Vital Signs" website at: https://climate.nasa.gov/vital-signs/land-ice. Below each graph on this page is a link to a webpage with time-series data. The data download requires a user to create a login, but this step is free and available to all. The two aggregated GRACE time series are based on gridded data sets that JPL has published at: https://grace.jpl.nasa.gov/data/get-data/jpl_global_mascons. Underlying data and other GRACE products are linked from: https://podaac.jpl.nasa.gov/GRACE. For more source data information, see Luthcke et al. (2013).

Methodology

5. Data Collection

IMBIE Data

IMBIE uses existing peer-reviewed estimates of ice sheet mass balance. The source estimates were developed using three different methods: gravimetry (measurement of gravitational fields via satellites), altimetry (measurement of the altitude of the ice sheet surface using airborne or satellite-mounted radar and laser instruments), and the input-output method (IOM). The IOM combines data about additions of ice to the ice sheet (e.g., input via snow) with estimates of ice loss from the ice sheet (e.g., calving to the ocean or ice melt at the ice sheet-ocean interface) with adjustments according to surface mass balance (SMB) models. All source estimates were aggregated to calculate a central estimate of ice sheet cumulative mass change over time. The most recent year of data will often have less sub-annual temporal resolution than previous years because fewer estimates can be processed in time for submission. Gravimetric and altimetric estimates were corrected for glacial isostatic adjustment (GIA) as described in Section 6 below.

Gravimetry estimates are all derived from the GRACE and GRACE-FO satellite missions; they only differ in the approaches used to analyze the data. For more details about how GRACE and GRACE-FO collect data, see "NASA JPL Data" below. The altimetry estimates are computed from data from the ICESat-1 (ICE), EnviSat (EV), ERS-1 (E1), ERS-2 (E2), and CryoSat-2 (CS2) satellite missions and the Airborne Topographic Mapping (ATM) and Land, Vegetation, and Ice Sensor (LVIS) airborne instruments. IOM estimates rely on radar, satellite imagery, and airborne measurements of ice thickness. IOM satellite data come from the Advanced Land Observation Satellite (ALOS), Terrastar-X (TSX), Radarsat-1 (R1), Radarsat-2 (R2), Cosmo-skymed (CSK), Sentinel-1 (S1), Landsat-8 (L8), E1, E2, and EV missions. The Greenland IMBIE estimate uses 16 gravimetry estimates, eight altimetry estimates, and three IOM estimates, collectively representing 19 years of gravimetry measurements, 16 years of radar altimeter measurements, and 29 years of IOM data. Since the previous IMBIE assessment, 12 estimates have been updated to include more recent years of data for Greenland. The Antarctica IMBIE estimate uses 16 gravimetry estimates, six altimetry estimates, and one IOM estimate, collectively representing 19 years of gravimetry measurements, 28 years of radar altimeter measurements, and 29 years of IOM data.

Since the previous IMBIE assessment, 13 estimates have been updated to include more recent years of data for Antarctica. Together, the updated IMBIE assessment provided here represents data for Antarctica and Greenland spanning the years 1992–2020. The data collection methods for each individual estimate are documented in the corresponding source paper and cited by Otosaka et al. (2023). Most of the sources listed in Table TD-1 provide direct data, but some were incorporated to verify underlying methods.

