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Glacial-isostatic contributions to present-day sea-level change around Greenland

Kevin Fleming, Johann Wünsch, Kurt Lambeck*

Department 1 Geodesy and Remote Sensing
GeoForschungsZentrum - Potsdam
Potsdam, Germany

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*Geodynamics Group
Research School of Earth Sciences
Australian National University
Canberra, Australia

Abstract

Present-day sea-level change around Greenland is examined by assessing the role played by glacial-isostatic adjustment (GIA). We consider the contributions from: (1) the ongoing GIA due to changes in the extent and thickness of the Greenland Ice Sheet (GIS) following the Last Glacial Maximum (LGM), (2) the equivalent signal associated with the continental ice masses located outside of Greenland, and (3) present-day changes in the GIS.

Changes in the GIS arising from the last glacial-interglacial transition generally result in falling sea level today. The contribution from ice-load changes outside of Greenland causes rising sea level, owing to Greenland's location on the collapsing forebulge that surrounds the former North American ice sheets. Combining predictions of these contributions gives results showing rising sea level in the southwest and falling sea level in the north and east. However, this is strongly dependent upon the neoglacial part of the GIS's history. The present-day behaviour of the GIS is predicted to cause falling sea level with rates of several mm yr^{-1} around areas experiencing the larger ice-load changes.

The available tide-gauge data are considered unusable by the standards of many workers. Nevertheless, we compare rates of local sea-level change inferred from this type of data with our predictions. In Southern Greenland, where the tide-gauge stations are located, sea level is predicted to be rising at a rate of 4 to 5 mm yr^{-1}. Our predictions match most of the rates obtained from the tide-gauge time series, with the exception of Qaqortoq where the inferred rates may also reflect additional oceanic and meteorological effects. Similarly, our predictions are consistent with GPS observations, with again the exception of Qaqortoq.

Keywords: Greenland Ice Sheet, glacial-isostatic adjustment, sea-level change.

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1 Introduction

Knowing the current state of the Greenland Ice Sheet (GIS), i.e. its growth or decay, is essential to our understanding of present-day and future sea-level change (e.g. Church et al., 2001). This is due to the fact that the GIS contains the equivalent of 7 m of water if distributed evenly over the oceans. It is also located in a region of significant climatic variability that has been marked by much faster climate change than the global average. Another issue is the matter of the ice sheet itself being an important influence on arctic climatic conditions, with its demise predicted to cause cooling over parts of the North Atlantic and Arctic Oceans, and warming over Siberia and Arctic Canada (e.g. Dethloff et al., 2004).

One possible way of placing constraints on the GIS's past and current behaviour is by examining present-day sea-level change. Sea-level change around Greenland is dominated by glacial-isostatic adjustment (GIA), which refers to the mechanical response of the Earth to changes in ice loading, both in the past and the present day. We subdivide the GIA contributions to sea-level change around Greenland as follows:

- The contribution from fluctuations in the extent of the GIS since the Last Glacial Maximum (LGM, *ca.* 21 ka BP). At the LGM, the GIS had expanded out to at least the current coastline over all of Greenland, reaching the continental shelf in some areas, namely the south, southeast and northwest, the latter resulting in the GIS coalescing with the Innuitian Ice Sheet covering Ellesmere Island (Funder & Hansen, 1996; England, 1999; Bennike & Björck, 2002; Bennike et al., 2002; Fleming & Lambeck, 2004). This phase ended *ca.* 7.5 ka BP, after which in some areas the GIS retreated behind the present-day margin by 10s of kilometres, readvancing during the *neoglaciation* after *ca.* 4 ka BP (e.g. Kelly, 1980; Weidick, 1996; van Tatenhove et al., 1996).

- The ongoing-GIA response resulting from the deglaciation of the continental ice sheets outside of Greenland following the LGM. The former North American ice sheets are the most important of these contributions, given their large size and proximity to Greenland.

- Present-day changes in the GIS. Resolving the current mass balance of the GIS has been hindered by its size and inaccessibility. However, over the last fifteen years, the use of satellite altimetry (e.g. Zwally et al., 1989), airborne laser altimetry (e.g. Krabill et al., 2000) and GPS (e.g. Thomas et al., 2000a) has greatly enhanced our knowledge of the GIS's current behaviour.

In addition, there is also the global sea-level signal resulting from steric changes in ocean volume and the addition of meltwater from land-based ice (e.g. Antonov et al., 2002; Miller & Douglas, 2004). For the purpose of this work, we will make use of published studies when considering these contributions.

We proceed as follows: In Section 2, we present predictions of the GIA contributions to present-day sea-level change around Greenland. Section 3 outlines present-day sea-level change around Greenland as recorded by tide-gauge time series. Section 4 compares our predictions with the observed sea-level change signal derived from the tide-gauge data. Our results are summarized in Section 5.

2 GIA contributions to sea-level change

2.1 Computer and input models

The computation programs and input models used to calculate the GIA predictions are recent versions developed at the Research School of Earth Sciences, the Australian National University (ANU, e.g. Nakada & Lambeck, 1987; Johnston, 1993; Lambeck & Johnston, 1998; Lambeck et al., 2003; Fleming & Lambeck, 2004). The calculations accommodate moving coastlines, the growth and decay of grounded ice and changes in the Earth's rotation. Details of the background theory and the development of the ice models are provided in the above cited works.

