



Mass balance of the Greenland Ice Sheet from 1992 to 2018

Shepherd, Andrew; Ivins, Erik; Rignot, Eric; Smith, Ben; van den Broeke, Michiel; Velicogna, Isabella; Whitehouse, Pippa; Briggs, Kate; Joughin, Ian; Krinner, Gerhard

Total number of authors:
90

Published in:
Nature

Link to article, DOI:
[10.1038/s41586-019-1855-2](https://doi.org/10.1038/s41586-019-1855-2)

Publication date:
2020

Document Version
Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):
Shepherd, A., Ivins, E., Rignot, E., Smith, B., van den Broeke, M., Velicogna, I., Whitehouse, P., Briggs, K., Joughin, I., Krinner, G., Nowicki, S., Payne, T., Scambos, T., Schlegel, N., Geruo, A., Agosta, C., Ahlstrøm, A., Babonis, G., Barletta, V. R., ... Team, T. IMBIE. (2020). Mass balance of the Greenland Ice Sheet from 1992 to 2018. *Nature*, 579, 233-239. <https://doi.org/10.1038/s41586-019-1855-2>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

1 Mass balance of the Greenland Ice Sheet from 1992-2018

2 The IMBIE Team*

3 Abstract

4 **In recent decades the Greenland Ice Sheet has been a major contributor to global sea-level rise ^{1,2},
5 and it is expected to be so in the future ³. Although increases in glacier flow ⁴⁻⁶ and surface melting
6 ⁷⁻⁹ have been driven by oceanic ¹⁰⁻¹² and atmospheric ^{13,14} warming, the degree and trajectory of
7 today's imbalance remain uncertain. Here we compare and combine 26 individual satellite
8 measurements of changes in the ice sheet's volume, flow and gravitational potential to produce a
9 reconciled estimate of its mass balance. Although the ice sheet was close to a state of balance in
10 the 1990's, annual losses have risen since then, peaking at 335 ± 62 billion tonnes per year in 2011.
11 In all, Greenland lost 3800 ± 339 billion tonnes of ice between 1992 and 2018, causing mean sea-
12 level to rise by 10.6 ± 0.9 millimetres. Using three regional climate models, we show that reduced
13 surface mass balance has driven 1971 ± 555 billion tonnes (52 %) of the ice loss owing to increased
14 meltwater runoff. The remaining 1827 ± 538 billion tonnes (48 %) of ice loss was due to increased
15 glacier discharge, which rose from 41 ± 37 billion tonnes per year in the 1990's to 87 ± 25 billion
16 tonnes per year since then. Between 2013 and 2017, the total rate of ice loss slowed to 217 ± 32
17 billion tonnes per year, on average, as atmospheric circulation favoured cooler conditions ¹⁵ and as
18 ocean temperatures fell at the terminus of Jakobshavn Isbræ ¹⁶. Cumulative ice losses from
19 Greenland as a whole have been close to the IPCC's predicted rates for their high-end climate
20 warming scenario ¹⁷, which forecast an additional 70 to 130 millimetres of global sea-level rise by
21 2100 when compared to their central estimate.**

22 Introduction

23 The Greenland Ice Sheet holds enough water to raise mean global sea level by 7.4 m ¹⁸. Its ice flows
24 to the oceans through a network of glaciers and ice streams ¹⁹, each with a substantial inland
25 catchment ²⁰. Fluctuations in the mass of the Greenland Ice Sheet occur due to variations in snow
26 accumulation, meltwater runoff, ocean-driven melting, and iceberg calving. In recent decades, there
27 have been marked increases in air ²¹ and ocean ¹² temperatures and reductions in summer cloud
28 cover ²² around Greenland. These changes have produced increases in surface runoff ⁸, supraglacial
29 lake formation ²³ and drainage ²⁴, iceberg calving ²⁵, glacier terminus retreat ²⁶, submarine melting
30 ^{10,11}, and ice flow ⁶, leading to widespread changes in the ice sheet surface elevation, particularly
31 near its margin (Figure 1).

32 Over recent decades, ice losses from Greenland have made a significant contribution to global sea-
33 level rise ², and model projections suggest that this imbalance will continue in a warming climate ³.
34 Since the early 1990's there have been comprehensive satellite observations of changing ice sheet
35 velocity ^{4,6}, elevation ²⁷⁻²⁹ and, between 2002 and 2016, its changing gravitational attraction ^{30,31},
36 from which complete estimates of Greenland Ice Sheet mass balance are determined ¹. Prior to the
37 1990's, only partial surveys of the ice sheet elevation ³² and velocity ³³ change are available. In
38 combination with models of surface mass balance (the net difference between precipitation,
39 sublimation and meltwater runoff) and glacial isostatic adjustment ³⁴, satellite measurements have
40 shown a fivefold increase in the rate of ice loss from Greenland overall, rising from 51 ± 65 Gt/yr
41 in the early 1990's to 263 ± 30 Gt/yr between 2005 and 2010 ¹. This ice loss has been driven by changes
42 in surface mass balance ^{7,21} and ice dynamics ^{5,33}. There was, however, a marked reduction in ice loss
43 between 2013 and 2018, as a consequence of cooler atmospheric conditions and increased

44 precipitation¹⁵. While the broad pattern of change across Greenland (Figure 1) is one of ice loss,
45 there is considerable variability; for example, during the 2000's just 4 glaciers were responsible for
46 half of the total ice loss due to increased discharge⁵, whereas many others contribute today³³.
47 Moreover, some neighbouring ice streams have been observed to speed up over this period while
48 others slowed down³⁵, suggesting diverse reasons for the changes that have taken place - including
49 their geometrical configuration and basal conditions, as well as the forcing they have experienced³⁶.
50 In this study we combine satellite altimetry, gravimetry, and ice velocity measurements to produce a
51 reconciled estimate of the Greenland Ice Sheet mass balance between 1992 and 2018, we evaluate
52 the impact of changes in surface mass balance and uncertainty in glacial isostatic adjustment, and
53 we partition the ice sheet mass loss into signals associated with surface mass balance and ice
54 dynamics. In doing so, we extend a previous assessment¹ to include more satellite and ancillary data
55 and to cover the period since 2012.

56 Data and Methods

57 We use 26 estimates of ice sheet mass balance derived from satellite altimetry (9 data sets), satellite
58 gravimetry (14 data sets) and the input-output method (3 data sets) to assess changes in Greenland
59 ice sheet mass balance. The satellite data were computed using common spatial^{20,37} and temporal
60 domains, and using a range of models to estimate signals associated with changes in surface mass
61 balance and glacial isostatic adjustment. Satellite altimetry provides direct measurements of
62 changing ice sheet surface elevation recorded at orbit crossing points³², along repeated ground
63 tracks²⁷, or using plane-fit solutions²⁸, and the ice sheet mass balance is estimated from these
64 measurements either by prescribing the density of the elevation fluctuation³⁸ or by making an
65 explicit model-based correction for changes in firn height³⁹. Satellite gravimetry measures
66 fluctuations in the Earth's gravitational field as computed using either global spherical harmonic
67 solutions³⁰ or using spatially-discrete mass concentration units³¹. Ice sheet mass changes are
68 determined after making model-based corrections for glacial isostatic adjustment³⁰. The input-
69 output method uses model estimates of surface mass balance⁷, which comprises the input, and
70 satellite observations of ice sheet velocity computed from radar⁶ and optical⁴⁰ imagery combined
71 with airborne measurements of ice thickness³³ to compute changes in marine-terminating glacier
72 discharge into the oceans, which comprises the output. The overall mass balance is the difference
73 between input and output. Not all annual surveys of ice sheet discharge are complete, and
74 sometimes regional extrapolations have to be employed to account for gaps in coverage³³. Because
75 they provide important ancillary data, we also assess 6 models of glacial isostatic adjustment and 10
76 models of surface mass balance.

77 To compare and aggregate the individual satellite data sets, we first adopt a common approach to
78 derive linear rates of ice sheet mass balance over 36-month intervals (see Methods). We then
79 compute error-weighted averages of all altimetry, gravimetry, and input-output group mass trends,
80 and we combine these into a single reconciled estimate of the ice sheet mass balance using error-
81 weighting of the group trends. Uncertainties in individual rates of mass change are estimated as the
82 root sum square of the linear model misfit and their measurement error, uncertainties in group rates
83 are estimated as the root mean square of the contributing time-series errors, and uncertainties in
84 reconciled rates are estimated as their root mean square error divided by the square root of the
85 number of independent groups. Cumulative uncertainties are computed as the root sum square of
86 annual errors, an approach that has been employed in numerous studies^{1,17,33,41} and assumes that
87 annual errors are not correlated over time. To improve on this assumption, it will be necessary to
88 consider the covariance of the systematic and random errors present within each mass balance
89 solution (see Methods).

90 Inter-comparison of satellite and model results

91 The satellite gravimetry and satellite altimetry data used in our assessment are corrected for the
92 effects of glacial isostatic adjustment, although the correction is relatively small for altimetry as it
93 appears as a change in elevation and not mass. The most prominent and consistent local signals of
94 glacial isostatic adjustment among the 6 models we have considered are two instances of uplift
95 peaking at about 5-6 mm/yr, one centered over northwest Greenland and Ellesmere Island, and one
96 over northeast Greenland (see Methods and Extended Data Figure 3). Although some models
97 identify a 2 mm/yr subsidence under large parts of the central and southern parts of the ice sheet, it
98 is absent or of lower magnitude in others, which suggests it is less certain (Extended Data Table 1).
99 The greatest difference among model solutions is at Kangerlussuaq Glacier in the southeast where a
100 study⁴² has shown that models and observations agree if a localized weak Earth structure associated
101 with overpassing the Iceland hotspot is assumed; the effect is to offset earlier estimates of mass
102 trends associated with glacial isostatic adjustment by about 20 Gt/yr. Farther afield, the highest
103 spread between modelled uplift occurs on Baffin Island and beyond due to variations in regional
104 model predictions related to the demise of the Laurentide Ice Sheet⁴². This regional uncertainty is
105 likely a major factor in the spread across the ice-sheet-wide estimates. Nevertheless, at -3 ± 20
106 Gt/yr, the mass signal associated with glacial isostatic adjustment in Greenland shows no coherent
107 substantive change and is negligible relative to reported ice sheet mass trends¹.

108 There is generally good agreement between the models of Greenland Ice Sheet surface mass
109 balance that we have assessed for determining mass input - particularly those of a similar class; for
110 example, 70% of all model estimated of runoff and accumulation fall within 1-sigma of their mean
111 (see Methods and Extended Data Table 2). The exceptions are a global reanalysis with coarse spatial
112 resolution that tends to underestimate runoff due to its poor delineation of the ablation zone, and a
113 snow process model that tends to underestimate precipitation and to overestimate runoff in most
114 sectors. Among the other 8 models, the average surface mass balance between 1980 and 2012 is
115 361 ± 40 Gt/yr, with a marked negative trend over time (Extended Data Figure 4) mainly due to
116 increased runoff⁷. At regional scale, the largest differences occur in the northeast, where two
117 regional climate models predict significantly less runoff, and in the southeast, where there is
118 considerable spread in precipitation and runoff across all models. All models show high temporal
119 variability in surface mass balance components, and all models show that the southeast receives the
120 highest net intake of mass at the surface due to high rates of snowfall originating from the Icelandic
121 Low⁴³. By contrast, the southwest, which features the widest ablation zone⁷, has experienced
122 alternate periods of net surface mass loss and gain over recent decades, and has the lowest average
123 surface mass balance across the ice sheet.