Table TD-1. IMBIE Data Sources

Technique	Data source
IOM	Andersen, M. L., Stenseng, L., Skourup, H., Colgan, W., Khan, S. A., Kristensen, S. S., Andersen, S. B., Box, J. E., Ahlstrøm, A. P., Fettweis, X., & Forsberg, R. (2015). Basin-scale partitioning of Greenland ice sheet mass balance components (2007–2011). *Earth and Planetary Science Letters*, *409*, 89–95. https://doi.org/10.1016/j.epsl.2014.10.015
IOM	Colgan, W., Mankoff, K. D., Kjeldsen, K. K., Bjørk, A. A., Box, J. E., Simonsen, S. B., Sørensen, L. S., Khan, S. A., Solgaard, A. M., Forsberg, R., Skourup, H., Stenseng, L., Kristensen, S. S., Hvidegaard, S. M., Citterio, M., Karlsson, N., Fettweis, X., Ahlstrøm, A. P., Andersen, S. B., … Fausto, R. S. (2019). Greenland ice sheet mass balance assessed by PROMICE (1995–2015). *Geological Survey of Denmark and Greenland Bulletin*, *43*. https://doi.org/10.34194/GEUSB-201943-02-01
IOM	Mouginot, J., Rignot, E., Bjørk, A. A., Van Den Broeke, M., Millan, R., Morlighem, M., Noël, B., Scheuchl, B., & Wood, M. (2019). Forty-six years of Greenland Ice Sheet mass balance from 1972 to 2018. *Proceedings of the National Academy of Sciences*, *116*(19), 9239–9244. https://doi.org/10.1073/pnas.1904242116
IOM	Rignot, E., Mouginot, J., Scheuchl, B., Van Den Broeke, M., Van Wessem, M. J., & Morlighem, M. (2019). Four decades of Antarctic Ice Sheet mass balance from 1979–2017. *Proceedings of the National Academy of Sciences*, *116*(4), 1095–1103. https://doi.org/10.1073/pnas.1812883116
Altimetry	Felikson, D., Urban, T. J., Gunter, B. C., Pie, N., Pritchard, H. D., Harpold, R., & Schutz, B. E. (2017). Comparison of elevation change detection methods From ICESat altimetry over the Greenland ice sheet. *IEEE Transactions on Geoscience and Remote Sensing*, *55*(10), 5494–5505. https://doi.org/10.1109/TGRS.2017.2709303
Altimetry	Gourmelen, N., Escorihuela, M. J., Shepherd, A., Foresta, L., Muir, A., Garcia-Mondéjar, A., Roca, M., Baker, S. G., & Drinkwater, M. R. (2018). CryoSat-2 swath interferometric altimetry for mapping ice elevation and elevation change. *Advances in Space Research*, *62*(6), 1226–1242. https://doi.org/10.1016/j.asr.2017.11.014
Altimetry	Gunter, B. C., Didova, O., Riva, R. E. M., Ligtenberg, S. R. M., Lenaerts, J. T. M., King, M. A., Van Den Broeke, M. R., & Urban, T. (2014). Empirical estimation of present-day Antarctic glacial isostatic adjustment and ice mass change. *The Cryosphere*, *8*(2), 743–760. https://doi.org/10.5194/tc-8-743-2014
Altimetry	Helm, V., Humbert, A., & Miller, H. (2014). Elevation and elevation change of Greenland and Antarctica derived from CryoSat-2. *The Cryosphere*, *8*(4), 1539–1559. https://doi.org/10.5194/tc-8-1539-2014
Altimetry	Khan, S. A., Kjær, K. H., Bevis, M., Bamber, J. L., Wahr, J., Kjeldsen, K. K., Bjørk, A. A., Korsgaard, N. J., Stearns, L. A., Van Den Broeke, M. R., Liu, L., Larsen, N. K., & Muresan, I. S. (2014). Sustained mass loss of the northeast Greenland ice sheet triggered by regional warming. *Nature Climate Change*, *4*(4), 292–299. https://doi.org/10.1038/nclimate2161
Altimetry	McMillan, M., Leeson, A., Shepherd, A., Briggs, K., Armitage, T. W. K., Hogg, A., Kuipers Munneke, P., Van Den Broeke, M., Noël, B., Van De Berg, W. J., Ligtenberg, S., Horwath, M., Groh, A., Muir,

