Recent contributions of glaciers and ice caps to sea level rise

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Introduction

"Glaciers and ice caps (GICs) are important contributors to present day global mean sea level rise(1–4). Most previous global mass balance estimates for GICs rely on extrapolation of sparse mass balance measurements(1,2,4) representing only a small fraction of the GIC area, leaving their overall contribution to sea level rise unclear. Here we show that GICs, excluding the Greenland and Antarctic peripheral GICs, lost mass at a rate of 148 +/-30 Gt yr^-1 from January 2003 to December 2010, contributing 0.41 +/- 0.08 mm yr^-1 to sea level rise. Our results are based on a global, simultaneous inversion of monthly GRACE-derived satellite gravity fields, from which we calculate the mass change over all ice-covered regions greater in area than 100 km^2 . The GIC rate for 2003–2010 is about 30 % smaller than the previous mass balance estimate that most closely matches our study period(2) . The high mountains of Asia, in particular, show a mass loss of only 4 +/- 20 Gt yr^-1 for 2003–2010, compared with 47–55 Gt yr^-1 in previously published estimates(2.5). For completeness, we also estimate that the Greenland and Antarctic ice sheets, including their peripheral GICs, contributed 1.06 +/- 0.19 mm yr^-1 to sea level rise over the same time period. The total contribution to sea level rise from all ice-covered regions is thus 1.48 +/- 0.26 mm yr^-1 , which agrees well with independent estimates of sea level rise originating from land ice loss and other terrestrial sources(6)."

Figure 1

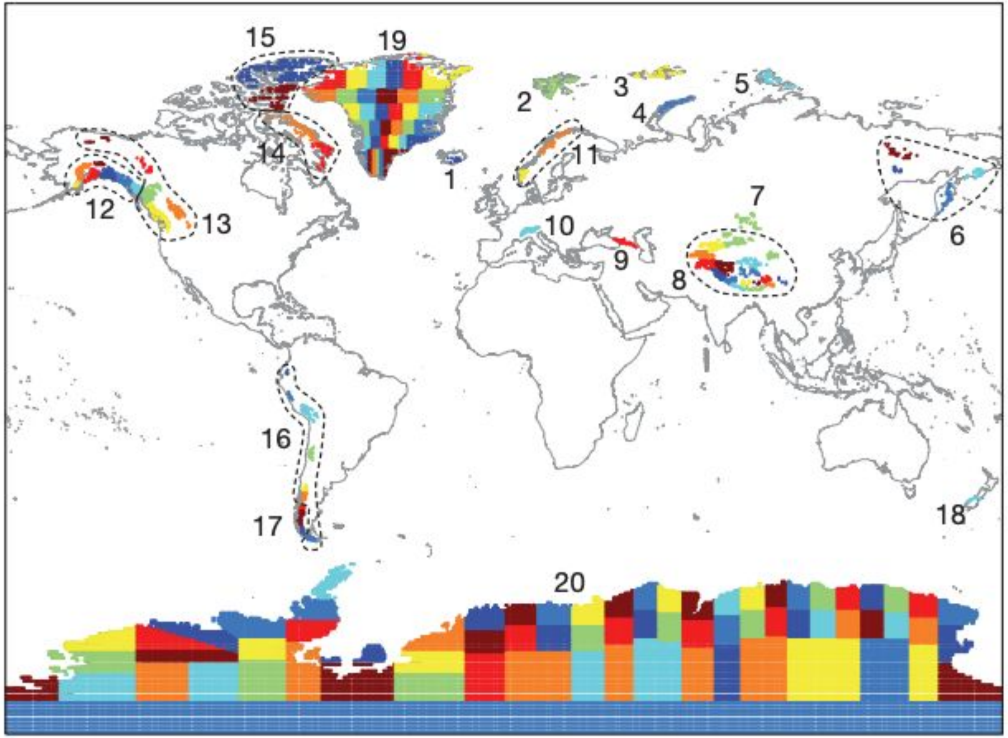

Figure 1 | Mascons for the ice-covered regions considered here. Each coloured region represents a single mascon. Numbers correspond to regions shown in Table 1. Regions containing more than one mascon are outlined with a dashed line.