124 We assessed the consistency of the satellite altimetry, gravimetry, and input-output method
125 estimates of Greenland Ice Sheet mass balance using common spatial and temporal domains (see
126 Figure 2 and Methods). In general, there is close agreement between estimates determined using
127 each approach, and the standard deviations of coincident altimetry, gravimetry, and input-output
128 method annual mass balance solutions are 40, 30, and 22 Gt/yr, respectively (Extended Data Table
129 3). Once averages were formed for each technique, the resulting estimates of mass balance were
130 also closely aligned (e.g. Extended Data Figure 6). For example, over the common period 2005 to
131 2015, the average Greenland Ice Sheet mass balance is -251 ± 63 Gt/yr and, by comparison, the
132 spread of the altimetry, gravimetry, and input-output method estimates is just 24 Gt/yr (Extended
133 Data Table 3). The estimated uncertainty of the aggregated mass balance solution (see Methods) is
134 larger than the standard deviation of model corrections for glacial isostatic adjustment (20 Gt/yr for
135 gravimetry) and for surface mass balance (40 Gt/yr), which suggests that their collective impacts

136 have been adequately compensated, and it is also larger than the estimated 30 Gt/yr mass losses
137 from peripheral ice caps⁴⁴, which are not accounted for in all individual solutions. In keeping with
138 results from Antarctica⁴¹, rates of mass loss determined using the input-output method are the
139 most negative, and those determined from altimetry are the least negative. However, the spread
140 among the three techniques is 6 times lower for Greenland than it is for Antarctica⁴¹, reflecting
141 differences in the ice sheet size, the complexity of the mass balance processes, and limitations of the
142 various geodetic techniques.

143 Ice sheet mass balance

144 We aggregated the average mass balance estimates from gravimetry, altimetry and the input-output
145 method to form a single, time-varying record (Figure 2) and then integrated these data to determine
146 the cumulative mass lost from Greenland since 1992 (Figure 3). Although Greenland has been losing
147 ice throughout most of the intervening period, the rate of loss has varied significantly. Between 1992
148 and 2012, the rate of ice loss progressively increased, reaching a maximum of 335 ± 62 Gt/yr in
149 2011, ahead of the extreme summertime surface melting that occurred in the following year¹⁴. Since
150 2012, however, the trend has reversed, with a progressive reduction in the rate of mass loss during
151 the subsequent period. By 2018 – the last complete year of our survey – the annual rate of ice mass
152 loss had reduced to 111 ± 71 Gt/yr. The highly variable nature of ice losses from Greenland is a
153 consequence of the wide range of physical processes that are affecting different sectors of the ice
154 sheet^{16,28,35}, which suggests that care should be taken when extrapolating sparse measurements in
155 space or time. Although the rates of mass loss we have computed between 1992 and 2011 are 18 %
156 less negative than those of a previous assessment, which included far fewer data sets¹, the results
157 are consistent given their respective uncertainties. Altogether, the Greenland Ice Sheet has lost 3800
158 ± 339 Gt of ice to the ocean since 1992, with roughly half of this loss occurring during the 6-year
159 period between 2006 and 2012.

160 To determine the proportion of mass lost due to surface and ice dynamical processes, we computed
161 the contemporaneous trend in Greenland Ice Sheet surface mass balance - the net balance between
162 precipitation and ablation⁷, which is controlled by interactions with the atmosphere (Figure 3). In
163 Greenland, recent trends in surface mass balance have been largely driven by meltwater runoff⁴³,
164 which has increased as the regional climate has warmed¹³. Because direct observations of ice sheet
165 surface mass balance are too scarce to provide full temporal and spatial coverage⁴⁵, regional
166 estimates are usually taken from atmospheric models that are evaluated with existing observations.
167 Our evaluation (see Methods) shows that the finer spatial resolution regional climate models
168 produce consistent results, likely due to their ability to capture local changes in melting and
169 precipitation associated with atmospheric forcing, and to resolve the full extent of the ablation zone
170⁴⁶. We therefore compare and combine estimates of Greenland surface mass balance derived from
171 three regional climate models; RACMO2.3p2⁴⁶, MARv3.6²¹ and HIRHAM⁹. To assess the surface
172 mass change across the Greenland Ice Sheet between 1980 and 2018, we accumulate surface mass
173 balance anomalies from each of the regional climate models (Extended Data Figure 7) and average
174 them into a single estimate (Figure 3). Surface mass balance anomalies are computed with respect
175 to the average between 1980 and 1990, which corresponds to a period of approximate balance⁸ and
176 is common to all models. In this comparison, all three models show that the Greenland Ice Sheet
177 entered abruptly into a period of anomalously low surface mass balance in the late 1990's and,
178 when combined, they show that the ice sheet lost 1971 ± 555 Gt of its mass due to meteorological
179 processes between 1992 and 2018 (Table 1).

180 Just over half (52 %) of all mass losses from Greenland – and much of their short-term variability –
181 have been due to variations in the ice sheet’s surface mass balance and its indirect impacts on firn
182 processes. For example, between 2007 and 2012, 71 % of the total ice loss (193 ± 37 Gt/yr) was due
183 to surface mass balance, compared to 28 % (22 ± 20 Gt/yr) over the preceding 15 years and 58 %
184 (139 ± 38 Gt/yr) since then (Table 1). The rise in the total rate of ice loss during the late-2000s
185 coincided with warmer atmospheric conditions, which promoted several episodes of widespread
186 melting and runoff ¹⁴. The reduction in surface mass loss since then is associated with a shift of the
187 North Atlantic Oscillation, which brought about cooler atmospheric conditions and increased
188 precipitation along the southeastern coast ¹⁵. Trends in the total ice sheet mass balance are not,
189 however, entirely due to surface mass balance and, by differencing these two signals, we can
190 estimate the total change in mass loss due to ice dynamical imbalance – i.e. the integrated, net mass
191 loss from those glaciers whose velocity does not equal their long-term mean (Figure 3). Although this
192 approach is indirect, it makes use of all the satellite observations and regional climate models
193 included in our study, overcoming limitations in the spatial and temporal sampling of ice discharge
194 estimates derived from ice velocity and thickness data. Our estimate shows that, between 1992 and
195 2018, Greenland lost 1827 ± 538 Gt of ice due to the dynamical imbalance of glaciers relative to their
196 steady state, accounting for 48 % of the total imbalance (Table 1). Losses due to increased ice
197 discharge rose sharply in the early 2000’s when Jakobshavn Isbræ ¹⁰ and several other outlet glaciers
198 in the southeast ⁴⁷ sped up, and the discharge losses are now four times higher than in the 1990’s.
199 For a period between 2002 and 2007, ice dynamical imbalance was the major source of ice loss from
200 the ice sheet as a whole, although the situation has since returned to be dominated by surface mass
201 losses as several glaciers have slowed down ¹⁶.

202 Despite a reduction in the overall rate of ice loss from Greenland between 2013 and 2018 (Figure 2),
203 the ice sheet mass balance remained negative, adding 10.6 ± 0.9 mm to global sea level since 1992.
204 Although the average sea level contribution is 0.42 ± 0.08 mm/yr, the five-year average rate varied
205 by a factor 5 over the 25-year period, peaking at 0.75 ± 0.08 mm/yr between 2007 and 2012. The
206 variability in Greenland ice loss illustrates the importance of accounting for yearly fluctuations when
207 attempting to close the global sea level budget ². Satellite records of ice sheet mass balance are also
208 an important tool for evaluating numerical models of ice sheet evolution ⁴⁸. In their 2013
209 assessment, the Intergovernmental Panel on Climate Change (IPCC) predicted ice losses from
210 Greenland due to surface mass balance and glacier dynamics under a range of scenarios, beginning
211 in 2007 ¹⁷ (Figure 4). Although ice losses from Greenland have fluctuated considerably during the 12-
212 year period of overlap between the IPCC predictions and our reconciled time series, the total change
213 and average rate (0.69 mm/yr) are close to the upper range predictions (0.72 mm/yr), which implies
214 a 70 to 130 mm of sea-level rise by the year 2100 above central estimates. The drop in ice losses
215 between 2013 and 2018, however, shifted rates towards the lower end projections, and a longer
216 period of comparison is required to establish whether the upper trajectory will continue to be
217 followed. Even greater sea level contribution cannot be ruled out if feedbacks between the ice sheet
218 and other elements of the climate system are underestimated by current ice sheet models ³.
219 Although the volume of ice stored in Greenland is a small fraction of that in Antarctica (12 %), its
220 recent losses have been ~ 36 % higher ⁴¹ as a consequence of the relatively strong atmospheric ^{13,14}
221 and oceanic ^{10,11} warming that has occurred in its vicinity, and its status as a major source of sea-
222 level rise is expected to continue ^{3,17}.

223 Conclusions

224 We combine 26 satellite estimates of ice sheet mass balance and assess 10 models of ice sheet
225 surface mass balance and 6 models of glacial isostatic adjustment, to show that the Greenland Ice

226 Sheet lost 3800 ± 339 Gt of ice between 1992 and 2018. During the common period 2005 to 2015,
227 the spread of mass balance estimates derived from satellite altimetry, gravimetry, and the input-
228 output method is 24 Gt/yr, or 10% of the estimated rate of imbalance. The rate of ice loss has
229 generally increased over time, rising from 18 ± 28 Gt/yr between 1992 to 1997, peaking at 270 ± 27
230 Gt/yr between 2007 and 2012, and reducing to 239 ± 20 Gt/yr between 2012 and 2017. Just over
231 half (1971 ± 555 Gt, or 52 %) of the ice losses are due to reduced surface mass balance (mostly
232 meltwater runoff) associated with changing atmospheric conditions^{13,14}, and these changes have
233 also driven the shorter-term temporal variability in ice sheet mass balance. Despite variations in the
234 imbalance of individual glaciers^{4,5,33}, ice losses due to increasing discharge from the ice sheet as a
235 whole have risen steadily from 41 ± 37 Gt/yr in the 1990's to 87 ± 25 Gt/yr since then, and account
236 for just under half of all losses (48 %) over the survey period.

237 Our assessment shows that estimates of Greenland Ice Sheet mass balance derived from satellite
238 altimetry, gravimetry, and the input-output method agree to within 20 Gt/yr, that model estimates
239 of surface mass balance agree to within 40 Gt/yr, and that model estimates of glacial isostatic
240 adjustment agree to within 20 Gt/yr. These differences represent a small fraction (13 %) of the
241 Greenland Ice Sheet mass imbalance and are comparable to its estimated uncertainty (13 Gt/yr).
242 Nevertheless, there is still departure among models of glacial isostatic adjustment in northern
243 Greenland. Spatial resolution is a key factor in the degree to which models of surface mass balance
244 can represent ablation and precipitation at local scales, and estimates of ice sheet mass balance
245 determined from satellite altimetry and the input-output method continue to be positively and
246 negatively biased, respectively, compared to those based on satellite gravimetry (albeit by small
247 amounts). More satellite estimates of ice sheet mass balance at the start (1990's) and end (2010's)
248 of our record would help to reduce the dependence on fewer data during those periods; although
249 new missions^{49,50} will no doubt address the latter, further analysis of historical satellite data is
250 required to address the former.