Technique	Data source
	A., & Gilbert, L. (2016). A high-resolution record of Greenland mass balance. *Geophysical Research Letters*, *43*(13), 7002–7010. https://doi.org/10.1002/2016GL069666
Altimetry	Nilsson, J., Gardner, A., Sandberg Sørensen, L., & Forsberg, R. (2016). Improved retrieval of land ice topography from CryoSat-2 data and its impact for volume-change estimation of the Greenland Ice Sheet. *The Cryosphere*, *10*(6), 2953–2969. https://doi.org/10.5194/tc-10-2953-2016
Altimetry	Schröder, L., Horwath, M., Dietrich, R., Helm, V., Van Den Broeke, M. R., & Ligtenberg, S. R. M. (2019). Four decades of Antarctic surface elevation changes from multi-mission satellite altimetry. *The Cryosphere*, *13*(2), 427–449. https://doi.org/10.5194/tc-13-427-2019
Altimetry	Shepherd, A., Gilbert, L., Muir, A. S., Konrad, H., McMillan, M., Slater, T., Briggs, K. H., Sundal, A. V., Hogg, A. E., & Engdahl, M. E. (2019). Trends in Antarctic ice sheet elevation and mass. *Geophysical Research Letters*, *46*(14), 8174–8183. https://doi.org/10.1029/2019GL082182
Altimetry	Sørensen, L. S., Simonsen, S. B., Nielsen, K., Lucas-Picher, P., Spada, G., Adalgeirsdottir, G., Forsberg, R., & Hvidberg, C. S. (2011). Mass balance of the Greenland ice sheet (2003–2008) from ICESat data—the impact of interpolation, sampling and firn density. *The Cryosphere*, *5*(1), 173–186. https://doi.org/10.5194/tc-5-173-2011
Altimetry	Zwally, H. J., Li, J., Robbins, J. W., Saba, J. L., Yi, D., & Brenner, A. C. (2015). Mass gains of the Antarctic ice sheet exceed losses. *Journal of Glaciology*, *61*(230), 1019–1036. https://doi.org/10.3189/2015JoG15J071
Gravimetry	Andrews, S. B., Moore, P., & King, M. A. (2014). Mass change from GRACE: a simulated comparison of Level-1B analysis techniques. *Geophysical Journal International*, *200*(1), 503–518. https://doi.org/10.1093/gji/ggu402
Gravimetry	Blazquez, A., Meyssignac, B., Lemoine, J., Berthier, E., Ribes, A., & Cazenave, A. (2018). Exploring the uncertainty in GRACE estimates of the mass redistributions at the Earth surface: Implications for the global water and sea level budgets. *Geophysical Journal International*, *215*(1), 415–430. https://doi.org/10.1093/gji/ggy293
Gravimetry	Bonin, J., & Chambers, D. (2013). Uncertainty estimates of a GRACE inversion modelling technique over Greenland using a simulation. *Geophysical Journal International*, *194*(1), 212–229. https://doi.org/10.1093/gji/ggt091
Gravimetry	Forsberg, R., Sørensen, L., & Simonsen, S. (2017). Greenland and Antarctica ice sheet mass changes and effects on global sea level. *Surveys in Geophysics*, *38*(1), 89–104. https://doi.org/10.1007/s10712-016-9398-7
Gravimetry	Gardner, A. S., Moholdt, G., Scambos, T., Fahnstock, M., Ligtenberg, S., Van Den Broeke, M., & Nilsson, J. (2018). Increased West Antarctic and unchanged East Antarctic ice discharge over the last 7 years. *The Cryosphere*, *12*(2), 521–547. https://doi.org/10.5194/tc-12-521-2018
Gravimetry	Groh, A., & Horwath, M. (2021). Antarctic ice mass change products from GRACE/GRACE-FO using tailored sensitivity kernels. *Remote Sensing*, *13*(9), 1736. https://doi.org/10.3390/rs13091736
Gravimetry	Harig, C., & Simons, F. J. (2012). Mapping Greenland's mass loss in space and time. *Proceedings of the National Academy of Sciences*, *109*(49), 19934–19937. https://doi.org/10.1073/pnas.1206785109
Gravimetry	Horvath, A. G. (2017). *Retrieving geophysical signals from current and future satellite missions* [Doctoral dissertation, Technical University of Munich].
Gravimetry	Luthcke, S. B., Sabaka, T. J., Loomis, B. D., Arendt, A. A., McCarthy, J. J., & Camp, J. (2013). Antarctica, Greenland and Gulf of Alaska land-ice evolution from an iterated GRACE global