Table 1

Table 1 | Inverted 2003–2010 mass balance rates

Region	Rate (Gt yr^{-1})
1. Iceland	−11 ± 2
2. Svalbard	−3 ± 2
3. Franz Josef Land	0 ± 2
4. Novaya Zemlya	−4 ± 2
5. Severnaya Zemlya	−1 ± 2
6. Siberia and Kamchatka	2 ± 10
7. Altai	3 ± 6
8. High Mountain Asia	−4 ± 20
8a. Tianshan	−5 ± 6
8b. Pamirs and Kunlun Shan	−1 ± 5
8c. Himalaya and Karakoram	−5 ± 6
8d. Tibet and Qilian Shan	7 ± 7
9. Caucasus	1 ± 3
10. Alps	−2 ± 3
11. Scandinavia	3 ± 5
12. Alaska	−46 ± 7
13. Northwest America excl. Alaska	5 ± 8
14. Baffin Island	−33 ± 5
15. Ellesmere, Axel Heiberg and Devon Islands	−34 ± 6
16. South America excl. Patagonia	−6 ± 12
17. Patagonia	−23 ± 9
18. New Zealand	2 ± 3
19. Greenland ice sheet + PGICs	−222 ± 9
20. Antarctica ice sheet + PGICs	−165 ± 72
Total	−536 ± 93
GICs excl. Greenland and Antarctica PGICs	−148 ± 30
Antarctica + Greenland ice sheet and PGICs	−384 ± 71
Total contribution to SLR	1.48 ± 0.26 mm yr^{-1}
SLR due to GICs excl. Greenland and Antarctica PGICs	0.41 ± 0.08 mm yr^{-1}
SLR due to Antarctica + Greenland ice sheet and PGICs	1.06 ± 0.19 mm yr^{-1}

Uncertainties are given at the 95% (2σ) confidence level.

Figure 2

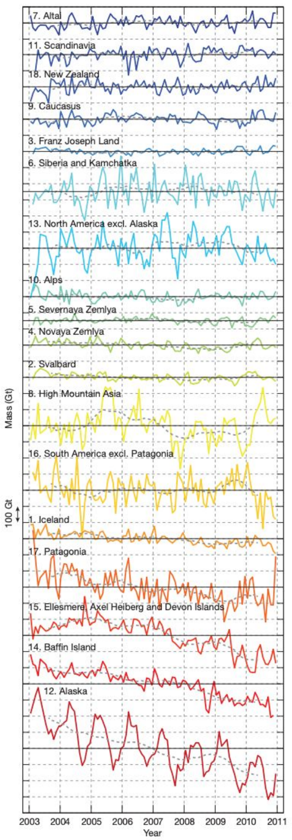

Figure 2 | Mass change during 2003–2010 for all GIC regions shown in Fig. 1 and Table 1. The black horizontal lines run through the averages of the time series. The grey lines represent 13-month-window, low-pass-filtered versions of the data. Time series are shifted for legibility. Modelled contributions from GIA, LIA and hydrology have been removed.

