Ice sheets

Global Warming Science, EPS101

Wanying Kang and Eli Tziperman

https://courses.seas.harvard.edu/climate/eli/Courses/EPS101/
There is very high confidence that glaciers world-wide are persistently shrinking as revealed by the time series of measured changes in glacier length, area, volume and mass (Figures TS.1 and TS.3). The few exceptions are regionally and temporally limited. Measurements of glacier change have increased substantially in number since AR4. Most of the new data sets, along with a globally complete glacier inventory, have been derived from satellite remote sensing.

There is very high confidence that, during the last decade, the largest contributions to global glacier ice loss were from glaciers in Alaska, the Canadian Arctic, the periphery of the Greenland ice sheet, the Southern Andes and the Asian mountains. Together these areas account for more than 80% of the total ice loss. Total mass loss from all glaciers in the world, excluding those on the periphery of the ice sheets, was very likely 226 [91 to 361] Gt yr\(^{-1}\) (sea level equivalent, 0.62 [0.25 to 0.99] mm yr\(^{-1}\)) in the period 1971–2009, 275 [140 to 410] Gt yr\(^{-1}\) (0.76 [0.39 to 1.13] mm yr\(^{-1}\)) in the period 1993–2009 and 301 [166 to 436] Gt yr\(^{-1}\) (0.83 [0.46 to 1.20] mm yr\(^{-1}\)) between 2005 and 2009. There is high confidence that current glacier extents are out of balance with current climatic conditions, indicating that glaciers will continue to shrink in the future even without further temperature increase.

There is very high confidence that the Greenland ice sheet has lost ice during the last two decades. Combinations of satellite and airborne remote sensing together with field data indicate with high confidence that the ice loss has occurred in several sectors and that large rates of mass loss have spread to wider regions than reported in AR4 (Figure TS.3). There is high confidence that the mass loss of the Greenland ice sheet has accelerated since 1992: the average rate has very likely increased from 34 [–6 to 74] Gt yr\(^{-1}\) over the period 1992–2001 (sea level equivalent, 0.09 [–0.02 to 0.20] mm yr\(^{-1}\)) to 215 [157 to 274] Gt yr\(^{-1}\) (0.59 [0.43 to 0.76] mm yr\(^{-1}\)) between 2005 and 2009.

Figure TS.3 | (Upper) Distribution of ice loss from Gravity Recovery and Climate Experiment (GRACE) time-variable gravity for (a) Antarctica and (b) Greenland, shown in cm of water per year for the period 2003–2012. (Lower) The assessment of the total loss of ice from glaciers and ice sheets in terms of mass (Gt) and sea level equivalent (mm). The contribution from glaciers excludes those on the periphery of the ice sheets.
Figure 4.17 | Rate of ice sheet loss in sea level equivalent averaged over 5-year periods between 1992 and 2011. These estimates are derived from the data in Figures 4.15 and 4.16.
Antarctic ice mass loss observations

GRACE Observations of Antarctic Ice Mass Changes

ice content: 30 million km³
~ 58 m sea level rise

Antarctic ice mass loss observations

GRACE Observations of Antarctic Ice Mass Changes

- Average Mass Loss: 125 Gigatons/year
- Sep 2002: 149
- Aug 2015: -1934

ice content: 30 million km³
~ 58 m sea level rise

The twin GRACE-FO satellites follow each other in orbit around the Earth, separated by about 220 km.

https://grace.jpl.nasa.gov/mission/grace-fo/
Greenland ice loss observations

ice content: 2.85 million km$^3$
~ 7.2m sea level rise

GRACE Observations of Greenland Ice Mass Changes

https://gracefo.jpl.nasa.gov/resources/33/greenland-ice-loss-2002-2016/
Greenland ice loss observations

ice content: 2.85 million km³
~ 7.2m sea level rise

GRACE Observations of Greenland Ice Mass Changes

Average Mass Loss: 281 Gigatons/year

https://gracefo.jpl.nasa.gov/resources/33/greenland-ice-loss-2002-2016/
Greenland Calving event, “Chasing ice” film

https://www.youtube.com/watch?v=hC3VTgIPoGU
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https://www.youtube.com/watch?v=hC3VTglPoGU
workshop #1: Observations and projections
Surface mass balance versus temperature.