Technique	Data source
	mascon solution. *Journal of Glaciology*, *59*(216), 613–631. https://doi.org/10.3189/2013JoG12J147
Gravimetry	Save, H., Bettadpur, S., & Tapley, B. D. (2016). High-resolution CSR GRACE RL05 mascons. *Journal of Geophysical Research: Solid Earth*, *121*(10), 7547–7569. https://doi.org/10.1002/2016JB013007
Gravimetry	Schrama, E. J. O., Wouters, B., & Rietbroek, R. (2014). A mascon approach to assess ice sheet and glacier mass balances and their uncertainties from GRACE data. *Journal of Geophysical Research: Solid Earth*, *119*(7), 6048–6066. https://doi.org/10.1002/2013JB010923
Gravimetry	Seo, K., Wilson, C. R., Scambos, T., Kim, B., Waliser, D. E., Tian, B., Kim, B., & Eom, J. (2015). Surface mass balance contributions to acceleration of Antarctic ice mass loss during 2003–2013. *Journal of Geophysical Research: Solid Earth*, *120*(5), 3617–3627. https://doi.org/10.1002/2014JB011755
Gravimetry	Velicogna, I., Sutterley, T. C., & Van Den Broeke, M. R. (2014). Regional acceleration in ice mass loss from Greenland and Antarctica using GRACE time-variable gravity data. *Geophysical Research Letters*, *41*(22), 8130–8137. https://doi.org/10.1002/2014GL061052
Gravimetry	Vishwakarma, B. D., Horwath, M., Devaraju, B., Groh, A., & Sneeuw, N. (2017). A data-driven approach for repairing the hydrological catchment signal damage due to filtering of GRACE products. *Water Resources Research*, *53*(11), 9824–9844. https://doi.org/10.1002/2017WR021150
Gravimetry	Wiese, D. N., Landerer, F. W., & Watkins, M. M. (2016). Quantifying and reducing leakage errors in the JPL RL05M GRACE mascon solution. *Water Resources Research*, *52*(9), 7490–7502. https://doi.org/10.1002/2016WR019344
Gravimetry	Wouters, B., Bamber, J. L., Van Den Broeke, M. R., Lenaerts, J. T. M., & Sasgen, I. (2013). Limits in detecting acceleration of ice sheet mass loss due to climate variability. *Nature Geoscience*, *6*(8), 613–616. https://doi.org/10.1038/ngeo1874
GIA	A, G., Wahr, J., & Zhong, S. (2013). Computations of the viscoelastic response of a 3-D compressible Earth to surface loading: An application to glacial isostatic adjustment in Antarctica and Canada. *Geophysical Journal International*, *192*(2), 557–572. https://doi.org/10.1093/gji/ggs030
GIA	Ivins, E. R., & James, T. S. (2005). Antarctic glacial isostatic adjustment: A new assessment. *Antarctic Science*, *17*(4), 541–553. https://doi.org/10.1017/S0954102005002968
GIA	Ivins, E. R., James, T. S., Wahr, J., O. Schrama, E. J., Landerer, F. W., & Simon, K. M. (2013). Antarctic contribution to sea level rise observed by GRACE with improved GIA correction. *Journal of Geophysical Research: Solid Earth*, *118*(6), 3126–3141. https://doi.org/10.1002/jgrb.50208
GIA	Khan, S. A., Sasgen, I., Bevis, M., Van Dam, T., Bamber, J. L., Wahr, J., Willis, M., Kjær, K. H., Wouters, B., Helm, V., Csatho, B., Fleming, K., Bjørk, A. A., Aschwanden, A., Knudsen, P., & Munneke, P. K. (2016). Geodetic measurements reveal similarities between post–Last Glacial Maximum and present-day mass loss from the Greenland ice sheet. *Science Advances*, *2*(9), e1600931. https://doi.org/10.1126/sciadv.1600931
GIA	Paulson, A., Zhong, S., & Wahr, J. (2007). Inference of mantle viscosity from GRACE and relative sea level data. *Geophysical Journal International*, *171*(2), 497–508. https://doi.org/10.1111/j.1365-246X.2007.03556.x
GIA	Peltier, W. R. (2004). Global glacial isostasy and the surface of the ice-age Earth: The ICE-5G (VM2) model and GRACE. *Annual Review of Earth and Planetary Sciences*, *32*(1), 111–149. https://doi.org/10.1146/annurev.earth.32.082503.144359