For the ongoing-GIA response arising from the deglaciation following the LGM, we consider the Greenlandic, North American (Laurentide, Innuitian and Cordilleran), European (Fennoscandian, Barents-Kara Seas and British Isles) and Antarctic ice sheets. The ice models describe the temporal and spatial variation in these ice sheets, including prescribed pre-LGM descriptions. Although changes in ice loading also occurred in other parts of the world (e.g. Patagonia and Iceland), only their contributions to eustatic sea level will be considered, since the associated GIA signal around Greenland is negligible.

The model describing changes in the present-day GIS is based on airborne-laser altimetry surveys. These surveys measure changes in the ice sheet's surface elevation, which is the sum of crustal (largely isostatic) movement and changes in ice-sheet thickness (Krabill et al., 2000; Abdalati et al., 2001). Ice-sheet thickness is in turn a function of not only the mass balance of the ice sheet, but other processes, such as snow compaction and the internal dynamics of the GIS, which may still be reacting to past changes and is in turn a factor affecting mass balance (e.g. Abe-Ouchi et al., 1994). Ice-sheet dynamics are particularly important for ice streams, where the largest surface-elevation changes occur (e.g Thomas et al., 2000b). In the following, we assume as a first approximation that the measured changes represent losses or gains in ice mass to obtain an order-of-magnitude estimate for this contribution to sea-level change.

The predictions of the Earth's viscoelastic response to changes in ice loading are based on three-layer earth models consisting of an elastic lithosphere of thickness h_L, an upper mantle of viscosity η_{UM} extending to the seismic discontinuity at 670 km depth, and a lower mantle of viscosity η_{LM} that extends to the core-mantle boundary. Within the uncertainties of the ice models, this three-layered representation has been found to be adequate (e.g. Lambeck & Johnston, 1998). The mantle is a Maxwell, viscoelastic, incompressible body and the density and elastic properties are taken from PREM (Dziewonski & Anderson, 1981). Lateral variability in mantle viscosity and lithosphere thickness is not considered.

The uncertainties in the predictions of the post-LGM contribution are divided between those resulting from our imperfect knowledge of the past extent and thickness of the late-Pleistocene ice sheets, and those from the earth-model parameter values. The uncertainties associated with the ice sheets outside of Greenland are accommodated using several models that represent upper and lower bounds on the extent and thickness changes in the North American ice sheets, as well as the optimum models currently used by ANU. The uncertainties arising from the Earth's viscoelastic response are estimated using a range of earth-model parameter values (Table 1) that best represent areas, such as Greenland, consisting of older, thick cratonic units (e.g. Nakada & Lambeck, 1987; Mitrovica, 1996; Lambeck et al., 1998).

Table 1: Upper and lower limits for the earth-model parameter values used to provide a measure of the uncertainty in the predictions resulting from our imperfect knowledge of the Earth's viscosity structure. The last column gives the parameter values that best represent regions such as Greenland.

Parameter		Lower limit	Upper limit	Nominal
Lithosphere thickness	h_{L} (km)	50	100	80
Upper-mantle viscosity	η_{UM} ($\times 10^{20}$ Pa s)	2	6	5
Lower-mantle viscosity	η_{LM} ($\times 10^{21}$ Pa s)	5	20	10

2.2   Ice-mass changes following the LGM

Figure 1 presents the contribution to sea-level change resulting from the changes in the GIS following the LGM. We first examine the response when excluding the neoglaciation. The ice model (Fleming & Lambeck, 2004) defines the GIS as having reached its current extent by 7.5 ka BP. The signal is dominated by falling sea levels (crustal uplift), particularly pronounced in the southwest, east and north, where the GIS had expanded the most during the last glacial period relative to the present-day (Figure 1a, see also Le Meur & Huybrechts, 2001; Tarasov & Peltier, 2002). The maximum rates are of the order of -5 mm yr^{-1}, with the associated uncertainties, derived from the range in the earth-model parameter values, being generally less than 1 mm yr^{-1}.

To examine the effect of a neoglacial component in the GIS's history, we incorporate a simple model in Southwest Greenland where we define the GIS as having continued to retreat after reaching the present-day margin by *ca.* 40 km over 1000 years before readvancing over the last three thousand years (Figure 2, van Tatenhove et al., 1996; Wahr et al., 2001; Fleming & Lambeck, 2004). A change of several mm yr^{-1} relative to the values shown in Figure 1a occurs in the areas of concern.

Figure 3 presents the predicted rate of sea-level change due to the ongoing GIA arising from changes in the continental ice sheets outside of Greenland following the LGM. This results in rising sea levels around Greenland, with values between 2 to 5 mm yr^{-1}, decreasing west to east (Figure 3a, see also Tarasov & Peltier, 2002). The contribution from the North American ice sheets is the dominant part, the rising sea level resulting from the collapse of the forebulge that surrounds those former ice masses and upon which Greenland is situated. We obtain an uncertainty of less than 1 mm yr^{-1}, found using the range of earth-model parameter values (Table 1) and maximum and minimum descriptions of the North American ice sheets.