Schematic of accumulation (blue), surface ablation (red), and net surface mass balance (green) as a function of surface atmospheric temperature. After Oerleman 1992.
Notes section 10.3: observed trends and projections
Both Greenland and Antarctica show mass loss, although it is not clear to what degree this is due to natural variability, and the prediction for Antarctica suggests mass gain, at least via SMB, in the next few decades.
RCP8.5 projections of surface mass balance changes over Greenland & Antarctica. (a) net SMB change from 1920 to 2100, cm/yr, averaged over 30 model ensemble members. calculated as change in snow accumulation minus in sublimation rate. blue shades: a gain in SMB. (b) Same, for Greenland. (c) blue line: time series of net SMB for AIS, Gt/yr, avg over 30 members. light-blue shading: 1 std over members. red line & shading: sublimation. (d) Same, for Greenland.
Notes section 10.2
Physical processes determining the ice mass balance
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Physical processes determining the ice mass balance

- Accumulation
- Ablation:
  - Albedo
  - Surface melting
  - Calving
  - Ice flow
  - Basal hydrology

Box 5.2, Figure 1 | Schematic illustration of multiple interactions between ice sheets, solid earth and the climate system which can drive internal variability and affect the coupled ice sheet-climate response to external forcings on time scales of months to millions of years. The inlay figure represents a typical height profile of atmospheric temperature and moisture in the troposphere.
The accumulation zone and ablation zone are separated by the Equilibrium Line Altitude (ELA), or so-called firn line (Firn is old snow).

[left: from lecture slides of ATMS 514 in UW; right: snowballearth.org]
Accumulation

Snow accumulation rate depends on elevation

https://tc.copernicus.org/articles/13/943/2019/

Figure 3(a) Comparison between CloudSat (blue dots with 2σ standard deviation bars) and MRR (red solid line with shaded area representing a 95% confidence interval) for the 17 February 2016 precipitation event at the DDU station. (b) Same as panel (a) for the 20 March 2016 event at the DDU station.
Accumulation

Snow accumulation rate depends on elevation

https://tc.copernicus.org/articles/13/943/2019/

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Below snow line, rain instead of snow
Accumulation

Snow accumulation rate depends on elevation

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**Figure 3(a)** Comparison between CloudSat (blue dots with 2σ standard deviation bars) and MRR (red solid line with shaded area representing a 95% confidence interval) for the 17 February 2016 precipitation event at the DDU station. **(b)** Same as panel **(a)** for the 20 March 2016 event at the DDU station.
Accumulation

Snow accumulation rate depends on elevation

Maximum snow accumulation occurs at intermediate heights

Below snow line, rain instead of snow

Figure 3(a) Comparison between CloudSat (blue dots with 2σ standard deviation bars) and MRR (red solid line with shaded area representing a 95% confidence interval) for the 17 February 2016 precipitation event at the DDU station. (b) Same as panel (a) for the 20 March 2016 event at the DDU station.

https://tc.copernicus.org/articles/13/943/2019/
Accumulation temperature-precipitation feedback

Figure 3. Temperature history according to calibrated isotope curve, corrected for elevation changes. The data have been smoothed with a 250-year triangular filter so that the effect of different elevation corrections, corresponding to different marginal retreat distances, can be seen.

Figure 5. Accumulation rate histories for different marginal retreat distances.

higher accumulation rate in warmer climates
Accumulation

temperature-precipitation feedback

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higher accumulation rate in warmer climates
Ablation, ice flow
Antarctic ice streams

Ablation, ice flow
Antarctic ice streams

Ablation, ice flow
Greenland ice streams

NASA video: https://www.youtube.com/watch?v=GDXq8Oa5d5Q
Ablation, ice flow

Greenland ice streams

NASA video: https://www.youtube.com/watch?v=GDXq8Oa5d5Q
workshop 2: Ice stream acceleration
Ablation
Surface melting/ sublimation/ positive degree days

Melting and sublimation occur mostly during summer, when the surface air temperature is higher than the melting temperature.