251 References

- 252 1. Shepherd, A. *et al.* A Reconciled Estimate of Ice-Sheet Mass Balance. *Science* **338**, 1183–1189
253 (2012).
- 254 2. WCRP Global Sea Level Budget Group. Global sea-level budget 1993–present. *Earth System*
255 *Science Data* **10**, 1551–1590 (2018).
- 256 3. Pattyn, F. *et al.* The Greenland and Antarctic ice sheets under 1.5 °C global warming. *Nature Clim*
257 *Change* **8**, 1053–1061 (2018).
- 258 4. Moon, T., Joughin, I., Smith, B. & Howat, I. 21st-Century Evolution of Greenland Outlet Glacier
259 Velocities. *Science* **336**, 576–578 (2012).
- 260 5. Enderlin, E. M. *et al.* An improved mass budget for the Greenland ice sheet. *Geophysical*
261 *Research Letters* **41**, 866–872 (2014).

- 262 6. Rignot, E. & Kanagaratnam, P. Changes in the Velocity Structure of the Greenland Ice Sheet.
263 *Science* **311**, 986–990 (2006).
- 264 7. Broeke, M. van den *et al.* Partitioning Recent Greenland Mass Loss. *Science* **326**, 984–986
265 (2009).
- 266 8. Trusel, L. D. *et al.* Nonlinear rise in Greenland runoff in response to post-industrial Arctic
267 warming. *Nature* **564**, 104–108 (2018).
- 268 9. Lucas-Picher, P. *et al.* Very high resolution regional climate model simulations over Greenland:
269 Identifying added value. *Journal of Geophysical Research: Atmospheres* **117**, (2012).
- 270 10. Holland, D. M., Thomas, R. H., de Young, B., Ribergaard, M. H. & Lyberth, B. Acceleration of
271 Jakobshavn Isbræ triggered by warm subsurface ocean waters. *Nature Geoscience* **1**, 659–664
272 (2008).
- 273 11. Seale, A., Christoffersen, P., Mugford, R. I. & O’Leary, M. Ocean forcing of the Greenland Ice
274 Sheet: Calving fronts and patterns of retreat identified by automatic satellite monitoring of
275 eastern outlet glaciers. *Journal of Geophysical Research: Earth Surface* **116**, (2011).
- 276 12. Straneo, F. & Heimbach, P. North Atlantic warming and the retreat of Greenland’s outlet
277 glaciers. *Nature* **504**, 36–43 (2013).
- 278 13. Hanna, E., Mernild, S. H., Cappelen, J. & Steffen, K. Recent warming in Greenland in a long-term
279 instrumental (1881–2012) climatic context: I. Evaluation of surface air temperature records.
280 *Environ. Res. Lett.* **7**, 045404 (2012).
- 281 14. Fettweis, X. *et al.* *Brief communication* ‘Important role of the mid-tropospheric atmospheric
282 circulation in the recent surface melt increase over the Greenland ice sheet’. *The Cryosphere* **7**,
283 241–248 (2013).
- 284 15. Bevis, M. *et al.* Accelerating changes in ice mass within Greenland, and the ice sheet’s sensitivity
285 to atmospheric forcing. *PNAS* **116**, 1934–1939 (2019).
- 286 16. Khazendar, A. *et al.* Interruption of two decades of Jakobshavn Isbrae acceleration and thinning
287 as regional ocean cools. *Nat. Geosci.* **12**, 277–283 (2019).

- 288 17. Church, J. A. *et al.* Sea Level Change. in *Climate Change 2013: The Physical Science Basis.*
289 *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel*
290 *on Climate Change* (eds. Stocker, T. F. *et al.*) 1137–1216 (Cambridge University Press, 2013).
291 doi:10.1017/CBO9781107415324.026.
- 292 18. Morlighem, M. *et al.* BedMachine v3: Complete Bed Topography and Ocean Bathymetry
293 Mapping of Greenland From Multibeam Echo Sounding Combined With Mass Conservation.
294 *Geophysical Research Letters* **44**, 11,051–11,061 (2017).
- 295 19. Joughin, I., Smith, B. E., Howat, I. M., Scambos, T. & Moon, T. Greenland flow variability from
296 ice-sheet-wide velocity mapping. *Journal of Glaciology* **56**, 415–430 (2010).
- 297 20. Zwally, H. J., Giovinetto, M. B., Beckley, M. A. & Saba, J. L. Antarctic and Greenland drainage
298 systems. (2012).
- 299 21. Fettweis, X. *et al.* Reconstructions of the 1900–2015 Greenland ice sheet surface mass balance
300 using the regional climate MAR model. *The Cryosphere* **11**, 1015–1033 (2017).
- 301 22. Hofer, S., Tedstone, A. J., Fettweis, X. & Bamber, J. L. Decreasing cloud cover drives the recent
302 mass loss on the Greenland Ice Sheet. *Science Advances* **3**, e1700584 (2017).
- 303 23. Leeson, A. A. *et al.* Supraglacial lakes on the Greenland ice sheet advance inland under warming
304 climate. *Nature Climate Change* **5**, 51–55 (2015).
- 305 24. Palmer, S., McMillan, M. & Morlighem, M. Subglacial lake drainage detected beneath the
306 Greenland ice sheet. *Nat Commun* **6**, 1–7 (2015).
- 307 25. Nick, F. M. *et al.* The response of Petermann Glacier, Greenland, to large calving events, and its
308 future stability in the context of atmospheric and oceanic warming. *Journal of Glaciology* **58**,
309 229–239 (2012).
- 310 26. Joughin, I. *et al.* Ice-front variation and tidewater behavior on Helheim and Kangerdlugssuaq
311 Glaciers, Greenland. *Journal of Geophysical Research: Earth Surface* **113**, (2008).
- 312 27. Pritchard, H. D., Arthern, R. J., Vaughan, D. G. & Edwards, L. A. Extensive dynamic thinning on
313 the margins of the Greenland and Antarctic ice sheets. *Nature* **461**, 971–975 (2009).

- 314 28. McMillan, M. *et al.* A high-resolution record of Greenland mass balance. *Geophysical Research*
315 *Letters* **43**, 7002–7010 (2016).
- 316 29. Sandberg Sørensen, L. *et al.* 25 years of elevation changes of the Greenland Ice Sheet from ERS,
317 Envisat, and CryoSat-2 radar altimetry. *Earth and Planetary Science Letters* **495**, 234–241 (2018).
- 318 30. Velicogna, I. & Wahr, J. Greenland mass balance from GRACE. *Geophysical Research Letters* **32**,
319 (2005).
- 320 31. Luthcke, S. B. *et al.* Recent Greenland Ice Mass Loss by Drainage System from Satellite Gravity
321 Observations. *Science* **314**, 1286–1289 (2006).
- 322 32. Zwally, H. J., Bindschadler, R. A., Brenner, A. C., Major, J. A. & Marsh, J. G. Growth of Greenland
323 Ice Sheet: Measurement. *Science* **246**, 1587–1589 (1989).
- 324 33. Mouginot, J. *et al.* Forty-six years of Greenland Ice Sheet mass balance from 1972 to 2018. *PNAS*
325 **116**, 9239–9244 (2019).
- 326 34. Lecavalier, B. S. *et al.* A model of Greenland ice sheet deglaciation constrained by observations
327 of relative sea level and ice extent. *Quaternary Science Reviews* **102**, 54–84 (2014).
- 328 35. King, M. D. *et al.* Seasonal to decadal variability in ice discharge from the Greenland Ice Sheet.
329 *The Cryosphere* **12**, 3813–3825 (2018).
- 330 36. Porter, D. F. *et al.* Identifying Spatial Variability in Greenland’s Outlet Glacier Response to Ocean
331 Heat. *Front. Earth Sci.* **6**, (2018).
- 332 37. Rignot, E. & Mouginot, J. Ice flow in Greenland for the International Polar Year 2008–2009.
333 *Geophysical Research Letters* **39**, (2012).
- 334 38. Sørensen, L. S. *et al.* Mass balance of the Greenland ice sheet (2003–2008) from ICESat data –
335 the impact of interpolation, sampling and firn density. *The Cryosphere* **5**, 173–186 (2011).
- 336 39. Zwally, H. J. *et al.* Greenland ice sheet mass balance: distribution of increased mass loss with
337 climate warming; 2003–07 versus 1992–2002. *Journal of Glaciology* **57**, 88–102 (2011).

- 338 40. Rosenau, R., Scheinert, M. & Dietrich, R. A processing system to monitor Greenland outlet
339 glacier velocity variations at decadal and seasonal time scales utilizing the Landsat imagery.
340 *Remote Sensing of Environment* **169**, 1–19 (2015).
- 341 41. The IMBIE Team. Mass balance of the Antarctic Ice Sheet from 1992 to 2017. *Nature* **558**, 219–
342 222 (2018).
- 343 42. Khan, S. A. *et al.* Geodetic measurements reveal similarities between post–Last Glacial
344 Maximum and present-day mass loss from the Greenland ice sheet. *Science Advances* **2**,
345 e1600931 (2016).
- 346 43. Ettema, J. *et al.* Higher surface mass balance of the Greenland ice sheet revealed by high-
347 resolution climate modeling. *Geophysical Research Letters* **36**, (2009).
- 348 44. Bolch, T. *et al.* Mass loss of Greenland’s glaciers and ice caps 2003–2008 revealed from ICESat
349 laser altimetry data. *Geophysical Research Letters* **40**, 875–881 (2013).
- 350 45. Vernon, C. L. *et al.* Surface mass balance model intercomparison for the Greenland ice sheet.
351 *The Cryosphere* **7**, 599–614 (2013).
- 352 46. Noël, B. *et al.* Modelling the climate and surface mass balance of polar ice sheets using RACMO2
353 – Part 1: Greenland (1958–2016). *The Cryosphere* **12**, 811–831 (2018).
- 354 47. Howat, I. M., Joughin, I., Fahnestock, M., Smith, B. E. & Scambos, T. A. Synchronous retreat and
355 acceleration of southeast Greenland outlet glaciers 2000–06: ice dynamics and coupling to
356 climate. *Journal of Glaciology* **54**, 646–660 (2008).
- 357 48. Shepherd, A. & Nowicki, S. Improvements in ice-sheet sea-level projections. *Nature Climate*
358 *Change* **7**, 672–674 (2017).
- 359 49. Markus, T. *et al.* The Ice, Cloud, and land Elevation Satellite-2 (ICESat-2): Science requirements,
360 concept, and implementation. *Remote Sensing of Environment* **190**, 260–273 (2017).
- 361 50. Flechtner, F. *et al.* What Can be Expected from the GRACE-FO Laser Ranging Interferometer for
362 Earth Science Applications? *Surv Geophys* **37**, 453–470 (2016).
- 363

364 Supplementary Information

This table is an excel spreadsheet

Supplementary Table 1 This table contains details of the satellite datasets used in this study.