Figure 4 presents the total ongoing-GIA response around Greenland, using the GIS ice model that incorporates a neoglaciation. Spatial variability of the order of several mm yr^{-1} is noted around the island, and it is expected that these results would be significantly modified if neoglacial contributions were included in other parts of Greenland, such as the east and northwest. Examining the uncertainties, found using the range of earth-model parameter values (Table 1) and maximum and minimum descriptions of the North American ice sheets, we observe that they are comparable with the response in the southwest, leading to the possibility that the GIA contribution may be either positive (rising sea levels) or slightly negative (falling sea levels) in this region.
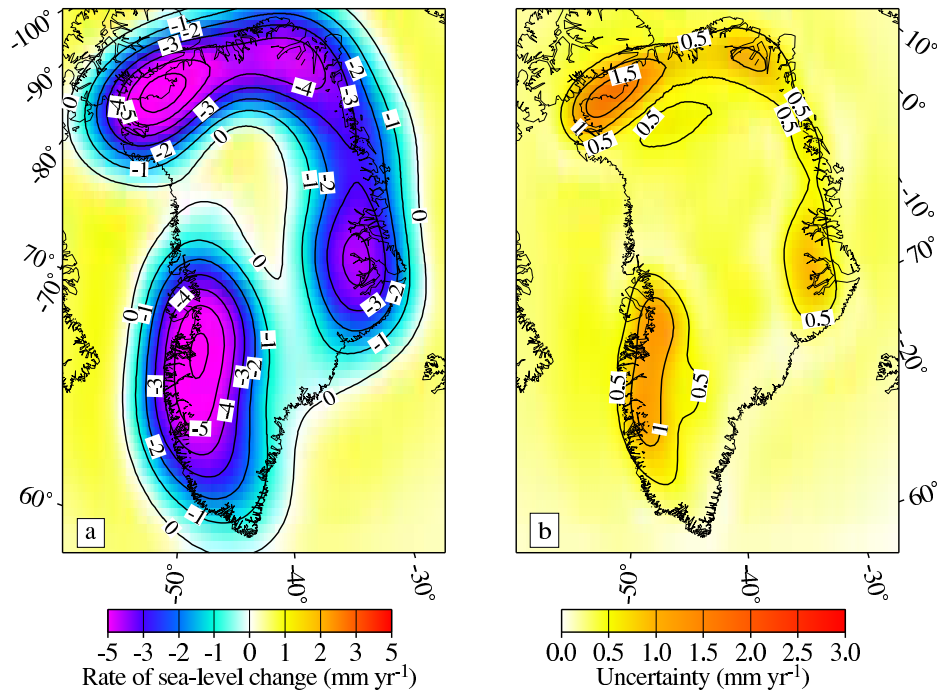
Figure 1: (a) Predicted present-day rate of sea-level change (mm yr^{-1}) around Greenland resulting from the effect of changes in the Greenland Ice Sheet following the Last Glacial Maximum. (b) The uncertainty (mm yr^{-1}) associated with these predictions, based on a range of earth-model parameter values (Table 1).
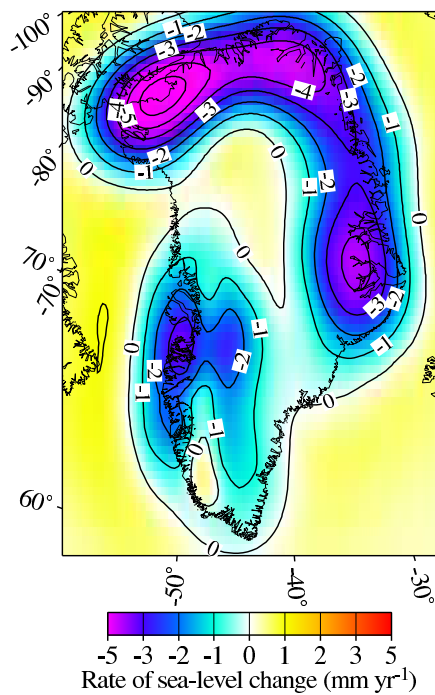