Technique	Data source
GIA	Peltier, W. R., Argus, D. F., & Drummond, R. (2015). Space geodesy constrains ice age terminal deglaciation: The global ICE-6G_C (VM5a) model. *Journal of Geophysical Research: Solid Earth*, *120*(1), 450–487. https://doi.org/10.1002/2014JB011176
GIA	Schrama, E. J. O., Wouters, B., & Rietbroek, R. (2014). A mascon approach to assess ice sheet and glacier mass balances and their uncertainties from GRACE data. *Journal of Geophysical Research: Solid Earth*, *119*(7), 6048–6066. https://doi.org/10.1002/2013JB010923
GIA	Simpson, M. J. R., Milne, G. A., Huybrechts, P., & Long, A. J. (2009). Calibrating a glaciological model of the Greenland ice sheet from the Last Glacial Maximum to present-day using field observations of relative sea level and ice extent. *Quaternary Science Reviews*, *28*(17–18), 1631–1657. https://doi.org/10.1016/j.quascirev.2009.03.004
GIA	Whitehouse, P. L., Bentley, M. J., Milne, G. A., King, M. A., & Thomas, I. D. (2012). A new glacial isostatic adjustment model for Antarctica: Calibrated and tested using observations of relative sea-level change and present-day uplift rates. *Geophysical Journal International*, *190*(3), 1464–1482. https://doi.org/10.1111/j.1365-246X.2012.05557.x
SMB	Fettweis, X., Franco, B., Tedesco, M., Van Angelen, J. H., Lenaerts, J. T. M., Van Den Broeke, M. R., & Gallée, H. (2013). Estimating the Greenland ice sheet surface mass balance contribution to future sea level rise using the regional atmospheric climate model MAR. *The Cryosphere*, *7*(2), 469–489. https://doi.org/10.5194/tc-7-469-2013
SMB	Van Wessem, J. M., Reijmer, C. H., Morlighem, M., Mouginot, J., Rignot, E., Medley, B., Joughin, I., Wouters, B., Depoorter, M. A., Bamber, J. L., Lenaerts, J. T. M., Van De Berg, W. J., Van Den Broeke, M. R., & Van Meijgaard, E. (2014). Improved representation of East Antarctic surface mass balance in a regional atmospheric climate model. *Journal of Glaciology*, *60*(222), 761–770. https://doi.org/10.3189/2014JoG14J051

Table TD-2. Satellite Data Sets, GIA Models, and SMB Models

Technique or area	Satellite mission or model	Operational years
IOM	ERS-1	1992–1996
IOM	ERS-2	1996–2012
IOM	RADARSAT-1	2000–2008
IOM	ENVISAT	2003–2012
IOM	ALOS/PALSAR	2006–2011
IOM	RADARSAT-2	2007–2016
IOM	TerraSAR-X	2008–2019
IOM	COSMO-SkyMed	2008–2019
IOM	Landsat-8	2013–2019
IOM	Sentinel-1	2013–2019
Altimetry	ERS-1	1992–1996
Altimetry	ERS-2	1995–2011
Altimetry	ENVISAT	2003–2012
Altimetry	ICESat	2003–2009
Altimetry	CryoSat-2	2011–2018

Technique or area	Satellite mission or model	Operational years
Gravimetry	GRACE	2003–2016
Gravimetry	GRACE-FO	2018–2020
GIA: Antarctica	A13	2004–2014
GIA: Antarctica	A13 and W12a	2003–2018
GIA: Antarctica	ICE-5G and W12a	2003–2019
GIA: Antarctica	IC-6G	2003–2018
GIA: Antarctica	ICE-6G and A13	2003–2019
GIA: Antarctica	ICE-6G and IJ05_R2	2003–2020
GIA: Antarctica	IJ05 and W12a	2004–2014
GIA: Antarctica	IJ05_R2	1992–2009
GIA: Antarctica	IJ05_R2 and A13	2003–2019
GIA: Antarctica	IJ05_R2 and Paulson07	2004–2014
GIA: Antarctica	IJ05_R2 and Simpson09	2003–2018
GIA: Antarctica	IJ05_R2 and W12a	1992–2017
GIA: Antarctica	Khan_2016 and W12a	2012–2017
GIA: Antarctica	Schrama14	2004–2015
GIA: Antarctica	W12a	2004–2013
GIA: Greenland	A13	2003–2019
GIA: Greenland	ICE-5G	2003–2019
GIA: Greenland	ICE-6G	2003–2020
GIA: Greenland	ICE-5G and ICE-6G	2003–2019
GIA: Greenland	ICE-6G and A13	2003–2019
GIA: Greenland	Paulson07	2003–2016
GIA: Greenland	Schrama14	2003–2016
GIA: Greenland	Simpson09	2003–2018
SMB: Antarctica	RACMO 2.3	1992–2019
SMB: Greenland	MAR 3.2	1992–2019
SMB: Greenland	MAR 3.5.2	1996–2019
SMB: Greenland	RACMO 2.3	2007–2011

NASA JPL Data

The NASA JPL time series in Figure 1 of this indicator represents one widely cited approach for interpreting measurements from the GRACE satellite mission. The GRACE mission consists of a pair of identical satellites that fly about 137 miles apart in a polar orbit around the Earth—one leading and one trailing. These satellites measure relatively small variations in the Earth's gravitational field, such as variations related to the mass of ice that has accumulated on top of the Earth's crust and the amount of water stored on land or underground (e.g., the amount of water in an aquifer). The satellites detect these variations by using GPS and a microwave system to continually measure the exact distance between the satellites. The Earth's gravitational pull affects this distance; for example, when the leading satellite reaches an area of slightly stronger gravity due to a relatively high concentration of mass (such as a thick ice sheet), gravity pulls the leading satellite slightly away from the trailing satellite. This method can be used to measure accumulations of ice that rest on the Earth's crust—i.e., land-based ice sheets—but not floating ice shelves or sea ice, which simply displace an equivalent mass of liquid ocean water.