365

366 Acknowledgements

367 This work is an outcome of the Ice Sheet Mass Balance Inter-Comparison Exercise (IMBIE) supported
368 by the ESA Climate Change Initiative and the NASA Cryosphere Program. A.S. was additionally
369 supported by a Royal Society Wolfson Research Merit Award and the UK Natural Environment
370 Research Council Centre for Polar Observation and Modelling.

371

372 Author Contributions

373 A.S. and E.I. designed and led the study. E.R., B.S., M.v.d.B., I.V. and P.W. led the input–output-
374 method, altimetry, surface mass balance (SMB), gravimetry and glacial isostatic adjustment (GIA)
375 experiments, respectively. G.K., S.N., T.P., T.Sc. provided additional supervision on glaciology, K.B.,
376 A.H., I.J., M.E. and T.W. provided additional supervision on satellite observations, and N.S. provided
377 additional supervision on GIA. G.M., M.E.P., and T.Sl. performed the mass balance data collation and
378 analysis. T.Sl. performed the AR5 data analysis. P.W. and I.S. performed the GIA data analysis.
379 M.v.W. and T.Sl. performed the SMB data analysis. A.S., E.I., K.B., M.E., N.G., A.H., H.K., M.M., I.O.,
380 I.S., T.Sl., M.v.W., and P.W. wrote the manuscript; A.S. led the writing, E.I., K.B., M.E., and T.Sl. led
381 the drafting and editing, M.v.W. led the SMB text, P.W. and I.S. led the GIA text, and N.G., A.H., H.K.,
382 M.M., and I.O. contributed elsewhere. A.S., K.B., H.K., G.M., M.E.P, I.S., S.B.S., T.Sl., P.W., and M.v.W.
383 prepared the figures and tables, with particular focus on Fig. 1 (S.B.S), Fig. 3 (T.Sl.), Fig. 4 (T.Sl.),
384 Extended Data Fig. 2 (K.B.), Extended Data Fig. 3 (P.W.), Extended Data Fig. 2 (M.v.W.), Extended
385 Data Table 1 (P.W. and I.S.), Extended Data Table 2 (M.v.W.), and Supplementary Table 1 (H.K. and
386 T.Sl.); G.M. and M.E.P. led the production of all other figures and tables. All authors participated in
387 the data interpretation and commented on the manuscript.

388

389 Competing Interests

390 The authors declare no competing interests.

391

392 The IMBIE Team

393 Andrew Shepherd^{1*}, Erik Ivins², Eric Rignot^{2,3}, Ben Smith⁴, Michiel van den Broeke⁵, Isabella
394 Velicogna^{2,3}, Pippa Whitehouse⁶, Kate Briggs¹, Ian Joughin⁴, Gerhard Krinner⁷, Sophie Nowicki⁸, Tony
395 Payne⁹, Ted Scambos¹⁰, Nicole Schlegel², Geruo A³, Cécile Agosta¹¹, Andreas Ahlstrøm¹², Greg
396 Babonis¹³, Valentina R. Barletta¹⁴, Anders A. Bjørk¹⁵, Alejandro Blazquez¹⁶, Jennifer Bonin¹⁷, William
397 Colgan¹², Beata Csatho¹³, Richard Cullather¹⁸, Marcus E. Engdahl¹⁹, Denis Felikson⁸, Xavier Fettweis¹¹,
398 Rene Forsberg¹⁴, Anna E. Hogg¹, Hubert Gallee⁷, Alex Gardner², Lin Gilbert²⁰, Noel Gourmelen²¹,
399 Andreas Groh²², Brian Gunter²³, Edward Hanna²⁴, Christopher Harig²⁵, Veit Helm²⁶, Alexander
400 Horvath²⁷, Martin Horvath²², Shfaqat Khan¹⁴, Kristian K. Kjeldsen^{12,28}, Hannes Konrad²⁹, Peter L.
401 Langen³⁰, Benoit Lecavalier³¹, Bryant Loomis⁸, Scott Luthcke⁸, Malcolm McMillan³², Daniele Melini³³,

402 Sebastian Mernild^{34,35,36,37}, Yara Mohajerani³, Philip Moore³⁸, Ruth Mottram³⁰, Jeremie Mouginot^{3,7},
403 Gorka Moyano³⁹, Alan Muir²⁰, Thomas Nagler⁴⁰, Grace Nield⁶, Johan Nilsson², Brice Noël⁵, Ines
404 Otsaka¹, Mark E. Pattle³⁹, W. Richard Peltier⁴¹, Nadège Pie⁴², Roelof Rietbroek⁴³, Helmut Rott⁴⁰,
405 Louise Sandberg Sørensen¹⁴, Ingo Sasgen²⁶, Himanshu Save⁴², Bernd Scheuchi³, Ernst Schrama⁴⁴,
406 Ludwig Schröder^{22,26}, Ki-Weon Seo⁴⁵, Sebastian B. Simonsen¹⁴, Thomas Slater¹, Giorgio Spada⁴⁶, Tyler
407 Sutterley³, Matthieu Talpe², Lev Tarasov³¹, Willem Jan van de Berg⁵, Wouter van der Wal^{44, 47},
408 Melchior van Wessem⁵, Bramha Dutt Vishwakarma⁴⁸, David Wiese², David Wilton⁴⁹, Thomas
409 Wagner⁵⁰, Bert Wouters^{5,47} & Jan Wuite⁴⁰

410

411 ¹Centre for Polar Observation and Modelling, University of Leeds, Leeds, UK. ²NASA Jet Propulsion
412 Laboratory, California Institute of Technology, Pasadena, CA, USA. ³Department of Earth System
413 Science, University of California, Irvine, CA, USA. ⁴Department of Earth and Space Sciences,
414 University of Washington, Seattle, WA, USA. ⁵Institute for Marine and Atmospheric Research,
415 Utrecht University, Utrecht, The Netherlands. ⁶Department of Geography, Durham University,
416 Durham, UK. ⁷Institute of Environmental Geosciences, Université Grenoble Alpes, Grenoble, France.
417 ⁸Cryospheric Sciences Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA. ⁹School
418 of Geographical Sciences, University of Bristol, Bristol, UK. ¹⁰Earth Science and Observation Center,
419 University of Colorado, Boulder, CO, USA. ¹¹Department of Geography, University of Liège, Liège,
420 Belgium. ¹²Geological Survey of Denmark and Greenland, Copenhagen, Denmark. ¹³Department of
421 Geology, State University of New York at Buffalo, Buffalo, NY, USA. ¹⁴DTU Space, National Space
422 Institute, Technical University of Denmark, Kongens Lyngby, Denmark. ¹⁵Department of Geosciences
423 and Natural Resource Management, University of Copenhagen, Copenhagen, Denmark. ¹⁶LEGOS,
424 Université de Toulouse, Toulouse, France. ¹⁷College of Marine Sciences, University of South Florida,
425 Tampa, FL, USA. ¹⁸Global Modeling and Assimilation Office, NASA Goddard Space Flight Center,
426 Greenbelt, MD, USA. ¹⁹ESA-ESRIN, Frascati, Italy. ²⁰Mullard Space Science Laboratory, University
427 College London, Holmbury St Mary, UK. ²¹School of Geosciences, University of Edinburgh, Edinburgh,
428 UK. ²²Institute for Planetary Geodesy, Technische Universität Dresden, Dresden, Germany. ²³Daniel
429 Guggenheim School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA, USA.
430 ²⁴School of Geography, University of Lincoln, Lincoln, UK. ²⁵Department of Geosciences, University of
431 Arizona, Tucson, AZ, USA. ²⁶Alfred Wegener Institute, Helmholtz Centre for Polar and Marine
432 Research, Bremerhaven, Germany. ²⁷Institute of Astronomical and Physical Geodesy, Technical
433 University Munich, Munich, Germany. ²⁸GeoGenetics, Globe Institute, University of Copenhagen,
434 Copenhagen, Denmark. ²⁹Deutscher Wetterdienst, Offenbach, Germany. ³⁰Danish Meteorological
435 Institute, Copenhagen, Denmark. ³¹Department of Physics and Physical Oceanography, Memorial
436 University of Newfoundland, St. Johns, Newfoundland and Labrador, Canada. ³²University of
437 Lancaster, Lancaster, UK. ³⁴Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy ³⁴Nansen
438 Environmental and Remote Sensing Centre, Bergen, Norway. ³⁵Faculty of Engineering and Science,
439 Western Norway University of Applied Sciences, Sogndal, Norway. ³⁶Direction of Antarctic and Sub-
440 Antarctic Programs, Universidad de Magallanes, Punta Arenas, Chile, ³⁷Geophysical Institute,
441 University of Bergen, Norway. ³⁸School of Engineering, Newcastle University, Newcastle upon Tyne,
442 UK. ³⁹isardSAT, Barcelona, Spain. ⁴⁰ENVEO, Innsbruck, Austria. ⁴¹Department of Physics, University of
443 Toronto, Toronto, Ontario, Canada. ⁴²Center for Space Research, University of Texas, Austin, TX, USA.
444 ⁴³Institute of Geodesy and Geoinformation, University of Bonn, Bonn, Germany. ⁴⁴Department of
445 Space Engineering, Delft University of Technology, Delft, The Netherlands. ⁴⁵Department of Earth
446 Science Education, Seoul National University, Seoul, South Korea. ⁴⁶Dipartimento di Scienze Pure e
447 Applicate, Università di Urbino "Carlo Bo", Italy. ⁴⁷Department of Civil Engineering, Delft University of
448 Technology, Delft, The Netherlands. ⁴⁸Geodetic Institute, University of Stuttgart, Stuttgart, Germany.
449 ⁴⁹Department of Computer Science, University of Sheffield, UK. ⁵⁰NASA Headquarters, Washington
450 D.C., USA.

451 *Corresponding author: Andrew Shepherd a.shepherd@leeds.ac.uk

452 Figure and Table Legends

453 **Figure 1 | Greenland Ice Sheet elevation change.** Rate of elevation change of the Greenland Ice
454 Sheet determined from ERS, ENVISAT, and CryoSat-2 satellite radar altimetry (top row) and from the
455 HIRHAM5 surface mass balance model (bottom row, ice equivalent), over successive five-year
456 epochs (left to right; 1992-1997, 1997-2002, 2002-2007, 2007-2012, 2012-2017). Reproduced from
457 the data in Ref ²⁹.

458

459 **Figure 2 | Greenland Ice Sheet mass balance.** Rate of mass change (dM/dt) of the Greenland Ice
460 Sheet as determined from the satellite-altimetry (red), input-output method (blue) and gravimetry
461 (green) assessments included in this study. In each case, dM/dt is computed at annual intervals from
462 time series of relative mass change using a three-year window. An average of estimates across each
463 class of measurement technique is also shown for each year (black). The estimated 1σ , 2σ and 3σ
464 ranges of the class average is shaded in dark, mid and light grey, respectively; 97 % of all estimates
465 fall within the 1σ range, given their estimated individual errors. The equivalent sea level contribution
466 of the mass change is also indicated, and the number of individual mass-balance estimates collated
467 at each epoch is shown below each chart entry.