The positive degree day empirical fit to surface melting provides a simple way to estimate total melting over a year:

Melting (m/year) = (factor) x (sum of daily mean surface air temperatures above 0, over one year)

\[ PDD = \sum_{i} (T_i - T_m) \mathcal{H}(T_i - T_m) \]

Sum over all days in a year
Temperature at day \( i \)
Melting temperature
Heaviside function \([\mathcal{H}(x)=0 \text{ for } x<0, \text{ 1 otherwise}]\)

Example: daily temperatures=[-5, 2, 4] \( \Rightarrow \) PDD=6
Observations: Cryosphere

Key variable related to the determination of the Greenland ice sheet mass changes. (a) Mean surface mass balance for 1989–2004 from regional atmospheric climate models (see Glossary) verified using re-analysis data (see Glossary) (Hanna et al., 2011), or interpolation of independent Regional atmospheric climate models (see Glossary) (Ettema et al., 2009). (b) Ice sheet velocity for 2007–2009 determined from satellite data, showing fastest flow in red, fast flow in blue and slower flow in green and yellow (Rignot and Mouginot, 2012). (c) Changes in ice sheet surface elevation for 2003–2008 determined from ICESat altimetry, with elevation decrease in red to increase in blue (Pritchard et al., 2009). (d) Temporal evolution of ice loss determined from GRACE time-variable gravity, shown in cm of water per year for 2003–2012, color coded red (loss) to blue (gain) (Velicogna, 2009).

Figure 4.13 | Key variable related to the determination of the Greenland ice sheet mass changes. (c) Changes in ice sheet surface elevation for 2003–2008 determined from ICESat altimetry, with elevation decrease in red to increase in blue (Pritchard et al., 2009). (d) Temporal evolution of ice loss determined from GRACE time-variable gravity, shown in cm of water per year for 2003–2012, color coded red (loss) to blue (gain) (Velicogna, 2009).
Repeated altimetric survey allows measurement of rates of sur
(107 Gt (Ettema et al., 2009). The 17% uncertainty is based on a comparison of
the mass budget method.

(b) 2003–2006 and (c) 2006–2012, colour coded red (loss) to blue (gain) (Velicogna, 2009). Fields shown in (a) and (b) are used together with ice thickness (see Figure 4.18) in
Figure 4.14.

Key fields relating to the determination of Antarctica ice sheet mass changes. (c) Changes in ice sheet surface elevation for 2003–2008 determined from ICESat altimetry, with elevation decrease in red to increase in blue (Pritchard et al., 2009). (d) Temporal evolution of ice loss determined from GRACE time-variable gravity, shown in cm of water per year for 2003–2012, color coded red (loss) to blue (gain) (Velicogna, 2009).

Figure 4.14 | Key fields relating to the determination of Antarctica ice sheet mass changes. (c) Changes in ice sheet surface elevation for 2003–2008 determined from ICESat altimetry, with elevation decrease in red to increase in blue (Pritchard et al., 2009). (d) Temporal evolution of ice loss determined from GRACE time-variable gravity, shown in cm of water per year for 2003–2012, color coded red (loss) to blue (gain) (Velicogna, 2009).
workshop 3:
Positive Degree Days
Information from Paleoclimate Archives

Chapter 5

Box 5.2, Figure 1 | Schematic illustration of multiple interactions between ice sheets, solid earth and the climate system which can drive internal variability and affect the coupled ice sheet–climate response to external forcings on time scales of months to millions of years. The inlay figure represents a typical height profile of atmospheric temperature and moisture in the troposphere.

Moisture
Temperature
Height

subglacial lakes
geothermal heat
ice shelf
iceberg
sea-ice
calving
atmosphere-ice sheet interaction
ocean-atmosphere interaction
ocean

stationary wave feedback

albedo
land-ice sheet interaction
dust
ablation zone
moulins
snow
accumulation
dust

10^3–10^5 years

1–10^3 years

soot
fire

IPCC AR5 2013

Albedo
Physical processes determining mass balance
The surface temperature is largely controlled by the **albedo** (the surface reflectivity of sunlight).

**Positive melting-albedo feedback:** The low albedo of melting ponds leads to more sunlight absorption, higher surface temperature, and enhanced melting.