The original GRACE satellites were launched in March 2002 and collected data until 2017. The GRACE-FO mission was launched in 2018 with two new satellites performing the same type of measurement. For more information about the satellites and their measurement equipment, visit: www.nasa.gov/missions/grace-fo.

6. Indicator Derivation

IMBIE Data

The IMBIE team took the 27 cumulative mass change time series for Greenland and the 23 time series for Antarctica and combined them into a reconciled time series of rate of mass change for each ice sheet.

Greenland and Antarctica reflect the use of similar aggregation techniques. IMBIE converted individual estimates of mass balance from cumulative mass trends to rates of mass change. They then averaged the monthly rates of mass change over a year-long period to reduce the impact of seasonality. Next, they combined the individual time series for each measurement technique (gravimetry, altimetry, and IOM), which resulted in one combined time series for each of the three techniques. This was done with an error-weighted average approach for Greenland and Antarctica. Another error-weighted averaging step was used to combine all three techniques and derive an aggregate estimate of annual cumulative mass change. For Antarctica, IMBIE calculated separate results for each major section of the ice sheet—East Antarctica, West Antarctica, and the Antarctic Peninsula—because each of these regions has unique climatic and geological characteristics. The three Antarctic regions have been combined for the estimate shown in Figure 1 of this indicator.

Prior to averaging, all gravimetric and altimetric estimates were corrected for GIA. This correction is made because the Earth's crust adjusts upward or downward in response to changes in the mass of ice or water on top of it. In the case of gravimetry, this means the gravitational signal from GIA is commingled with the gravitational signal from changes in ice mass, and it must be removed from the equation to isolate only the change in ice mass. Altimetry requires an analogous adjustment. Estimates of GIA vary, so IMBIE's methods considered multiple estimates (see Tables TD-1 and TD-2).

For more detail about indicator derivation methods, see Otosaka et al. (2023). To enable comparison with NASA JPL data in Figure 1, EPA shifted each IMBIE time series to use the same reference point—that is, setting the year 2002 to zero.

NASA JPL Data

Multiple organizations have developed methods to process raw data from GRACE. This indicator uses a method developed and refined by JPL, which was chosen for this indicator because it has been established in the peer-reviewed scientific literature and federal government climate science reports. NASA currently uses it as the source for its "Vital Signs" indicator on land-based ice (https://climate.nasa.gov/vital-signs/ice-sheets).

JPL's approach divides the Earth's surface into an 0.5-degree by 0.5-degree grid and uses a spherical cap mascon (mass concentration element) approach to characterize monthly variations in gravitational fields within each grid cell. These methods are described in more detail at: https://grace.jpl.nasa.gov/data/get-data/jpl_global_mascons and documented by Watkins et al. (2015). The data have been corrected for GIA using methods described by Peltier et al. (2018).

For this indicator, JPL combined monthly data across all the grid cells for Greenland and Antarctica to develop an aggregated monthly time series showing monthly change in mass relative to the first measurement in 2002, which is set to zero as a point of reference. Thus, the lines in Figure 1 show the cumulative change in mass over time. Each year has seven to 12 data points plotted as decimal values (e.g., 2002.5 would be exactly halfway through the year). Figure 1 shows a gap in the JPL time series from mid-2017 to mid-2018, representing the gap between the GRACE and GRACE-FO missions.

7. Quality Assurance and Quality Control

Data validation and quality assurance and quality control procedures for IMBIE's source data are documented in the individual articles cited in Section 5. Otosaka et al. (2023) describe quality assurance considerations that the team used when selecting data sources for inclusion, quantifying uncertainties, and correcting for GIA. Each satellite has an accelerometer to measure non-gravitational accelerations such as atmospheric drag, so these non-gravitational influences can be removed from the results.