468

469 **Figure 3 | Cumulative anomalies in Greenland Ice Sheet total mass, surface mass balance and ice**
470 **dynamics.** The total change (dark blue) is determined as the integral of the average rate of ice sheet
471 mass change (Figure 2). The change in surface mass balance (green) is determined from three
472 regional climate models relative to their mean over the period 1980-1990. The change associated
473 with ice dynamics (light blue) is determined as the difference between the change in total and
474 surface mass. The estimated 1σ uncertainties of the cumulative changes are shaded. The dotted line
475 shows the result of a previous assessment ¹. The equivalent sea level contribution of the mass
476 change is also indicated. Vertical lines mark consecutive five-year epochs since the start of our
477 satellite record in 1992.

478

479 **Figure 4 | Observed and predicted sea level contribution due to Greenland Ice Sheet mass change.**
480 The global sea-level contribution from Greenland Ice Sheet mass change according to this study
481 (black line) and IPCC AR5 projections between 1992–2040 (left) and 2040–2100 (right) including
482 upper (red), mid (orange), and lower (blue) estimates from the sum of modelled surface mass
483 balance and rapid ice dynamical contributions. Darker coloured lines represent pathways from the
484 five AR5 scenarios in order of increasing emissions: RCP2.6, RCP4.5, RCP6.0, SRES A1B and RCP8.5.
485 Shaded areas represent the spread of AR5 emissions scenarios and the 1σ estimated error on the
486 IMBIE data. The bar chart plot (inset) shows the average annual rates of sea-level rise (in mm/yr)
487 during the overlap period 2007–2018 and their standard deviations. Cumulative AR5 projections
488 have been offset to make them equal to the observational record at their start date (2007).

489

490 **Table 1 | Rates of Greenland Ice Sheet total, surface, and dynamical mass change.** Total rates were
491 determined from all satellite measurements over various epochs, rates of surface mass change were
492 determined from three regional climate models, and rates of dynamical mass change were
493 determined as the difference. The period 1992–2011 is included for comparison to a previous
494 assessment ¹, which reported a mass-balance estimate of -142 ± 49 Gt/yr based on far fewer data.

495 The small differences in our updated estimate is due to our inclusion of more data and an updated
496 aggregation scheme (see Methods). Errors are 1σ .

497

498

499 Table 1
500

Region	1992-1997 (Gt/yr)	1997-2002 (Gt/yr)	2002-2007 (Gt/yr)	2007-2012 (Gt/yr)	2012-2017 (Gt/yr)	1992-2011 (Gt/yr)	1992-2018 (Gt/yr)
Total	-18 ± 28	-48 ± 35	-175 ± 30	-270 ± 27	-238 ± 29	-117 ± 16	-148 ± 13
Surface	26 ± 35	-15 ± 36	-78 ± 36	-193 ± 37	-139 ± 38	-57 ± 18	-76 ± 16
Dynamics	-43 ± 45	-33 ± 50	-97 ± 47	-77 ± 46	-100 ± 48	-60 ± 24	-73 ± 21

501

502

503 Methods

504 Data

505 In this assessment we analyse 5 groups of data: estimates of ice sheet mass-balance determined
506 from 3 distinct classes of satellite observations - altimetry, gravimetry and the input–output method
507 (IOM) - and model estimates of surface mass balance (SMB) and glacial isostatic adjustment (GIA).
508 Each dataset is computed following previously reported methods (based on references 28, 33, 38, 54
509 to 61, 72, 87 to 120 and detailed in Supplementary Table 1) and, for consistency, they are
510 aggregated within common spatial and temporal domains. Altogether, 26 separate ice sheet mass
511 balance datasets were used - 9 derived from satellite altimetry, 3 derived from the input-output
512 method, and 14 derived from satellite gravimetry - with a combined period running from 1992 to
513 2018 (Extended Data Figure 1). We also assess 6 model estimates of GIA (Extended Data Table 1) and
514 10 model estimates of SMB (Extended Data Table 2).

515 Drainage Basins

516 We analyse mass trends using two ice sheet drainage basin sets (Extended Data Figure 2), to allow
517 consistency with those used in the first IMBIE assessment ¹, and to evaluate an updated definition
518 tailored towards mass budget assessments. The first set comprises 19 drainage basins delineated
519 using surface elevation maps derived from ICESat-1 with a total area of 1,703,625 km ^{2,20}. The second
520 drainage basin set is an updated definition considering other factors such as the direction of ice flow
521 and includes 6 basins with a combined area of 1,723,300 km ^{2,37}. The two drainage basin sets differ
522 by 1% in area at the scale of the Greenland Ice Sheet, and this has a negligible impact on mass trends
523 when compared to the estimated uncertainty of individual techniques.

524 Glacial isostatic adjustment

525 GIA - the delayed response of Earth's interior to temporal changes in ice loading - affects estimates
526 of ice sheet mass balance determined from satellite gravimetry and, to a lesser extent, satellite
527 altimetry ⁵¹. Here, we compare 6 independent models of GIA in the vicinity of the Greenland Ice
528 Sheet (Extended Data Table 1). The GIA model solutions we did consider differ for a variety of
529 reasons, including differences in their physics, in their computational approach, in their prescriptions
530 of solid Earth unloading during the last glacial cycle and their Earth rheology, and in the data sets
531 against which they are evaluated. Although alternative ice histories (e.g. ⁵²) and mantle viscosities
532 (e.g. ⁵³) are available, we restricted our comparison to those contributed to our assessment. No
533 approach is generally accepted as optimal, and so we evaluate the models by computing the mean
534 and standard deviation of their predicted uplift rates (Extended Data Figure 3). We also estimate the
535 contribution of each model to gravimetric mass trends using a common processing approach ⁴¹
536 which puts special emphasis on the treatment of low spherical harmonic degrees in the GIA-related
537 trends in the gravitational field.

538 The highest rates of GIA-related uplift occur in northern Greenland - though this region also exhibits
539 marked variability among the solutions, as does the area around Kangerlussuaq Glacier to the
540 southeast. Even though the model spread is high in northern Greenland, the signal in this sector is
541 also consistently high in most solutions. However, none of the GIA models considered here fully
542 captures all areas of high uplift present in the models, and so it is possible there is a bias towards
543 low values in the average field across the ice sheet overall. The models yield an average adjustment
544 for GRACE estimates of Greenland Ice Sheet mass balance of -3 Gt/yr, with a standard deviation of
545 around 20 Gt/yr. The spread is likely in part due to differences in the way each model accounts for
546 GIA in North America which is ongoing and impacts western Greenland, and so care must be taken
547 when estimating mass balance at basin scale. Local misrepresentation of the solid Earth response

548 can also have a relatively large impact stemming especially from lateral variations of solid-Earth
549 properties^{42,54}, and revisions of the current state of knowledge can be expected³⁴.

550 Surface mass balance

551 Here, ice-sheet SMB is defined as total precipitation minus sublimation, evaporation and meltwater
552 runoff, i.e. the interaction of the atmosphere and the superficial snow and firn layers, for example
553 through mass exchanges via precipitation, sublimation, and runoff, and through mass redistribution
554 by snowdrift, melting, and refreezing. We compare 10 estimates of Greenland Ice Sheet SMB derived
555 using a range of alternative approaches; 4 regional climate models (RCM's), 2 downscaled RCM's, a
556 global reanalysis, 2 downscaled model reanalyses of climate data, and 1 gridded model of snow
557 processes driven by climate model output (Extended Data Table 2).

558 Although SMB models of similar class tend to produce similar results, there are larger differences
559 between classes – most notably the global reanalysis and the process model which lead to estimates
560 of SMB that are significantly higher and lower than all other solutions, respectively. The regional
561 climate model solutions agree well at the scale of individual drainage sectors, with the largest
562 differences occurring in north-east Greenland (Extended Data Figure 4). The snow process model
563 tends to underestimate SMB when compared to the other solutions we have considered in various
564 sectors of the ice sheet, at times even yielding negative SMB, while the global reanalysis tends to
565 overestimate it.

566 Across all models, the average SMB of the Greenland Ice Sheet between 1980 to 2012 is 351 Gt/yr
567 and the standard deviation is 98 Gt/yr. However, the spread among the 8 RCM's and downscaled
568 reanalyses is considerably smaller; these solutions lead to an average Greenland Ice Sheet SMB of
569 361 Gt/yr with a standard deviation of 40 Gt/yr over the same period. By comparison, the global
570 reanalysis and process model lead to ice sheet wide estimates of SMB that are significantly larger
571 (504 Gt/yr) and smaller (125 Gt/yr) than this range, respectively. Model resolution is an important
572 factor when estimating SMB and its components, as respective contributions where only the spatial
573 resolution differed yield regional differences. Additionally, the underlying model domains were
574 identified as a source of discrepancy in the case of the Greenland Ice Sheet, as some products would
575 allocate the ablation area outside the given mask.

576 Individual estimates of ice sheet mass balance

577 To standardise our comparison and aggregation of the 26 individual satellite estimates of Greenland
578 Ice Sheet mass balance, we applied a common approach to derive rates of mass change from
579 cumulative mass trends⁴¹. Rates of mass change were computed over 36-month intervals centred
580 on regularly spaced (monthly) epochs within each cumulative mass trend time series, oversampling
581 the individual time series where necessary. At each epoch, rates of mass change were estimated by
582 fitting a linear trend to data within the surrounding 36-month time window using a weighted least-
583 squares approach, with each point weighted by its measurement error. The associated mass trend
584 uncertainties were estimated as the root sum square of the regression error and the measurement
585 error. Time series were truncated by half the moving-average window period at the start and end of
586 their period. The emerging rates of mass change were then averaged over 12-month periods to
587 reduce the impact of seasonal cycles.

588 **Gravimetry** We include 14 estimates of Greenland Ice Sheet ice sheet mass balance determined
589 from GRACE satellite gravimetry which together span the period 2003 to 2016 (Extended Data Figure
590 1). 10 of the gravimetry solutions were computed using spherical harmonic solutions to the global
591 gravity field and 4 were computed using spatially defined mass concentration units (Supplementary
592 Table 1). An unrestricted range of alternative GIA corrections were used in the formation of the

593 gravimetry mass balance solutions based on commonly-adopted model solutions and their variants
594 ^{34,54-60} (Supplementary Table 1). All of the gravimetry mass balance solutions included in this study
595 use the same degree-1 coefficients to account for geocenter motion ⁶¹ and, although an alternative
596 set is now available ⁶², the estimated improvement in certainty is small in comparison to their
597 magnitude and spread. There was some variation in the sampling of the individual gravimetry data
598 sets, and their collective effective (weighted mean) temporal resolution is 0.08 years. Overall, there
599 is good agreement between rates of Greenland Ice Sheet mass change derived from satellite
600 gravimetry (Extended Data Figure 5); all solutions show the ice sheet to be in a state of negative
601 mass balance throughout their survey periods, with mass loss peaking in 2011 and reducing
602 thereafter. During the period 2005 to 2015, annual rates of mass change determined from satellite
603 gravimetry differ by 97 Gt/yr on average, and their average standard deviation is 30 Gt/yr (Extended
604 Data Table 3).