**Biological albedo feedback:** Algae in melting ponds can further darken the ice and reduce the albedo. Remote forest fires result in soot over the ice and albedo change.
Ablation

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5.3.3 Last Glacial Maximum and Equilibrium Climate Sensitivity

The LGM is characterized by a large temperature response (Section 5.3.3.1) to relatively well-defined radiative perturbations (Section 5.2), linked to atmospheric CO$_2$ concentration around 200 ppm (Section 5.2.2) and large ice sheets covering northern Europe and North America. This can be used to evaluate climate models (Braconnot et al. (2012b); see Sections 9.7 and 10.8) and to estimate ECS from the combined use of proxy information and simulations (Section 5.3.3.2).

5.3.3.1 Last Glacial Maximum Climate

Since AR4, synthesis of proxy LGM temperature estimates was completed for SST (MARGO Project Members, 2009), and for land SAT (Bartlein et al., 2011) (Box 5.1, Figure 1). The Multiproxy Approach for the Reconstruction of the Glacial Ocean Surface (MARGO) SST synthesis expanded earlier work (CLIMAP Project Members, 1976, 1981; Sarnthein et al., 2003a; Sarnthein et al., 2003b) by using multiple proxies (Table 5.2). The land SAT synthesis is based on pollen data, following the Cooperative Holocene Mapping Project (COHMAP Members, 1988).

Climate models and proxy data consistently show that mean annual SST change (relative to pre-industrial) is largest in the mid-latitude North Atlantic (up to –10ºC), and the Mediterranean (about –6ºC) (MARGO Project Members, 2009, Box 5.1, Table 5.2). Warming and seasonally ice-free conditions are reconstructed, however, in the north-eastern North Atlantic, in the eastern Nordic Seas and north Pacific, albeit with large uncertainty because of the different interpretation of proxy data (de Vernal et al., 2006). SAT reconstructions generally show year-round cooling, with regional exceptions such as Alaska (Bartlein et al., 2011). Modelling studies show how atmospheric dynamics influenced by ice sheets affect regional temperature patterns in the North.
Ablation: Calving
break-up of ice into ocean at edge of ice sheet

A giant piece of ice breaks off the Perito Moreno Glacier in Patagonia, Argentina

Stretching and compression create crevasses
Ablation
A Massive Glacier Calving in 2013

https://www.youtube.com/watch?v=1s5-lvHVDqq
Ablation
A Massive Glacier **Calving** in 2013

https://www.youtube.com/watch?v=1s5-IvHVDqq
break-up of ice into ocean at edge of ice sheet

basal & lateral drag stretch ice sheet, creating crevasses
Ablation: Calving

break-up of ice into ocean at edge of ice sheet

T1

zone of ice stretching

icefall crevasses open

steep slope gradient


T2

icefall crevasses transported to glacier margin

steep slope gradient

calving

lake

steep landscape also causes crevasses
Calving due to hydro-fracturing

Calving may start once the crevasses reach sea level, as buoyancy forces may overcome yield stress (Benn et al. 2007)

Fig. 12. Schematic illustration of first-order calving in response to longitudinal stretching. Surface crevasses propagate downward to a depth d in response to the velocity gradient $\partial U_B / \partial x$. Calving is assumed to occur when $d=h$ (after Benn et al., in press). Benn et al. 2007
From 31 January 2002 to March 2002 the **Larsen B sector** partially collapsed and parts broke up, 3,250 squared km of ice 220 m thick, an area comparable to the US state of Rhode Island.
Ablation

Calving due to hydro-fracturing: **Larsen B ice shelf**

From 31 January 2002 to March 2002 the **Larsen B sector** partially collapsed and parts broke up, 3,250 squared km of ice 220 m thick, an area comparable to the US state of Rhode Island.