Figure 2: Predicted present-day rate of sea-level change (mm yr^{-1}) around Greenland resulting from the effect of changes in the Greenland Ice Sheet following the Last Glacial Maximum, including a neoglacial contribution in the southwest.
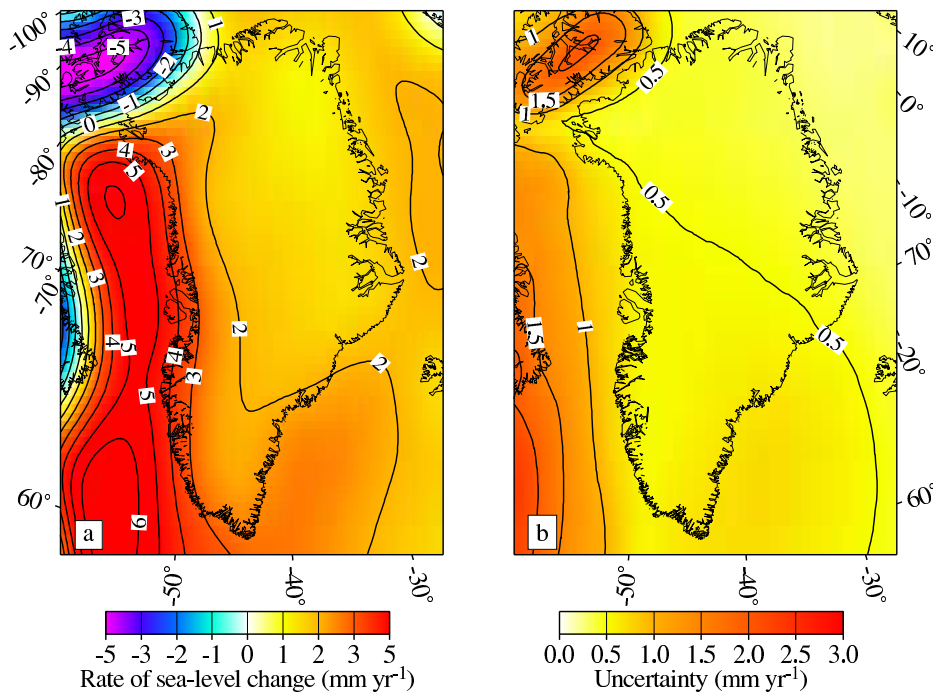
Figure 3: (a) Predicted present-day rate of sea-level change (mm yr^{-1}) around Greenland resulting from the effect of changes in the late-Pleistocene continental ice sheets outside of Greenland following the Last Glacial Maximum. (b) The uncertainty (mm yr^{-1}) associated with these predictions, based on a range of ice- and earth-model parameter values (see text for details).
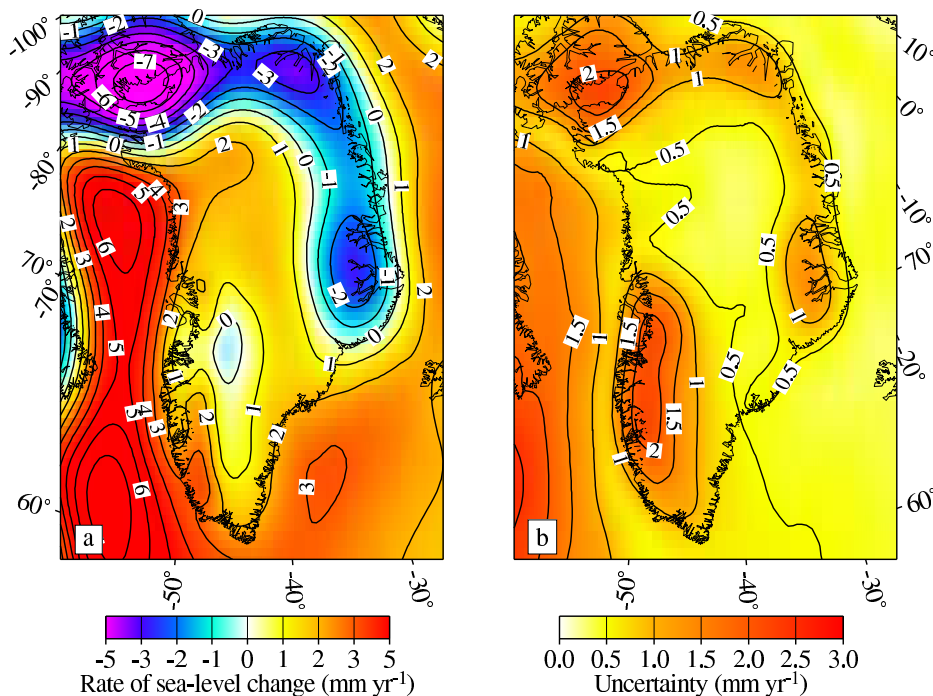

Figure 4: (a) Predicted present-day rate of sea-level change (mm yr^{-1}) around Greenland resulting from the changes in the late-Pleistocene ice sheets following the Last Glacial Maximum (the Greenlandic contribution includes a neoglacial component). (b) The uncertainty (mm yr^{-1}) associated with these predictions, based on a range of ice- and earth-model parameter values (see text for details).

2.3 Present-day changes in the Greenland Ice Sheet

Predictions of sea-level displacement resulting from changes in the present-day GIS, using an ice model derived from airborne laser-altimetry measurements (Krabill et al., 2000; Abdalati et al., 2001) are shown in Figure 5 for: (a) a rigid earth and (b) the nominal earth model (Table 1). The contribution associated with the rigid earth is generally less than -1 mm yr^{-1}. Using the nominal earth model results in falling sea levels of several mm yr^{-1} around areas experiencing the larger changes in ice mass (e.g. the southeast), largely a result of the Earth's elastic response to the prescribed ice-load changes. Around most of Greenland, this contribution is less than that predicted from the ongoing-GIA response discussed previously (Figure 1a), although in the southeast, the resulting values are of a similar magnitude.
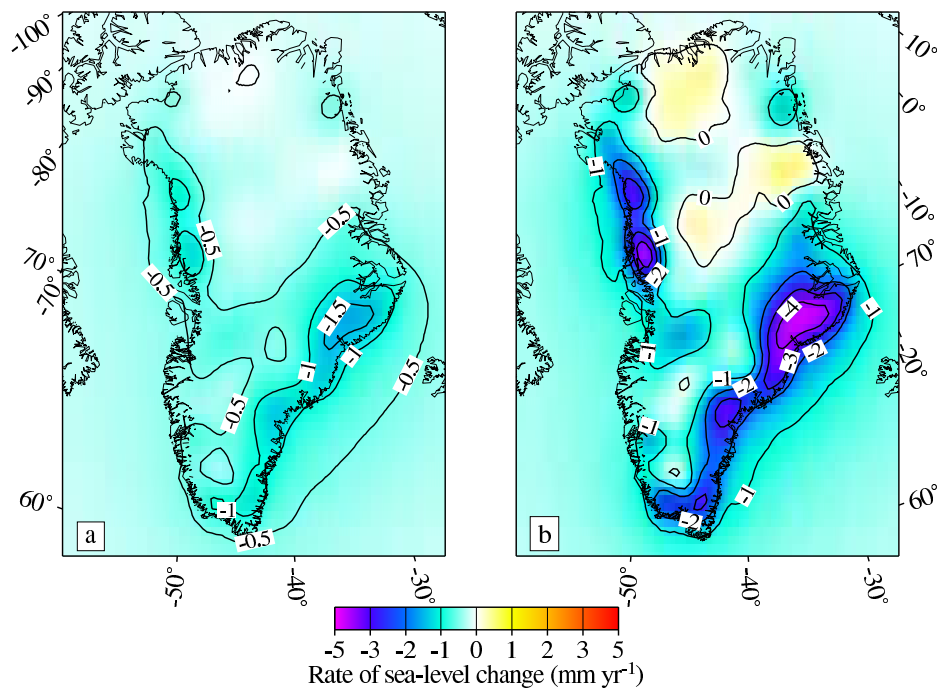