605 **Altimetry** We include 9 estimates of Greenland Ice Sheet mass balance determined from satellite
606 altimetry which together span the period 2004 to 2018 (Extended Data Figure 1). 3 of the solutions
607 are derived from radar altimetry, 4 from laser altimetry, and 2 use a combination of both
608 (Supplementary Table 1). The altimetry mass trends are also computed using a range of approaches,
609 including crossovers, planar fits, and repeat track analyses. The laser altimetry mass trends are
610 computed from ICESat-1 data as constant rates of mass change over their respective survey periods,
611 while the radar altimetry mass trends are computed from EnviSat and/or CryoSat-2 data with a
612 temporal resolution of between 1 and 72 months. In consequence, the altimetry solutions have an
613 effective collective temporal resolution of 0.74 years. Mass changes are computed after making
614 corrections for alternative sources of surface elevation change, including glacial isostatic and elastic
615 adjustment, and firn height changes (see Supplementary Table 1). Despite the range of input data
616 and technical approaches, there is good overall agreement between rates of mass change
617 determined from the various satellite altimetry solutions (Extended Data Figure 5). All altimetry
618 solutions show the Greenland Ice Sheet to be in a state of negative mass balance throughout their
619 survey periods, with mass loss peaking in 2012 and reducing thereafter. During the period 2005 to
620 2015, annual rates of mass change determined from satellite altimetry differ by 111 Gt/yr on
621 average, and, their average standard deviation is 40 Gt/yr (Extended Data Table 3). The greatest
622 variance lies among the 4 laser altimetry mass balance solutions which range from -248 to -128 Gt/yr
623 between 2004 and 2010; aside from methodological differences, possible explanations for this high
624 spread include the relatively short period over which the mass trends are determined, the poor
625 temporal resolution of these data sets, and the rapid change in mass balance occurring during the
626 period in question.

627 **Input-Output Method** We include 3 estimates of Greenland Ice Sheet mass balance determined
628 from the input-output method which together span the period 1992 to 2015 (Extended Data Figure
629 1). Although there are relatively few data sets by comparison to the gravimetry and altimetry
630 solutions, the input-output data provide information on the partitioning of the mass change (surface
631 processes and/or ice dynamics) cover a significantly longer period and are therefore an important
632 record of changes in Greenland Ice Sheet mass during the 1990's. The input-output method makes
633 use of a wide range of satellite imagery (e.g. ^{6,40,63-68}) combined with measurements of ice thickness
634 (e.g. ⁶⁹) for computing ice sheet discharge (output), and several alternative SMB model estimates of
635 snow accumulation (input) and runoff (output) (see Supplementary Table 1). 2 of the input-output
636 method datasets exhibit temporal variability across their survey periods, and 2 provide only constant
637 rates of mass changes. Although these latter records are relatively short, they are an important
638 marker with which variances among independent estimates can be evaluated. The collective
639 effective (weighted mean) temporal resolution of the input-output method data is 0.14 years,

640 although it should be noted that in earlier years the satellite ice discharge component of the data
641 are relatively sparsely sampled in time (e.g. ⁷⁰). There is good overall agreement between rates of
642 mass change determined from the input-output method solutions (Extended Data Figure 5). During
643 the period 2005 to 2015, annual rates of mass change determined from the 4 input-output data sets
644 differ by up to 47 Gt/yr on average, and their average standard deviation is 22 Gt/yr (Extended Data
645 Table 3). These differences are comparable to the estimated uncertainty of the individual techniques
646 and are also small relative to the estimated mass balance over the period in question. In addition to
647 showing that the Greenland Ice Sheet was in a state of negative mass balance since 2000, with mass
648 loss peaking in 2012 and reducing thereafter, the input-output method data show that the ice sheet
649 was close to a state of balance prior to this period ³³.

650 [Aggregate estimate of ice sheet mass balance](#)

651 To produce an aggregate estimate of Greenland Ice Sheet mass balance, we combine the 14
652 gravimetry, 9 altimetry, and 3 input-output method datasets to produce a single 26-year record
653 spanning the period 1992 to 2018. First, we combine the gravimetry, altimetry, and the input-output
654 method data separately into three time-series by forming an error-weighted average of individual
655 rates of ice sheet mass change computed using the same technique (Extended Data Figure 6). At
656 each epoch, we estimate the uncertainty of these time-series as the root mean square of their
657 component time-series errors. We then combine the mass balance time-series derived from
658 gravimetry, altimetry, and the input-output method to produce a single, aggregate (reconciled)
659 estimate, computed as the error-weighted mean of mass trends sampled at each epoch. We
660 estimated the uncertainty of this reconciled rate of mass balance as either the root mean square
661 departure of the constituent mass trends from their weighted-mean or the root mean square of
662 their uncertainties, whichever is larger, divided by the square root of the number of independent
663 satellite techniques used to form the aggregate. Cumulative uncertainties are computed as the root
664 sum square of annual errors, on the assumption that annual errors are not correlated over time. This
665 assumption has been employed in numerous mass balance studies ^{1,17,33,41}, and its effect is to reduce
666 cumulative errors by a factor 2.2 over the 5-year periods we employ in this study (Table 1). If some
667 sources of error are temporally correlated, the cumulative uncertainty may therefore be
668 underestimated. In a recent study, for example, it is estimated that 30 % of the annual mass balance
669 error is systematic ⁷¹, and in this instance the cumulative error may be 37 % larger. On the other
670 hand, the estimated annual error on aggregate mass trends reported in this study (61 Gt/yr) are 70%
671 larger than the spread of the independent estimates from which they are combined (36 Gt/yr)
672 (Extended Data Table 3), which suggests the underlying errors may be overestimated by a similar
673 degree. A more detailed analysis of the measurement and systematic errors is required to improve
674 the cumulative error budget.

675 During the period 2004 to 2015, when all three satellite techniques were in operation, there is good
676 agreement between changes in ice sheet mass balance on a variety of timescales (Extended Data
677 Figure 6). In Greenland, there are large annual cycles in mass superimposed on equally prominent
678 interannual fluctuations as well as variations of intermediate (~5 years) duration. These signals are
679 consistent with fluctuations in SMB that have been identified in meteorological records ^{1,72}, and are
680 present within the time-series of mass balance emerging from all three satellite techniques, to
681 varying degrees, according to their effective temporal resolution. For example, correlated seasonal
682 cycles are apparent in the gravimetry and input-output method mass balance time series, because
683 their effective temporal resolutions are sufficiently short (0.08 and 0.14 years, respectively) to
684 resolve such changes. However, at 0.74 years, the effective temporal resolution of the altimetry
685 mass balance time series is too coarse to detect cycles on sub-annual timescales. Nevertheless,

686 when the aggregated mass balance data emerging from all three experiment groups are degraded to
687 a common temporal resolution of 36 months, the time-series are well correlated ($0.63 < r^2 < 0.80$) and,
688 over longer periods, all techniques identify the marked increases in Greenland Ice Sheet mass loss
689 peaking in 2012. During the period 2005 to 2015, annual rates of mass change determined from all
690 three techniques differ by up 148 Gt/yr on average, and their average standard deviation is 39 Gt/yr
691 - a value that is small when compared to their estimated uncertainty (63 Gt/yr)(Extended Data Table
692 3).

693

694 Methods References

- 695 51. Wahr, J., Wingham, D. & Bentley, C. A method of combining ICESat and GRACE satellite data to
696 constrain Antarctic mass balance. *Journal of Geophysical Research: Solid Earth* **105**, 16279–
697 16294 (2000).
- 698 52. Lambeck, K., Rouby, H., Purcell, A., Sun, Y. & Sambridge, M. Closing the sea level budget at the
699 Last Glacial Maximum. *PNAS* **111**, 15861–15862 (2014).
- 700 53. Caron, L., Métivier, L., Greff-Lefftz, M., Fleitout, L. & Rouby, H. Inverting Glacial Isostatic
701 Adjustment signal using Bayesian framework and two linearly relaxing rheologies. *Geophys J Int*
702 **209**, 1126–1147 (2017).
- 703 54. Peltier, W. R., Argus, D. F. & Drummond, R. Space geodesy constrains ice age terminal
704 deglaciation: The global ICE-6G_C (VM5a) model. *Journal of Geophysical Research: Solid Earth*
705 **120**, 450–487 (2015).
- 706 55. Paulson, A., Zhong, S. & Wahr, J. Inference of mantle viscosity from GRACE and relative sea level
707 data. *Geophys J Int* **171**, 497–508 (2007).
- 708 56. Peltier, W. R. Global Glacial Isostasy and the Surface of the Ice-Age Earth: The ICE-5G (VM2)
709 Model and GRACE. *Annual Review of Earth and Planetary Sciences* **32**, 111–149 (2004).
- 710 57. Simpson, M. J. R., Milne, G. A., Huybrechts, P. & Long, A. J. Calibrating a glaciological model of
711 the Greenland ice sheet from the Last Glacial Maximum to present-day using field observations
712 of relative sea level and ice extent. *Quaternary Science Reviews* **28**, 1631–1657 (2009).

- 713 58. A, G., Wahr, J. & Zhong, S. Computations of the viscoelastic response of a 3-D compressible
714 Earth to surface loading: an application to Glacial Isostatic Adjustment in Antarctica and Canada.
715 *Geophys J Int* **192**, 557–572 (2013).
- 716 59. Schrama, E. J. O., Wouters, B. & Rietbroek, R. A mascon approach to assess ice sheet and glacier
717 mass balances and their uncertainties from GRACE data. *Journal of Geophysical Research: Solid*
718 *Earth* **119**, 6048–6066 (2014).
- 719 60. Klemann, V. & Martinec, Z. Contribution of glacial-isostatic adjustment to the geocenter motion.
720 *Tectonophysics* **511**, 99–108 (2011).
- 721 61. Swenson, S., Chambers, D. & Wahr, J. Estimating geocenter variations from a combination of
722 GRACE and ocean model output. *Journal of Geophysical Research: Solid Earth* **113**, (2008).
- 723 62. Sun, Y., Riva, R. & Ditmar, P. Optimizing estimates of annual variations and trends in geocenter
724 motion and J2 from a combination of GRACE data and geophysical models. *Journal of*
725 *Geophysical Research: Solid Earth* **121**, 8352–8370 (2016).
- 726 63. Nagler, T., Rott, H., Hetzenecker, M., Wuite, J. & Potin, P. The Sentinel-1 Mission: New
727 Opportunities for Ice Sheet Observations. *Remote Sensing* **7**, 9371–9389 (2015).
- 728 64. Mouginot, J., Rignot, E., Scheuchl, B. & Millan, R. Comprehensive Annual Ice Sheet Velocity
729 Mapping Using Landsat-8, Sentinel-1, and RADARSAT-2 Data. *Remote Sensing* **9**, 364 (2017).
- 730 65. Joughin, I., Smith, B. E. & Howat, I. Greenland Ice Mapping Project: ice flow velocity variation at
731 sub-monthly to decadal timescales. *The Cryosphere* **12**, 2211–2227 (2018).
- 732 66. Lemos, A. *et al.* Ice velocity of Jakobshavn Isbræ, Petermann Glacier, Nioghalvfjærdsfjorden, and
733 Zachariæ Isstrøm, 2015–2017, from Sentinel 1-a/b SAR imagery. *The Cryosphere* **12**, 2087–2097
734 (2018).
- 735 67. Joughin, I. *et al.* Continued evolution of Jakobshavn Isbrae following its rapid speedup. *Journal of*
736 *Geophysical Research: Earth Surface* **113**, (2008).
- 737 68. Joughin, I., Abdalati, W. & Fahnestock, M. Large fluctuations in speed on Greenland's
738 Jakobshavn Isbræ glacier. *Nature* **432**, 608–610 (2004).