Animation of MODIS data by Alex Forman

https://en.wikipedia-on-ipfs.org/wiki/List_of_Antarctic_and_sub-Antarctic_islands.html

https://commons.wikimedia.org/wiki/File:Antarctic-Peninsula-Ice-Shelves.png
Ablation

**Calving** due to melting at waterline


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T1

- High stress at crevasse tip
- Erosional notch forms
- Block tips forward
- Crevasse propagates
- Very high stress at crevasse tip
- Notch undercuts ice cliff

Ablation

Calving: role of buoyancy forces

A: Longitudinal extension

B: Melt-undercutting

C: Buoyant calving - ice foot

D: Buoyant calving - full thickness

Calving glaciers and ice shelves; Douglas I. Benn, Jan A. Åström, 2018

Figure 2. A selection of key calving styles: (a) rifting due to longitudinal extension, (b) collapse of overhang following undercutting by subaqueous melt, (c) buoyant calving: release of a protruding ‘ice foot’ below the waterline and (d) buoyant calving: uplift of a super-buoyant glacier tongue.
Notes section 10.2.3
Calving
workshop #4
Calving
Section 5.3.3.1: Last Glacial Maximum Climate

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notes section 10.2.4
Ice flow, MISI (use following slides)
Ice flow: Marine Ice Sheet Instability (MISI)

Snow Accumulation ($P$)

Bed ($b$)

Grounding line flux ($Q_g = cH^5$)

Ice transport is larger when the grounding line ice is thicker.

From Alex Robel
Marine Ice Sheet Instability (MISI) scenario (1): melting by a warmer ocean

Snow Accumulation (P)

Grounding line flux ($Q_g = cH^5$)

Bed ($b$)

From Alex Robel
Marine Ice Sheet Instability (MISI) scenario (1): melting by a warmer ocean

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Bed ($b$)

From Alex Robel

(Weertman 1974 and many others)
Marine Ice Sheet Instability (MISI) scenario (1): melting by a warmer ocean

Snow Accumulation (P)

From Alex Robel

Grounding line flux ($Q_g$)

Bed ($b$)

From Alex Robel

stable

unstable

stable

Possible Grounding Line Position

Accumulation
Grounding Line Flux

0 500 1000 1500

Grounding Line Position (km)

Flux

Global Warming Science 101: Ice sheets, Wanying Kang and Eli Tziperman
Marine Ice Sheet Instability (MISI) leading to ice retreat in Greenland

(dash red: previous estimate of topography; note large difference from previous topography)

Front position (year)

1930 1960 1990 2017

Potential Temperature (°C)

-0.5 1 3 5

Morgen N ice stream:
“Largest retreat on a retrograde slope after 1965, doubled its speed since 1990s”
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Moisture
Temperature
Height
Subglacial lakes
Geothermal heat flux
Ice shelf
Iceberg
Sea-ice
Calving
Ocean-atmosphere interaction
Ocean-ice sheet interaction
Atmosphere-ice sheet interaction
Land-ice sheet interaction
Ablation zone
Moulins
Soot
Dust
Fire
Ablation
zone
Stationary wave feedback
Bedrock adjustment
Subglacial lakes

5.3.3 Last Glacial Maximum and Equilibrium
Climate Sensitivity

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Ablation

Moulins and basal hydrology


Moulins transport water to base, can accelerate ice flow
Ablation
Moulins and basal hydrology

Moulins transport water to base, can accelerate ice flow

notes section 10.2.5
Basal hydrology
workshop #5
Basal hydrology
**Future Projections are highly uncertain**

FAQ 13.2, Figure 1 | Illustrative synthesis of projected changes in SMB and outflow by 2100 for (a) Greenland and (b) Antarctic ice sheets. Colours shown on the maps refer to projected SMB change between the start and end of the 21st century using the RACMO2 regional atmospheric climate model under future warming scenarios A1B (Antarctic) and RCP4.5 (Greenland). For Greenland, average equilibrium line locations during both these time periods are shown in purple and green, respectively. Ice-sheet margins and grounding lines are shown as black lines, as are ice-sheet sectors. For Greenland, results of flowline modelling for four major outlet glaciers are shown as inserts, while for Antarctica the coloured rings reflect projected change in outflow based on a probabilistic extrapolation of observed trends. The outer and inner radius of each ring indicate the upper and lower bounds of the two-thirds probability range of the contribution, respectively (scale in upper right); red refers to mass loss (sea level rise) while blue refers to mass gain (sea level fall). Finally, the sea level contribution is shown for each ice sheet (insert located above maps) with light grey referring to SMB (model experiment used to generate the SMB map is shown as a dashed line) and dark grey to outflow. All projections refer to the two-in-three probability range across all scenarios.
The End!