Figure 5: Predicted present-day rate of sea-level change (mm yr^{-1}) around Greenland resulting from current changes in the Greenland Ice Sheet (Krabill et al., 2000) for the cases of: (a) a rigid earth and (b) the nominal viscoelastic earth model (Table 1).

3 Tide-gauge time series

The tide-gauge time series used in this study are metric-monthly averages from the Permanent Service for Mean Sea Level (PSMSL, Woodworth & Player, 2003). Figure 6 shows the location of the tide-gauge stations in Greenland registered with the PSMSL, with some details listed in Table 2. Only Southern Greenland is covered, with most stations providing less than 10 years of observations, the exception being Nuuk (formerly Godthåb). These data are considered inadequate by many workers (e.g. Douglas, 1997), however, until longer records become available, we will consider the four longest time series to obtain estimates for present-day sea-level change rates. The corresponding stations are: Sisimiut, Nuuk, Qaqortoq and Ammassalik.

To estimate local sea-level trends, we first remove the annual and semi-annual cycles from the PSMSL data. A linear trend was then fitted to the reduced data, the resulting gradients being the rate of sea-level change at each station. The inferred rates are listed in Table 3 with the time series shown in Figure 7. In each case, the inferred rates are the same within the estimated uncertainties, regardless of whether the annual and/or semi-annual cycles are removed. We find rising sea level at Nuuk, while sea level, when considering the uncertainties, may be either falling or rising at Sisimiut and Ammassalik. At Qaqortoq, sea level is falling at an unreasonably high rate that is not explainable by GIA.

A more detailed analysis has been carried out for the Nuuk time series. We make use of a linear-trend analysis diagram (Wolf et al., 2004) that describes the rates of sea-level change inferred using different time-interval segments of the reduced time series. The results are shown in Figure 8. The intention is to display the temporal variability in the rate of sea-level change. The larger rates of change that occur when shorter time intervals (e.g. 5 years) are used result from several periods with extreme sea-level values and a number of data gaps (e.g. around 1997), as seen from the data record (top of Figure 8). Unfortunately, little additional information can be drawn from this figure.

Table 2: Tide-gauge stations in Greenland registered with the Permanent Service for Mean Sea Level. FRV - Royal Danish Administration of Navigation and Hydrography, DMI - Danish Meteorological Institute. Only sites with the longer records are examined in this work (Sisimiut, Nuuk, Qaqortoq, Ammassalik). The numbers next to the station names correspond to the figure labels.

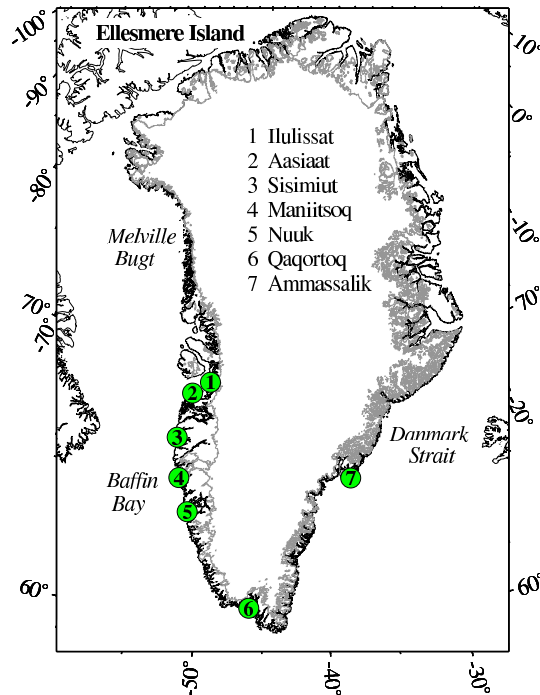| Station and authority	Location	Time interval/Supplementary information
(1) Ilulissat (FRV)	69°13'N/51°06'W	June 1992 to June 1997. Ceased operating June, 1997.
(2) Aasiaat (FRV)	68°43'N/52°53'W	June 1997 to June 1999.
(3) Sisimiut (FRV)	66°56'N/53°40'W	Sept. 1991 to Dec. 1999.
(4) Maniitsoq (FRV)	65°25'N/52°54'W	June 1997 to Dec. 1999.
(5) Nuuk (Godthåb) (FRV, DMI)	64°10'N/51°44'W	Jan. 1958 to Dec. 2001. Ceased operating 2002. Data from 1970 is only used as the station was relocated in 1969.
(6) Qaqortoq (FRV)	60°43'N/46°02'W	Sept. 1991 to Dec. 1999.
(7) Ammassalik (FRV)	65°30'N/37°00'W	Nov. 1990 to Dec. 1999.