Watkins et al. (2015) describe steps taken to validate NASA JPL's mascon methodology. Quality assurance and quality control procedures have been implemented throughout the stages of data collection and data processing, as described at: https://grace.jpl.nasa.gov/data/get-data/jpl_global_mascons and other sources cited therein.

Analysis

8. Comparability Over Time and Space

IMBIE Data

The IMBIE analysis is based on data sets that are collected consistently over space. That is, the satellites cover the entirety of each ice sheet, with polar orbits that ensure spatial gaps are as minimal as possible. However, IMBIE does contain data sets that cover differing time spans and with differing levels of temporal resolution. Steps have been taken to quantify and account for these differences.

Greenland

For the period when all three techniques were in operation (2003 to 2018), changes in ice sheet mass balance determined from the three techniques are in good agreement at an annual resolution. During these years, the standard deviation is 19 gigatonnes (Gt) per year and the reconciled rate of mass loss from all three techniques is 221 ± 22 Gt/year.

Antarctica

The IMBIE team assessed the degree to which the satellite techniques concur. To do so, they computed changes in ice sheet mass balance within common geographical regions and over a common interval of time, using the aggregated time series from each technique. The maximum duration of the overlap period was limited to the 17-year interval (2002–2019) when all three techniques were optimally operational. The reconciled rate of mass loss between 2003 and 2019 is 115 ± 24 Gt/year, with a standard deviation of 79 Gt/year for all three techniques. As the size of the region increases, so does the spread of estimates of ice sheet mass balance. East Antarctica, West Antarctica, and the Antarctic Peninsula have standard deviations of 54, 18, and 16 Gt/year respectively. At an annual resolution, the gravimetry and IOM time series are well correlated for West Antarctica and the Antarctic Peninsula. However, the altimetry mass balance time series is poorly correlated with the aggregated gravimetry and IOM data for East Antarctica and the Antarctic Peninsula. The IMBIE team has identified possible explanations for this phenomenon (Otosaka et al., 2023).

The comparison period is long in relation to the timescales over which surface mass balance fluctuations typically occur, so their potential effect on the overall inter-comparison is reduced. The IMBIE team reports that, "Overall, [they] find that the vast majority of individual estimates of annual rates of mass balance included in this study fall within the uncertainty bounds of [the] reconciled estimate, given their respective individual errors, with 96%, 83%, 83%, 76%, and 8% of those annual rates of mass change falling within the reconciled uncertainty range at GrIS, AIS, APIS, EAIS, and WAIS, respectively" (Otosaka et al., 2023).

NASA JPL Data

This indicator reflects consistent data collection and analytical methods over the entire timeframe from 2002 to present. Data were collected by the same types of satellite instruments throughout the period of record, with orbits that cover the entire Earth's surface. As processing methods have been developed and improved over time, these methods have been applied to all prior years of raw data. JPL's current approach includes a time correlation adjustment; it means that each new month of data also requires slight revisions to previous months' gravity estimates. Therefore, each time JPL adds a month to the published time series, they also revise all prior months as needed. See: https://grace.jpl.nasa.gov/data/get-data/jpl_global_mascons for more information about these adjustments to preserve comparability.

9. Data Limitations

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

1. This indicator does not provide data prior to 1992. Unlike the small glaciers in EPA's Glaciers indicator, the vast ice sheets of Greenland and Antarctica do not have enough *in situ* measurements over time and space to generate reliable estimates of changes in their overall mass balance. Therefore, it is necessary to use remote sensing data from satellites to measure changes in the total amount of ice stored in these ice sheets, unless one attempts to infer ice mass change based on observed sea level change.

2. The first pair of GRACE satellites ran from 2002 to 2017, greatly exceeding the five-year lifespan for which they were designed. Accordingly, NASA had to turn off the instruments at certain times to preserve limited battery life. These power conservation measures and other occasional instrument issues have led to some months with insufficient data for analysis. For a detailed accounting of missing days and months, see: https://grace.jpl.nasa.gov/data/grace_months. Nonetheless, NASA managed battery power strategically to allow enough data to be collected to continue to provide valid data for most of the months of the year until the GRACE-FO replacement mission could be launched (2018).

3. This indicator does not report on the total mass of ice present on Greenland or Antarctica, or on percentage change relative to the total ice mass. It is only able to report on the absolute change in mass compared with the base year of 1992. It also does not report on changes in the surface area of ice present.