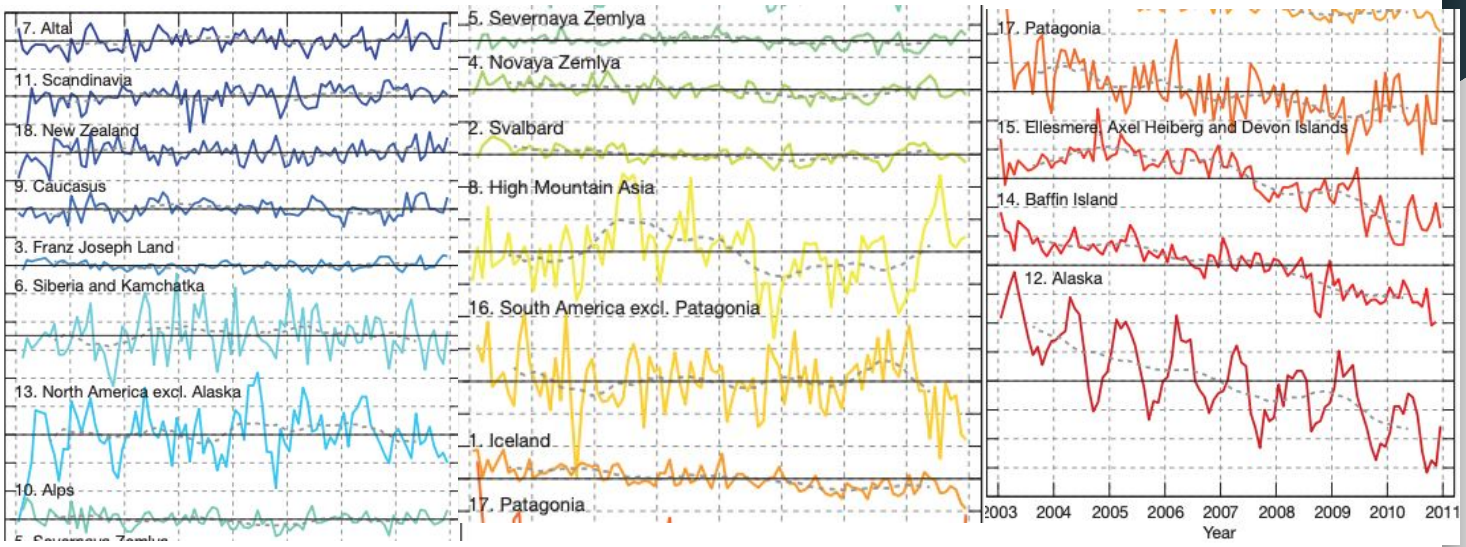

Figure 3

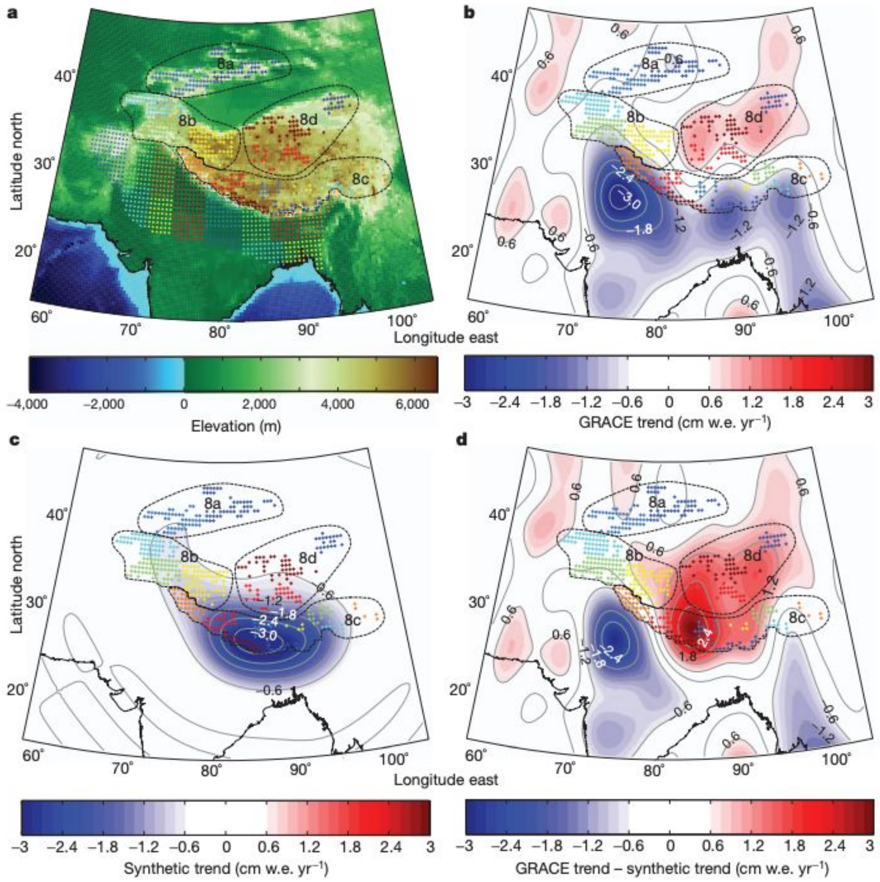

Figure 3 | HMA mass balance determination. a, Topographic map overlaid with the HMA mascons (crosses) and India plain mascons (dots); the dashed lines delimit the four HMA subregions (labelled as in Table 1). **b**, GRACE mass rate corrected for hydrology and GIA and smoothed with a 350-km Gaussian smoothing function, overlaid with the HMA mascons. w.e., water equivalent. **c**, Synthetic GRACE rates that would be caused by a total mass loss of 55 Gt yr^{-1} over HMA mascons, with 29 Gt yr^{-1} over the eastern Himalayas, after ref. 2. **d**, The difference between **b** and **c**.

Figure S1

Figure S1: Global mass trend from GRACE during 2003-2010. A 350 km Gaussian smoothing is applied. a: Grace mass trend , b: same as a, but corrected for the effects of hydrology and glacial isostatic adjustment, c: same as b, but with the inverted mascon mass estimates removed.