Figure 6: Location of tide-gauge stations in Greenland registered with the Permanent Service for Mean Sea Level (Table 2).
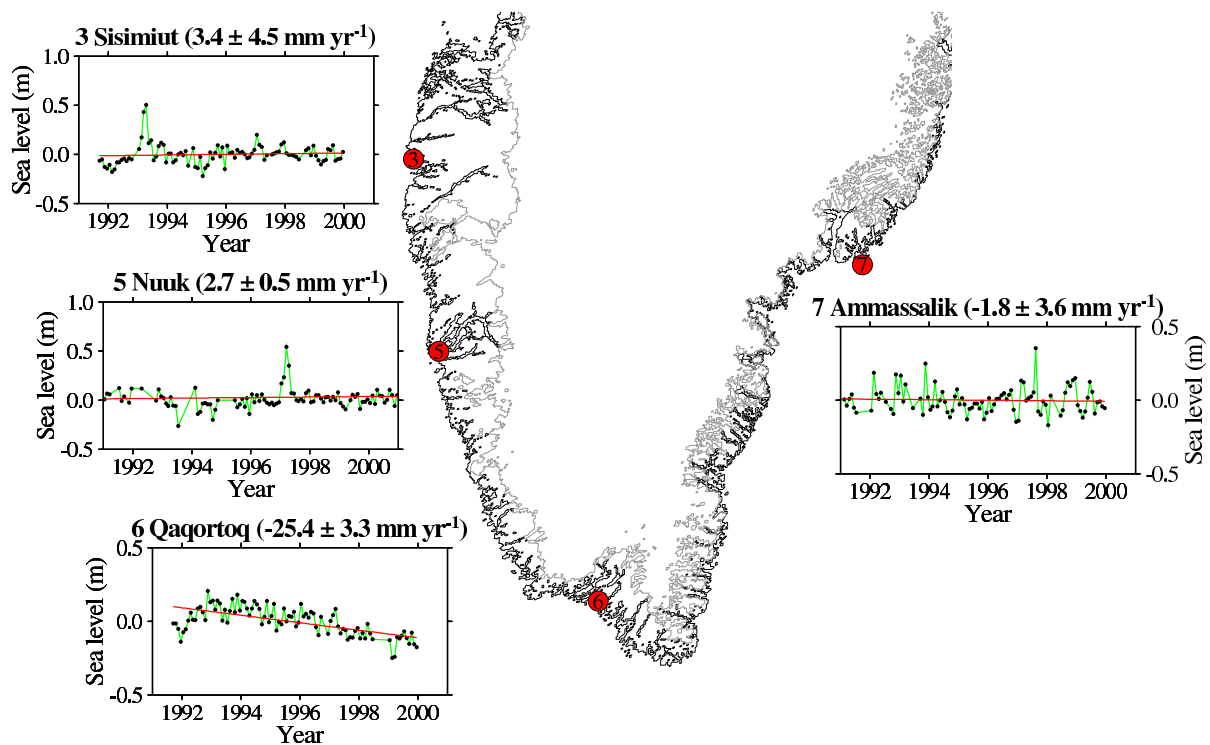

Figure 7: The tide-gauge time series used in this work (metric-monthly means, arbitrary benchmark, Permanent Service for Mean Sea Level, reduced for annual and semi-annual cycles). Also shown are the secular trends (mm yr^{-1}) inferred from the data (Table 3). The Nuuk time series is displayed over the same period as that of the other sites, although it is much longer. The full time series for Nuuk is shown in Figure 8.

Table 3: Present-day sea-level change inferred from Permanent Service for Mean Sea Level (PSMSL) metric-monthly-mean tide-gauge time series. Three results are presented: Rates inferred from the original PSMSL data, rates from the data with the annual cycle removed, and rates from the data with the annual and semi-annual cycles removed. The numbers next to the site names correspond to the labels in Figure 6.