- 739 69. Gogineni, S. *et al.* Coherent radar ice thickness measurements over the Greenland ice sheet.
740 *Journal of Geophysical Research: Atmospheres* **106**, 33761–33772 (2001).
- 741 70. Rignot, E. *et al.* Recent Antarctic ice mass loss from radar interferometry and regional climate
742 modelling. *Nature Geosci* **1**, 106–110 (2008).
- 743 71. Shepherd, A. *et al.* Trends in Antarctic Ice Sheet Elevation and Mass. *Geophysical Research*
744 *Letters* **46**, 8174–8183 (2019).
- 745 72. Wouters, B., Bamber, J. L., van den Broeke, M. R., Lenaerts, J. T. M. & Sasgen, I. Limits in
746 detecting acceleration of ice sheet mass loss due to climate variability. *Nature Geoscience* **6**,
747 613–616 (2013).
- 748 73. Rignot, E., Mouginot, J. & Scheuchl, B. Ice Flow of the Antarctic Ice Sheet. *Science* **333**, 1427–
749 1430 (2011).
- 750 74. Rignot, E., Mouginot, J. & Scheuchl, B. Antarctic grounding line mapping from differential
751 satellite radar interferometry. *Geophysical Research Letters* **38**, (2011).
- 752 75. Langen, P. L., Fausto, R. S., Vandecrux, B., Mottram, R. H. & Box, J. E. Liquid Water Flow and
753 Retention on the Greenland Ice Sheet in the Regional Climate Model HIRHAM5: Local and Large-
754 Scale Impacts. *Front. Earth Sci.* **4**, (2017).
- 755 76. Martinec, Z. & Hagedoorn, J. The rotational feedback on linear-momentum balance in glacial
756 isostatic adjustment. *Geophys J Int* **199**, 1823–1846 (2014).
- 757 77. Fretwell, P. *et al.* Bedmap2: improved ice bed, surface and thickness datasets for Antarctica. *The*
758 *Cryosphere* **7**, 375–393 (2013).
- 759 78. Martinec, Z. Spectral–finite element approach to three-dimensional viscoelastic relaxation in a
760 spherical earth. *Geophys J Int* **142**, 117–141 (2000).
- 761 79. Fleming, K. & Lambeck, K. Constraints on the Greenland Ice Sheet since the Last Glacial
762 Maximum from sea-level observations and glacial-rebound models. *Quaternary Science Reviews*
763 **23**, 1053–1077 (2004).

- 764 80. King, M. A., Whitehouse, P. L. & van der Wal, W. Incomplete separability of Antarctic plate
765 rotation from glacial isostatic adjustment deformation within geodetic observations. *Geophys J*
766 *Int* **204**, 324–330 (2016).
- 767 81. Spada, G., Melini, D. & Colleoni, F. *Computational Infrastructure for Geodynamics*. (2018).
- 768 82. Noël, B. *et al.* Evaluation of the updated regional climate model RACMO2.3: summer snowfall
769 impact on the Greenland Ice Sheet. *The Cryosphere* **9**, 1831–1844 (2015).
- 770 83. Noël, B. *et al.* A daily, 1 km resolution data set of downscaled Greenland ice sheet surface mass
771 balance (1958–2015). *The Cryosphere* **10**, 2361–2377 (2016).
- 772 84. Gelaro, R. *et al.* The Modern-Era Retrospective Analysis for Research and Applications, Version 2
773 (MERRA-2). *J. Climate* **30**, 5419–5454 (2017).
- 774 85. Wilton, D. J. *et al.* High resolution (1 km) positive degree-day modelling of Greenland ice sheet
775 surface mass balance, 1870–2012 using reanalysis data. *Journal of Glaciology* **63**, 176–193
776 (2017).
- 777 86. Mernild, S. H., Liston, G. E., Hiemstra, C. A. & Christensen, J. H. Greenland Ice Sheet Surface
778 Mass-Balance Modeling in a 131-Yr Perspective, 1950–2080. *J. Hydrometeor.* **11**, 3–25 (2010).
- 779 87. Bonin, J. & Chambers, D. Uncertainty estimates of a GRACE inversion modelling technique over
780 Greenland using a simulation. *Geophys J Int* **194**, 212–229 (2013).
- 781 88. Blazquez, A. *et al.* Exploring the uncertainty in GRACE estimates of the mass redistributions at
782 the Earth surface: implications for the global water and sea level budgets. *Geophys J Int* **215**,
783 415–430 (2018).
- 784 89. Forsberg, R., Sørensen, L. & Simonsen, S. Greenland and Antarctica Ice Sheet Mass Changes and
785 Effects on Global Sea Level. *Surv Geophys* **38**, 89–104 (2017).
- 786 90. Groh, A. & Horwath, M. The method of tailored sensitivity kernels for GRACE mass change
787 estimates. in (2016).
- 788 91. Harig, C. & Simons, F. J. Mapping Greenland’s mass loss in space and time. *PNAS* **109**, 19934–
789 19937 (2012).

- 790 92. Luthcke, S. B. *et al.* Antarctica, Greenland and Gulf of Alaska land-ice evolution from an iterated
791 GRACE global mascon solution. *Journal of Glaciology* **59**, 613–631 (2013).
- 792 93. Andrews, S. B., Moore, P. & King, M. A. Mass change from GRACE: a simulated comparison of
793 Level-1B analysis techniques. *Geophys J Int* **200**, 503–518 (2015).
- 794 94. Save, H., Bettadpur, S. & Tapley, B. D. High-resolution CSR GRACE RL05 mascons. *Journal of*
795 *Geophysical Research: Solid Earth* **121**, 7547–7569 (2016).
- 796 95. Seo, K.-W. *et al.* Surface mass balance contributions to acceleration of Antarctic ice mass loss
797 during 2003–2013. *Journal of Geophysical Research: Solid Earth* **120**, 3617–3627 (2015).
- 798 96. Velicogna, I., Sutterley, T. C. & Broeke, M. R. van den. Regional acceleration in ice mass loss from
799 Greenland and Antarctica using GRACE time-variable gravity data. *Geophysical Research Letters*
800 **41**, 8130–8137 (2014).
- 801 97. Vishwakarma, B. D., Horwath, M., Devaraju, B., Groh, A. & Sneeuw, N. A Data-Driven Approach
802 for Repairing the Hydrological Catchment Signal Damage Due to Filtering of GRACE Products.
803 *Water Resources Research* **53**, 9824–9844 (2017).
- 804 98. Wiese, D. N., Landerer, F. W. & Watkins, M. M. Quantifying and reducing leakage errors in the
805 JPL RL05M GRACE mascon solution. *Water Resources Research* **52**, 7490–7502 (2016).
- 806 99. Ivins, E. R. & James, T. S. Antarctic glacial isostatic adjustment: a new assessment. *Antarctic*
807 *Science* **17**, 541–553 (2005).
- 808 100. Ivins, E. R. *et al.* Antarctic contribution to sea level rise observed by GRACE with improved GIA
809 correction. *Journal of Geophysical Research: Solid Earth* **118**, 3126–3141 (2013).
- 810 101. Klemann, V. & Martinec, Z. Contribution of glacial-isostatic adjustment to the geocenter
811 motion. *Tectonophysics* **511**, 99–108 (2011).
- 812 102. Rodell, M. *et al.* The Global Land Data Assimilation System. *Bull. Amer. Meteor. Soc.* **85**, 381–
813 394 (2004).
- 814 103. Döll, P., Kaspar, F. & Lehner, B. A global hydrological model for deriving water availability
815 indicators: model tuning and validation. *Journal of Hydrology* **270**, 105–134 (2003).

- 816 104. Cheng, M., Tapley, B. D. & Ries, J. C. Deceleration in the Earth's oblateness. *Journal of*
817 *Geophysical Research: Solid Earth* **118**, 740–747 (2013).
- 818 105. Balmaseda, M. A., Mogensen, K. & Weaver, A. T. Evaluation of the ECMWF ocean reanalysis
819 system ORAS4. *Quarterly Journal of the Royal Meteorological Society* **139**, 1132–1161 (2013).
- 820 106. Pujol, M.-I. *et al.* DUACS DT2014: the new multi-mission altimeter data set reprocessed over 20
821 years. *Ocean Science* **12**, 1067–1090 (2016).
- 822 107. Menemenlis, D. *et al.* ECCO2: High Resolution Global Ocean and Sea Ice Data Synthesis. *AGU*
823 *Fall Meeting Abstracts* **2008**, OS31C-1292 (2008).
- 824 108. Dobslaw, H. *et al.* Simulating high-frequency atmosphere-ocean mass variability for dealiasing
825 of satellite gravity observations: AOD1B RL05. *Journal of Geophysical Research: Oceans* **118**,
826 3704–3711 (2013).
- 827 109. Carrère, L. & Lyard, F. Modeling the barotropic response of the global ocean to atmospheric
828 wind and pressure forcing - comparisons with observations. *Geophysical Research Letters* **30**,
829 (2003).
- 830 110. Csatho, B. M. *et al.* Laser altimetry reveals complex pattern of Greenland Ice Sheet dynamics.
831 *PNAS* **111**, 18478–18483 (2014).
- 832 111. Nilsson, J., Gardner, A., Sandberg Sørensen, L. & Forsberg, R. Improved retrieval of land ice
833 topography from CryoSat-2 data and its impact for volume-change estimation of the Greenland
834 Ice Sheet. *The Cryosphere* **10**, 2953–2969 (2016).
- 835 112. Gourmelen, N. *et al.* CryoSat-2 swath interferometric altimetry for mapping ice elevation and
836 elevation change. *Advances in Space Research* **62**, 1226–1242 (2018).
- 837 113. Gunter, B. C. *et al.* Empirical estimation of present-day Antarctic glacial isostatic adjustment and
838 ice mass change. *The Cryosphere* **8**, 743–760 (2014).
- 839 114. Helm, V., Humbert, A. & Miller, H. Elevation and elevation change of Greenland and Antarctica
840 derived from CryoSat-2. *The Cryosphere* **8**, 1539–1559 (2014).