Supplementary Figures and Legends

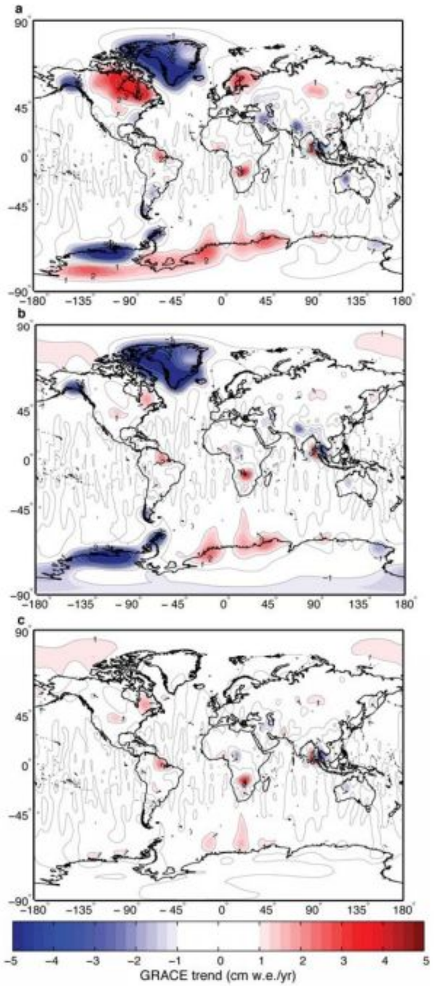

Figure S2

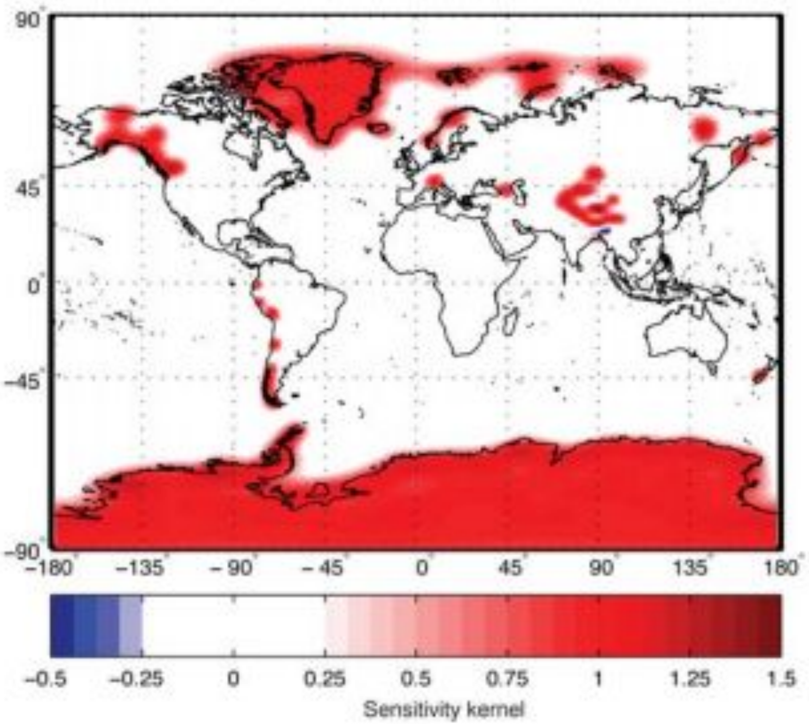

Figure S2: Sensitivity kernel for all glacierized regions represented by a mascon.

Figure S3

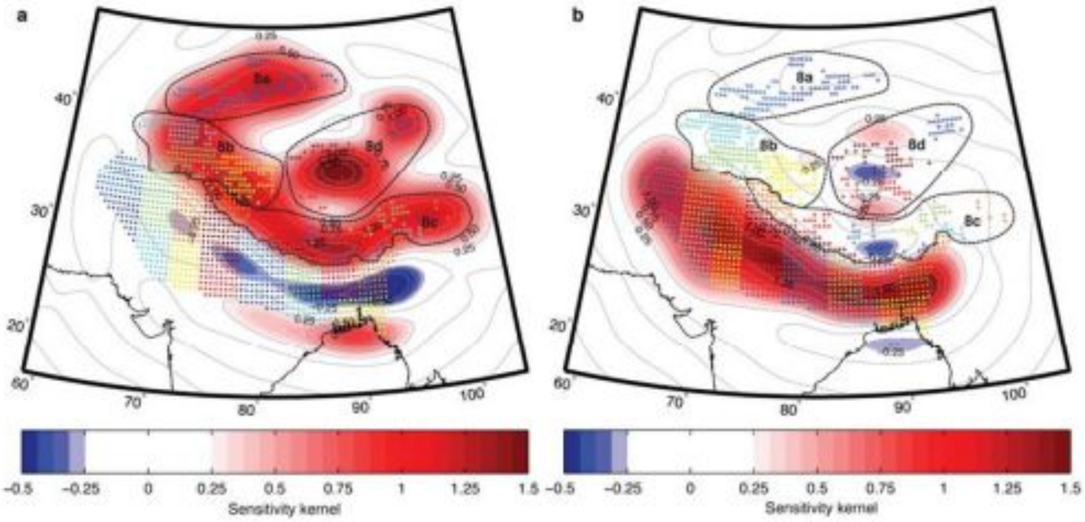

Figure S3: HMA mascons and plains mascons sensitivity kernels. a: HMA mascons sensitivity kernel, the dark-grey dashed lines delimit the boundaries between the four HMA sub regions. Colour symbols represent the mascons. b: same as a, but showing the sensitivity kernels for the plains mascons.