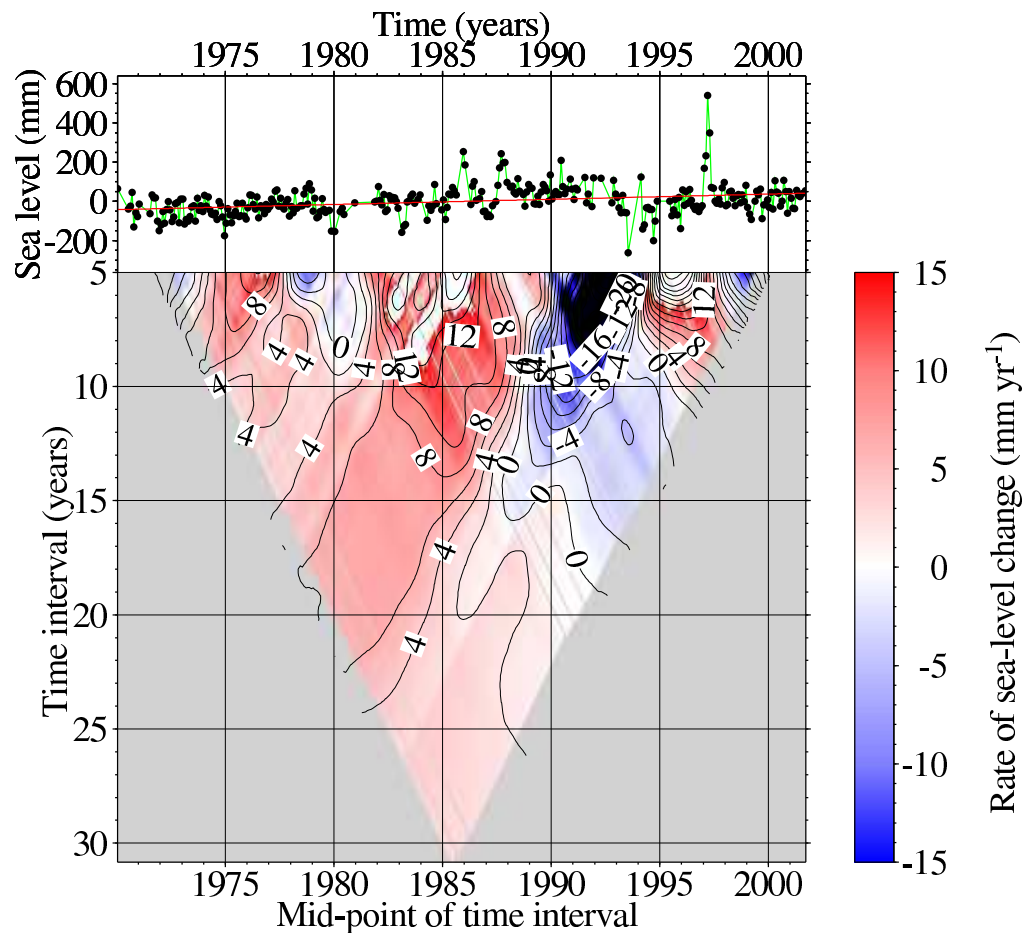| Station	Monthly (mm yr^{-1})	Monthly - annual (mm yr^{-1})	Monthly - annual - semiannual (mm yr^{-1})
(3) Sisimiut	4.8 ± 5.5	3.9 ± 4.6	3.4 ± 4.5
(5) Nuuk (Godthåb)	2.3 ± 0.7	2.6 ± 0.5	2.7 ± 0.5
(6) Qaqortoq	-28.1 ± 4.9	-25.3 ± 3.3	-25.4 ± 3.3
(7) Ammassalik	-0.4 ± 5.6	-1.6 ± 3.7	-1.8 ± 3.6

Figure 8: Linear-trend analysis diagram (Wolf et al., 2004) for Nuuk from reduced tide-gauge time series (corrected for annual and semi-annual cycles). Only data after 1970 is used (Table 2).

4   Comparing observations and predictions

We now compare our predictions with the values inferred from the tide-gauge time series. Figure 9a shows the predicted total present-day rate of sea-level change around Southern Greenland, found by incorporating the previously presented GIA contributions (Figures 2a, 3a and 4b), and an estimate for the global steric and meltwater contributions (1.5 ± 0.7 mm yr^{-1}, Church et al., 2001). Sea level is predicted to be rising around the entire region, with rates ranging between *ca.* 3 to 4 mm yr^{-1}, and a spatial variability of the order of 1 mm yr^{-1} along/near the larger fjords. As this variability is a function GIA, it would be useful to further assess past ice-sheet behaviour by methods such as GPS, provided a sufficiently extensive campaign network is deployed (e.g. Dietrich et al., 1998).

In Figure 9b, the predicted values are compared with those inferred for the considered tide-gauge stations (predictions for each station are included for completeness). We also include the crustal-uplift rates (with the global-average sea-level change value subtracted) found by three permanent GPS stations to provide independent, first-order approximations of present-day sea-level change; Kellyville (-5.8 $\pm$ 1.0 mm yr^{-1}), Kulusuk, adjacent to Ammassalik (-2.1 $\pm$ 1.5 mm yr^{-1}) (Wahr et al., 2001), and Qaqortoq (5.0 ± 0.7 mm yr^{-1}) (MIT, 2005). Kellyville is inland from Sisimiut by *ca.* 150 km, while the other two sites are within several kilometres of their associated tide-gauge stations. These GPS sites indicate crustal subsidence around Nuuk, Sisimiut and Ammassalik, a result of either present-day changes in the GIS (increasing ice load) or the ongoing effect of past ice-load changes.

The inferred and modelled results from Sisimiut (3), Nuuk (5) and Ammassalik (7) are comparable within their uncertainties, that are rather large for the inferred values (with the exception of Nuuk), such that sea-level may be either falling or rising. We however note that the inferred value for Qaqortoq (6) differs greatly from its prediction. Regarding the values inferred from the GPS observations, the results for Kellyville and Ammassalik are in agreement with our sea-level change predictions, but a discrepancy again arises for Qaqortoq.