- 841 115. Kjeldsen, K. K. *et al.* Improved ice loss estimate of the northwestern Greenland ice sheet.
842 *Journal of Geophysical Research: Solid Earth* **118**, 698–708 (2013).
- 843 116. Felikson, D. *et al.* Comparison of Elevation Change Detection Methods From ICESat Altimetry
844 Over the Greenland Ice Sheet. *IEEE Transactions on Geoscience and Remote Sensing* **55**, 5494–
845 5505 (2017).
- 846 117. Andersen, M. L. *et al.* Basin-scale partitioning of Greenland ice sheet mass balance components
847 (2007–2011). *Earth and Planetary Science Letters* **409**, 89–95 (2015).
- 848 118. Colgan, W. *et al.* Greenland ice sheet mass balance assessed by PROMICE (1995–2015).
849 *Geological Survey of Denmark and Greenland Bulletin* **43**, (2019).
- 850 119. van Wessem, J. M. *et al.* Updated cloud physics in a regional atmospheric climate model
851 improves the modelled surface energy balance of Antarctica. *The Cryosphere* **8**, 125–135 (2014).
- 852 120. Fettweis, X. *et al.* Estimating the Greenland ice sheet surface mass balance contribution to
853 future sea level rise using the regional atmospheric climate model MAR. *The Cryosphere* **7**, 469–
854 489 (2013).

855
856

857 Data availability

858 The aggregated Greenland Ice Sheet mass-balance data and estimated errors generated in this study
859 are freely available at <http://imbie.org> and at the NERC Polar Data Centre. The code used to
860 compute and aggregate rates of ice sheet mass change and their estimated errors are freely
861 available at <https://github.com/IMBIE>.

862 Extended Data Legends

863 **Extended Data Figure 1 | Ice sheet mass balance data sets.** Participant datasets used in this
864 study and their main contributors (a, top) and the number and class of data available in each
865 calendar year (b, bottom). The interval 2003 to 2010 includes almost all datasets and is
866 selected as the overlap period. Further details of the satellite observations used in this study
867 are provided in Supplementary Table 1.

868

869 **Extended Data Figure 2 | Greenland Ice Sheet drainage basins.** Basin used in this study,
870 according to the definitions of ref ²⁰ (a, left) and ref ³⁷ (b, right).

871

872 **Extended Data Figure 3 | Modelled glacial isostatic adjustment in Greenland.** Bedrock
873 uplift rates in Greenland averaged over the glacial isostatic adjustment (GIA) model
874 solutions used in this study (a, left), as well as their standard deviation (b, right). Further
875 details of the GIA models used in this study are provided in Extended Data Table 1. High
876 rates of uplift and subsidence associated with the former Laurentide Ice Sheet are apparent
877 to the southwest of Greenland.

878

879 **Extended Data Figure 4 | Surface mass balance of the Greenland Ice Sheet.** Time series of
880 surface mass balance (SMB) in (a) NW, (b) SW, (c) NE, (d) CW, (e) SE and (f) NO Greenland
881 Ice Sheet drainage basins (Extended Data Figure 2) ^{73,74}. Solid lines are annual averages of
882 the monthly data (dashed lines). Further details of the SMB models used in this study are
883 provided in Extended Data Table 2.

884

885 **Extended Data Figure 5 | Greenland Ice Sheet mass balance intra-comparison.** Individual
886 rates of Greenland ice-sheet mass balance used in this study as determined from satellite
887 altimetry (a, top), gravimetry (b, centre) and the input–output method (c, bottom). The
888 light-grey shading shows the estimated 1 σ uncertainty relative to the ensemble average.
889 The standard error of the mean solutions, per epoch, is shown in mid-grey.

890

891 **Extended Data Figure 6 | Greenland Ice Sheet mass balance inter-comparison.** Rate of
892 Greenland Ice Sheet mass balance as derived from the three techniques of satellite radar
893 and laser altimetry (red), input-output method (blue), and gravimetry (green), and their
894 arithmetic mean (gray). The estimated uncertainty is also shown (light shading) and is
895 computed as the root mean square of the component time-series errors.

896

897 **Extended Data Figure 7 | Cumulative Greenland Ice Sheet surface mass balance.** The
898 cumulative surface mass change (lightest blue) determined from an average of the
899 RACMO2.3p2 ⁴⁶ (light blue), MARv3.6 ²¹ (mid-blue) and HIRHAM ⁹ (dark blue) regional
900 climate models relative to their 1980-1990 means (see Methods). The estimated uncertainty
901 of the average change is also shown (shaded area) is computed as the average of the
902 uncertainties from each of the three models. RACMO2.3p2 uncertainties are based upon a
903 comparison to in-situ observations ³³. MARv3.6 uncertainties are evaluated from the
904 variability due to forcing from climate reanalyses ²¹. HIRHAM uncertainties are estimated
905 based on comparisons to in-situ accumulation and ablation data ⁷⁵. Cumulative uncertainties
906 are computed as the root sum square of annual errors, on the assumption that these errors
907 are not correlated over time ¹⁷.

908

909 **Extended Data Table 1. Glacial Isostatic Adjustment models.** Details of Glacial Isostatic
910 Adjustment (GIA) models used in this study.

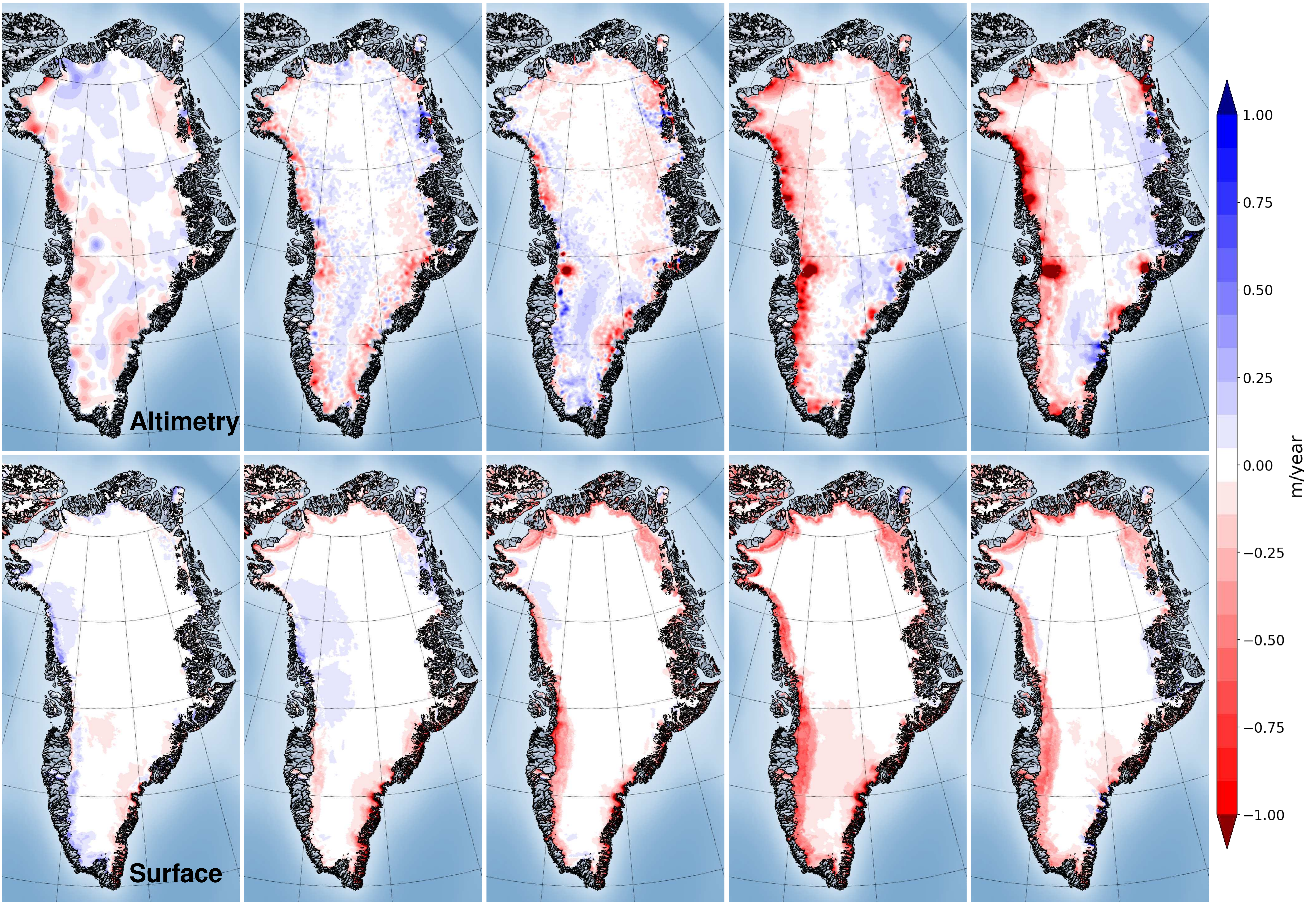
911 †Regional changes in mass associated with the GIA signal determined by the contributor.
912 ‡Regional changes in mass associated with the GIA signal calculated as an indicative rate
913 using spherical-harmonic degrees 3 to 90 and a common treatment of degree 2⁷⁶.
914 ^a Main reference publication(s).
915 ^b Model from main publication unless otherwise stated. Comma-separated values refer to
916 properties of a radially varying (1D, one-dimensional) Earth model: the first value is
917 lithosphere thickness (km), other values reflect mantle viscosity ($\times 10^{21}$ Pa s) for specific
918 layers; see relevant publication.
919 ^c GIA model details: SH=spherical harmonic (maximum degree indicated), FE=finite element,
920 C=compressible, IC=incompressible, RF=rotational feedback, SG=self-gravitation, OL=ocean
921 loading, 'x' = feature not included.
922 ^d RSL = relative sea-level data; GPS rates corrected for elastic response to contemporary ice
923 mass change.
924 ^e Earth model taken from ref⁵⁴
925 ^f Ice model taken from ref⁵⁴
926 ^g Different to ICE-6G_C in Antarctica, owing to the use of BEDMAP2⁷⁷ topography.

927

928 **Extended Data Table 2. Surface mass balance models.** Details of the surface mass balance
929 (SMB) models used in this study. ^a Main reference publication; additional references are
930 provided in Supplementary Table 1. ^b SMB model class; regional climate model (RCM),
931 global numerical analysis (GA), process model (PM). Native resolution (n) and downscaled
932 (d) models are also identified. ^c Averages over the period 1980 to 2012 for the
933 Greenland Ice Sheet excluding peripheral ice caps and using the drainage basins from ref³⁷.

934

935 **Extended Data Table 3: Rate of Greenland Ice Sheet mass change, 2005-2015.** Estimates of
936 ice-sheet mass balance from satellite altimetry, gravimetry the input–output method, and
937 from all three groups during the period 2005 to 2015. Also shown are the average standard
938 deviations (s.d.) and ranges of individual estimates within each group during the same
939 period.
940 *No altimetry data in 2010.



1992-1997

1997-2002

2002-2007

2007-2012

2012-2017

Altimetry
Gravimetry

Input-Output Method
All