Figure S4

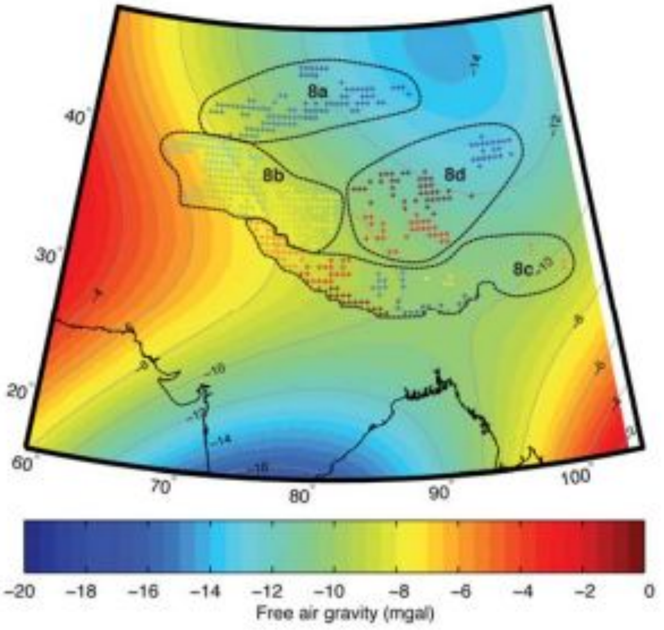

Figure S4. The static free-air gravity field over HMA from EGM96. Topographic contributions from the Himalaya and other mountainous regions are not evident, indicating a high degree of isostatic compensation.

Figure S5

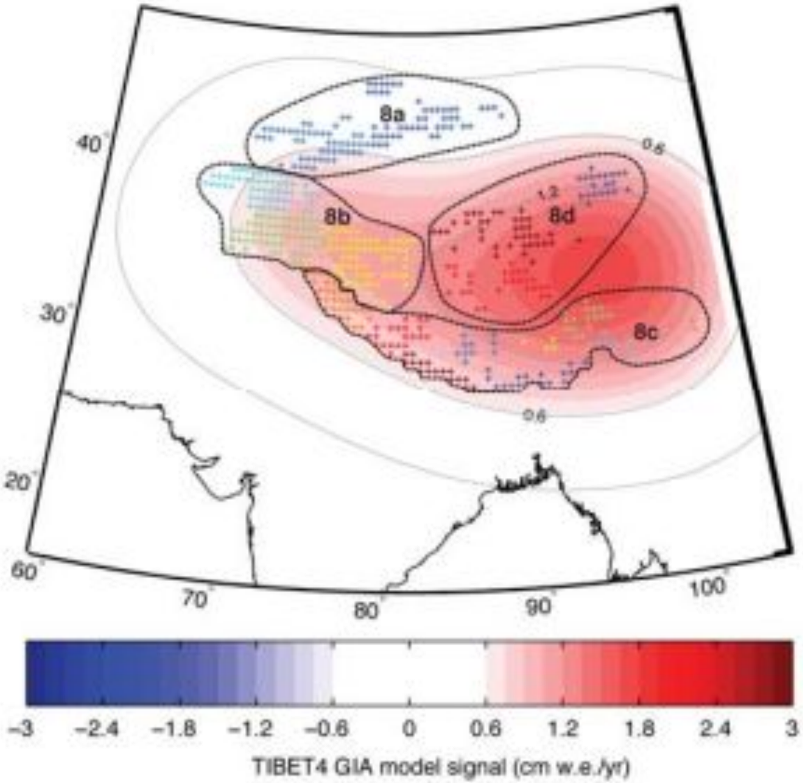

Figure S5: TIBET 4 glacial isostatic signal. HMA mascons are shown.

Figure S6

Figure S6: Mass change during 2003-2010 for all mascon regions shown in Fig. 1 and Table 1. The grey lines represent a 13-month window low pass filtered version of the data. Time series are shifted for legibility. Modelled contributions from GIA, LIA, and hydrology have been removed. Similar to Figure 2, but Greenland + PGIC and Antarctica + PGIC are also included.