A number of archaeological sites (Eskimo and Norse) indicate that sea level has been rising in many locations in Southern Greenland over the last few thousand years (Weidick, 1996). This rise is particularly marked in areas such as Herjolsnes (*ca.* 100 km south-east of Qaqortoq), where a Norse graveyard is partially submerged (Kuijpers et al., 1999). However, the rate and direction of sea-level change may vary significantly over time scales of decades. For example, at Angmagssalik in Southeast Greenland (near Ammassalik), sea level fell at a rate of 2.7 mm yr^{-1} between 1885 to 1950, and then rose by 7 mm yr^{-1} until 1957 (Saxov, 1961). Therefore, while our GIA predictions represent a long-term background signal, decadal changes, whether arising from changes in the GIS or from oceanographic and meteorological forcing processes, would have a major influence. For example, the falling sea level inferred for Qaqortoq, based on the tide-gauge and GPS time series, indicates significant uplift, although archaeological observations suggest the opposite.
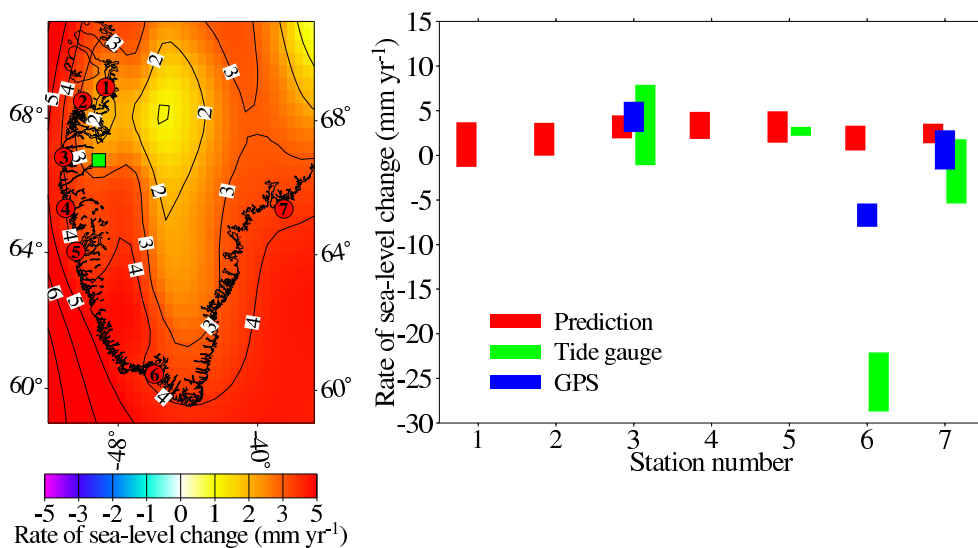
Figure 9: (a) Predicted total rate of sea-level change (mm yr^{-1}) for Southern Green-land. These results include the GIA contribution from the late-Pleistocene ice sheets, and an estimate for the global sea-level signal (1.5 mm yr^{-1}, Church et al., 2001). The numbered circles are the tide-gauge stations (Figure 6 and Table 2), while the green square is the Kellyville GPS site. The other GPS stations are sufficiently close to their corresponding tide-gauge station so as not to warrant an additional marker. (b) Comparison of local rates of sea-level change derived from the tide-gauge time series considered in this work (corrected for annual and semi-annual cycles, Table 3) with the associated predictions for each station, as well as the sea-level change that is equiva-lent to the crustal uplift rates (corrected for the global-average sea-level contribution) measured by permanent GPS stations (Kellyville, Kulusuk, Qaqortoq). The predicted sea-level change rates for all Southern Greenland tide-gauge stations are included for completeness.

5   Conclusions

We summarise our results as follows:

- The GIS's glacial-isostatic contribution resulting from its retreat from its Last Glacial Maximum extent generally causes falling sea level today. This signal is marked by significant spatial variability, mirroring the extent to which the GIS expanded during the last glacial cycle. This response is also strongly dependent upon the history of the GIS during the last few thousand years.

- The equivalent response from the deglaciation of the ice sheets outside of Greenland causes rising sea level around Greenland. This is largely the result of the collapsing forebulge that surrounded the former North American ice sheets.

- In coastal areas where the GIS today experiences the largest changes in ice loading (e.g. the southeast), the resulting rate of sea-level change is comparable in magnitude with that associated with the signal resulting from the glacial-interglacial transition.

We have inferred local sea-level change rates from the Permanent Service for Mean Sea Level metric-monthly-mean time series after removing the annual and semi-annual cycles. With the exception of Qaqortoq, the rates of sea-level change obtained from these time series are consistent, within their uncertainties, with the predicted values, and with estimates inferred from GPS observations.

Although the present-day changes in the GIS may cause significant sea-level change of several mm yr^{-1}, the uncertainties involved in our calculations, and in inferring trends from the tide-gauge data, mean that the methodology followed in this paper is, at the present time, unsuitable for constraining the present-day mass balance of the GIS. We therefore hope that current and forthcoming space missions (e.g. GRACE, GOCE and ICESat, Rummel et al., 2002; Zwally et al., 2002) will provide tighter constraints on Greenland's ice-mass balance.

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