10. Sources of Uncertainty

IMBIE Data

The IMBIE team compiled uncertainty estimates from each data source, then combined these estimates to calculate the uncertainty for each technique (gravimetry, altimetry, and IOM) and for the aggregate time series as a whole. IMBIE calculated cumulative uncertainties as the root sum square of annual errors. Overall one-sigma uncertainty estimates for IMBIE data are shown as error bars in Figure 1.

NASA JPL Data

Measurements made by any instrument can have an inherent uncertainty, although the measurement error for the GRACE instruments is relatively small. The methods used to process the data can also introduce errors, including “leakage” errors at the coastal boundary (i.e., grid cells that contain part land and part ocean) and additional leakage errors when resolving gravitational measurements into discrete mascons. The GIA correction introduces some uncertainty, particularly for the interior of East Antarctica, where less is known about some of the factors that influence GIA than in parts of the world that are more accessible for study (Martín-Español et al., 2016). Research is necessary to more fully understand the effects of GIA in Antarctic ice mass estimates.

Each monthly data point in the data set obtained from NASA at: https://climate.nasa.gov/vital-signs/land-ice has a corresponding one-sigma uncertainty estimate. JPL calculated these uncertainties using measurement errors provided in the JPL RL06.1Mv3 Mascon Solution (https://podaac.jpl.nasa.gov/dataset/TELLUS_GRAC-GRFO_MASCON_CRI_GRID_RL06.1_V3) and correcting for leakage errors as described by Wiese et al. (2016) for Antarctica and by Wiese et al. (2016) and Schlegel et al. (2016) for Greenland.

11. Sources of Variability

Ice sheet mass balance naturally fluctuates with seasonal variations in temperature, precipitation, and other climate factors. The approximately monthly observations in the NASA JPL reference lines in Figure 1 show these intra-annual variations, particularly for Greenland, where the graph clearly shows a repeating pattern of net accumulation in the colder months and net loss of ice in the warmer months.

These seasonal signals have been smoothed out of the IMBIE time series, so it is helpful to see the NASA JPL reference lines in Figure 1 to get a sense of the seasonal fluctuations inherent in these data.

Ice sheets can also be influenced by broader interannual variations in temperature, precipitation, and other factors. However, the availability of more than a decade of data allows this indicator to show overall trends that exceed both seasonal and interannual variability.

12. Statistical/Trend Analysis

IMBIE Data

The IMBIE team has reported the following results for 1992–2020 for Greenland and Antarctica (including one-sigma errors):

- Greenland: total loss of 4,892 ± 457 Gt of ice (Otosaka et al., 2023)
    - Average rate of loss: -169 ± 16 Gt/year (Otosaka et al., 2023)
- Antarctica: total loss of 2,671 ± 530 Gt of ice (Otosaka et al., 2023)
    - Average rate of loss: -92 ± 18 Gt/year (Otosaka et al., 2023)

IMBIE cautions against assuming a linear trend over the entire period of record, given that annual mass change has varied over time for both ice sheets and both show signs of accelerating ice loss. For a crude point of reference only, EPA has computed ordinary least-squares linear trends of -176.3 Gt/year for Greenland and -91.4 Gt/year for Antarctica based on IMBIE's most recent aggregate time series—the time series shown in Figure 1. Both of these trends are highly significant ($p < 0.0001$).

For a simple comparison with the NASA JPL trends (see below), EPA calculated the following least-squares linear trends from IMBIE data for 2002–2020 (both trends highly significant [$p < 0.0001$]):

- Greenland: -237.8 Gt/year
- Antarctica: -129.3 Gt/year

NASA JPL Data

NASA JPL has analyzed the data and reported the following trends for the period from April 2002 to November 2023:

- Greenland: -269.09 ± 21 Gt/year
- Antarctica: -141.59 ± 39 Gt/year

The errors listed here are one-sigma errors based on propagating monthly uncertainties into the trend and assuming uncorrelated observations—i.e., not adjusted for serial correlation. NASA has also incorporated uncertainty associated with GIA, per methods described by Velicogna and Wahr (2013).

EPA tested the data in this indicator by ordinary least-squares linear regression and found similar slopes (-269.0 and -137.7 Gt/year, respectively, through November 2023). Both trends are highly significant ($p < 0.0001$). These trends are likely higher than the trends reported above for IMBIE data because they only cover the more recent portion of the timeframe in Figure 1—a period of apparent acceleration in the rate of mass loss from both ice sheets.

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